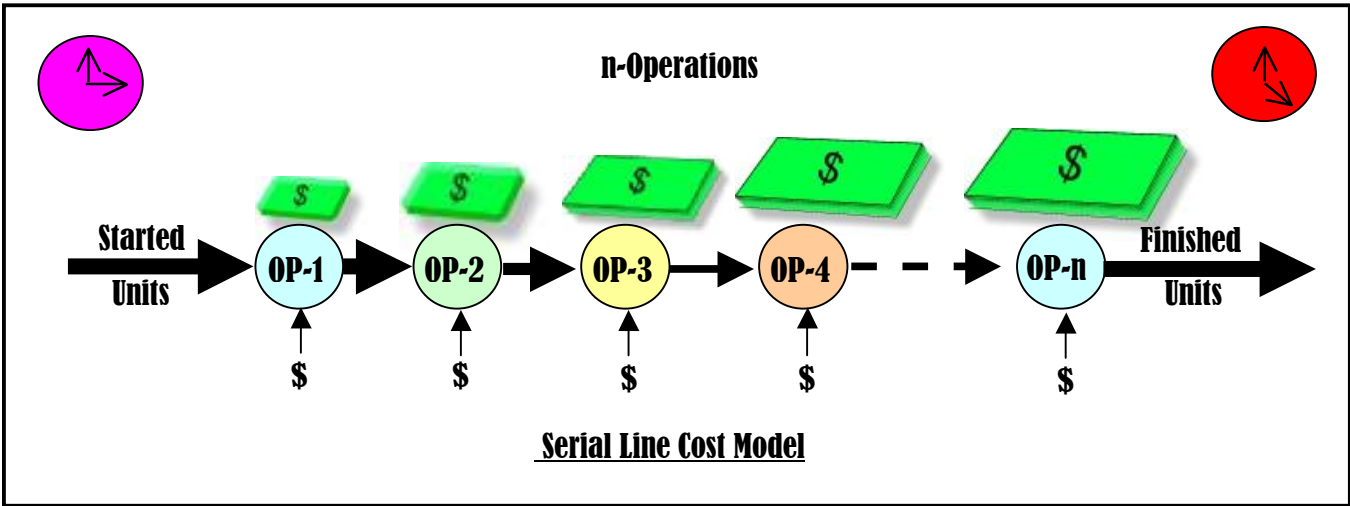


# Is WIP Investment Hurting Your Bottom Line?

by

Tim Archer



A Technical Paper from

*The Archer Tool Company, LLC*



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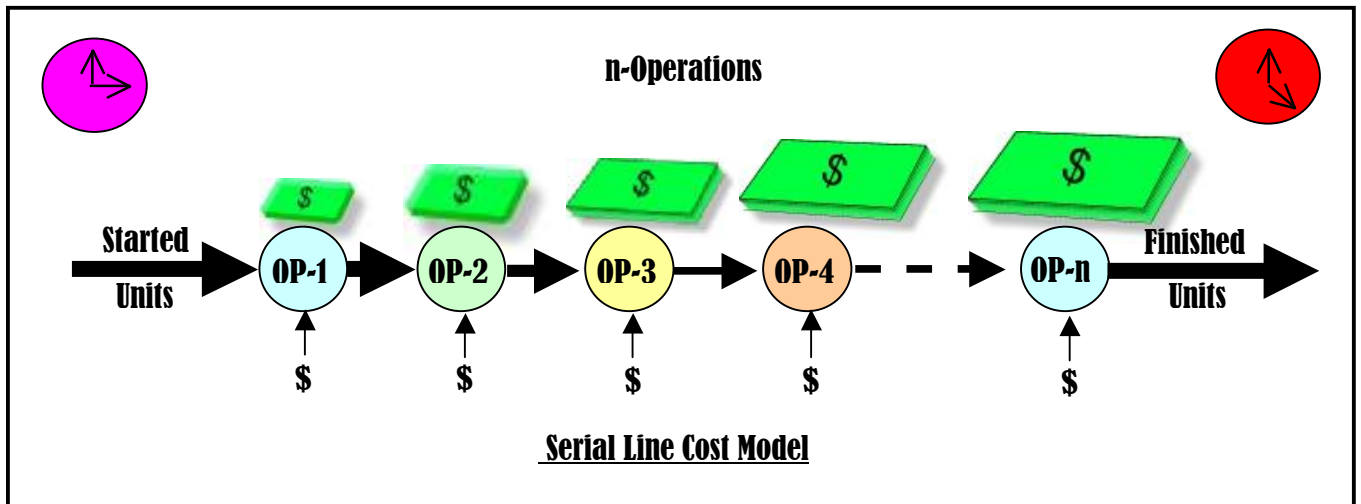
By Tim Archer

This paper defines WIP Investment and explains why it may be an important (and often neglected) characteristic of assembly lines. A strategy to minimize WIP Investment by operational sequencing is presented along with a discussion of the pros and cons of various trade-offs that exist between Cost-Efficiency and Time-Efficiency. The reader should gain a new perspective on this unique assembly line trait and how and when to minimize its negative impacts on cost performance.

## 1. "What is 'WIP Investment'?"

Peter Drucker is usually credited with the observation that Leadership and Management are the arts of "doing the right things right". In my career, I have taken his observation to heart, but I have also discovered a few additional dimensions including "Doing the right things right and in the *right sequence*". Nowhere is this more applicable than in the design of an assembly line especially in the area of Work-In-Process (WIP) Investment.

A simple cost model as shown below can represent most paced assembly lines (i.e. units move from one workstation to another at a specified time interval known as the *Cycle Time*). Each Operation (OP) requires an investment in resources (labor, materials, etc.) that have some monetary value (\$), and the investment accrues to a unit of production from operation to operation. The cumulative value of this investment at the last operation is the total cost per unit. The sum of all the accrued investment over each unit in the assembly line is the Total WIP Investment of the line.



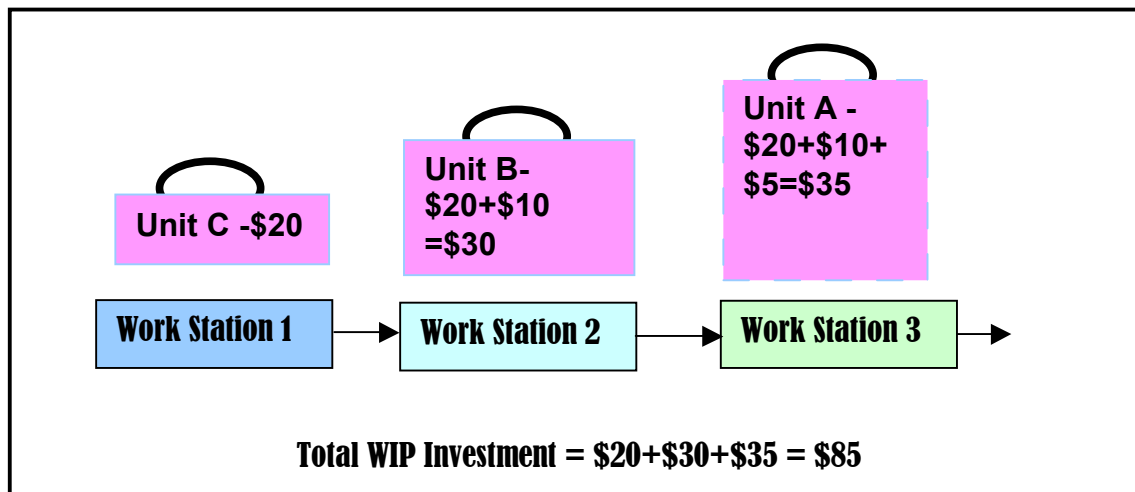
$$\text{Total WIP Investment} = \sum_{n=1}^N \sum_{i=1}^n C_i$$

Where  $C_i$  = the cost expended on Unit  $i$   
 $N$  = the total number of units in the line  
 $n, i$  = indices for summation denoting a particular operation

## 2. “How does production sequence affect WIP Investment in a paced assembly line?”

To illustrate WIP Investment and how it impacts costs, consider a fully populated paced assembly line with three Workstations. Each workstation expends cost on each unit that passes through (\$20, \$10, and \$5 respectively). At the end of a cycle, each workstation has a finished or unfinished unit in it. In the example below, Unit A has completed 3 Workstations and has \$35 of cost invested in it. Unit B has completed 2 Workstations and has \$30 invested in it. And likewise, Unit C has completed one Workstation and has \$20 of cost invested in it. So, at the end of one complete cycle, there is \$85 worth of cost trapped in the line.

### Example 1

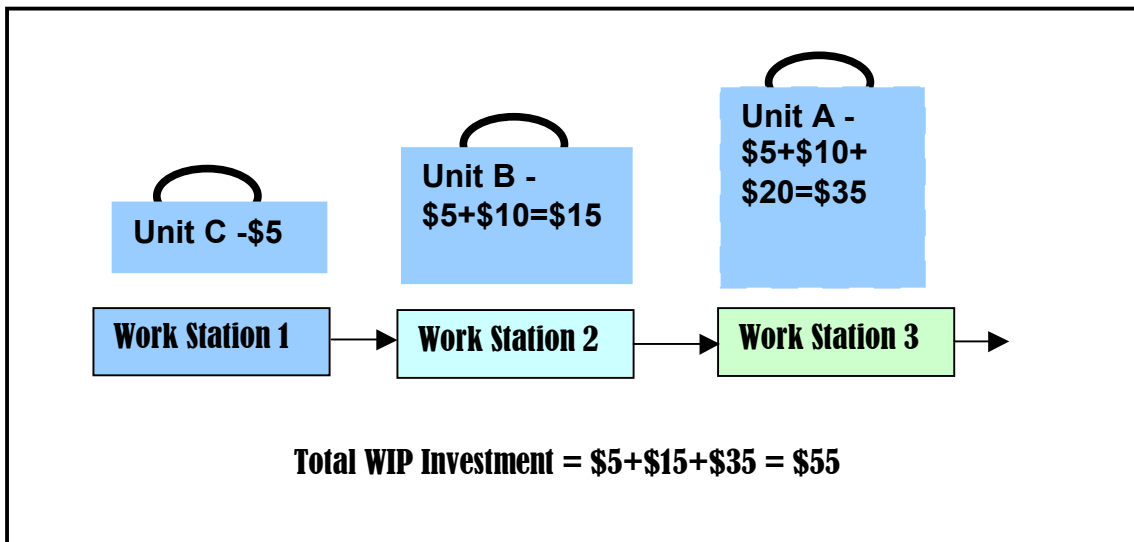


The table below shows the *Cash Flow* of the assembly line from Start-up to Shutdown while producing three complete units (Units A, B, and C). The investment in and out of each Workstation is tracked, and the Total Investment in WIP is calculated for each cycle. The highlighted cycle represents the maximum WIP investment and is the cycle that usually dominates the assembly line when all stations are populated and the line is not in Start-up or Shutdown mode and will be called a *Full Production Cycle*.

End of Cycle	Work Station Contents			Investment In (\$)	Investment Out (\$)	Investment In WIP (\$)
	WS-1	WS-2	WS-3			
-	Empty	Empty	Empty	0	0	0
1	Unit A	Empty	Empty	20	0	20
2	Unit B	Unit A	Empty	30	0	50
3	Unit C	Unit B	Unit A	35	0	85
4	Empty	Unit C	Unit B	15	35	65
5	Empty	Empty	Unit C	5	35	35
-	Empty	Empty	Empty	0	35	0
<b>Total</b>	-	-	-	105	105	-

$$\text{Average WIP Investment} = (20+50+85+65+35)/5=51$$

Now suppose these same operations could be sequenced in reverse order as shown below.



End of Cycle	Work Station Contents			Investment In (\$)	Investment Out (\$)	Investment In WIP (\$)
	WS-1	WS-2	WS-3			
-	Empty	Empty	Empty	0	0	0
1	Unit A	Empty	Empty	5	0	5
2	Unit B	Unit A	Empty	15	0	20
3	Unit C	Unit B	Unit A	35	0	55
4	Empty	Unit C	Unit B	30	35	50
5	Empty	Empty	Unit C	20	35	35
-	Empty	Empty	Empty	0	35	0
Total	-	-	-	105	105	-

$$\text{Average WIP Investment} = (5+20+55+50+35)/5=33$$

Assume the owner of the line is borrowing operating capital at an interest rate of 1% per period on outstanding balances and the investment in a completed unit is immediately recouped (paid off) when it exits the line. Also assume that all required capital for a cycle is committed at the beginning of the cycle. This means the owner of the line is only paying interest on an amount equal to the Investment in WIP at the end of the cycle. Below is a comparison of the two sequences. Note that Sequence 2 is a less expensive (i.e. *Cost Efficient*) sequence even though both sequences expend and recoup the same amount of capital (\$105)

End of Cycle	Sequence 1 Investment in WIP (\$)	Sequence 2 Investment in WIP (\$)	Sequence 1 Interest Cost (\$)	Sequence 2 Interest Cost (\$)
-	0	0	0	0
1	20	5	.2	.05
2	50	20	.5	.2
3	85	55	.85	.55
4	65	50	.65	.5
5	35	35	.35	.35
-	0	0	0	0
<b>Total Interest Cost</b>	-	-	<b>\$2.55</b>	<b>\$1.65</b>

Under this scenario, the total cost of producing three units using Sequence 1 is \$107.55, while Sequence 2 only costs \$106.65- a savings of \$0.90 or .8%. Not a big savings, but nonetheless, a savings. When you consider profit margins of 5-10%, an increase in profit of .8% can be significant if the volume is large. WIP Investment definitely affects the bottom line!

Now this was a very simple example with a few operations and a simple cost model. Real assembly lines have many operations with complex characteristics and cost allocation can be quite complex and convoluted. That said, sequencing to minimize the cost of WIP investment is worth looking into even if you don't borrow money to run your line. Why? Because: you always have the option to invest your money in other activities that bring a better return. Why tie up \$85 in Sequence 1 to generate 1 unit a cycle when Sequence 2 ties up only \$50 leaving \$30 to be invested elsewhere (maybe with a better return)?

### 3. "How do you sequence to reduce Investment in WIP?"

By inspection of our simple example, it is obvious that by sequencing the operations by ascending cost (i.e. lowest to highest), the result is the sequence with the least WIP Investment. This is OK for a "Rule of Thumb". However, blindly using this rule can have undesired consequences, because other management concerns may overshadow the desire to minimize WIP Investment. These concerns may include:

- Yield Loss
- Workstation Formation Costs
- Cost/Unit Goals
- Customer Responsiveness
- Utilization of labor and machine
- Start-up and Shutdown cycles

Although minimizing WIP Investment may not dominate management cost concerns, it can be one of many criteria used to evaluate any assembly line. By studying the

dynamics of WIP Investment in a line, the analyst can formulate strategies to improve performance in both *Time-* and *Cost- Efficiency*.

#### 4. “How can WIP Investment be used to evaluate assembly lines?”

To illustrate basic assembly line analysis and the dynamics and importance of WIP Investment, a simple assembly line will be examined. The *Assembly Line Tool* from Archer Tool will be used to analyze different production sequences. A free version of this tool is available at

[http://www.theindustrialanalyst.com/analysis\\_software/assembly\\_line\\_software.htm](http://www.theindustrialanalyst.com/analysis_software/assembly_line_software.htm) .

The example assembly line to be analyzed consists of 5 operations. The cycle time will be 92 minutes. The lot size is 10 units per lot. For simplicity, there is no yield loss. The only scheduling constraints are:

- The Saw operation must go first.
- The Paint operation must go last.

The name, time, and cost data for each operation are presented below. Archer Tool’s time and cost model includes fixed and variable elements. For example, for a 10 unit lot, Operation 1-Saw will expend  $1 + 6(10) = 61$  minutes and cost  $2 + 1(10) = 12$  dollars.

#### Example 2

Operation	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX
XXXXXXXXXX	Name	P-Time/OP (F)	P-Time/Unit (V)	Yield	Cost/OP (F)	Cost/Unit (V)
1 (Saw)	Saw	1	6	1.0	2	1
2 (Drill)	Drill	2	7	1.0	2	1
3 (Dip)	Dip	20	0	1.0	12	0.0
4 (Edge)	Edge	1	3	1.0	3	8
5 (Paint)	Paint	2	9	1.0	4	1

The precedence constraints are entered as shown below. An “X” denotes that the operation in the top row is a predecessor of (goes before) the operation in the first column.


Operation	1	2	3	4	5
XXXXXXXXXX	Saw	Drill	Dip	Edge	Paint
1 (Saw)	+++++				
2 (Drill)	X	+++++			
3 (Dip)	X		+++++		
4 (Edge)	X			+++++	
5 (Paint)	X	X	X	X	+++++


Note that the Dip operation has only fixed processing time and cost. This means that it takes the same amount of resources to dip 1 or many units since they can all be dipped at the same time for the same amount of time. This is often characteristic of chemical treatments or other non-unit specific processing tasks.

The *Assembly Line Tool* will generate a *Time-Efficient* Full Production Cycle sequence that minimizes the number of workstations for the example assembly line. The statistics - Cumulative Total Cost, Cumulative WIP Investment, and Cumulative Time in Line have been selected to provide information at each workstation. The result is shown below.

**Sequence 1**

Workstation	Champion
1	Saw, Edge,  (CUM Total Cost=95.) (CUM WIP Invest.=95.) (CUM Time in Line=92.)
2	Dip, Drill,  (CUM Total Cost=119.) (CUM WIP Invest.=214.) (CUM Time in Line=184.)
3	Paint,  (CUM Total Cost=133.) (CUM WIP Invest.=347.) (CUM Time in Line=276.)

Three Workstations 

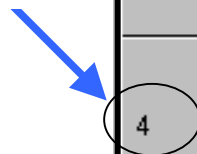
Total WIP Investment 

This sequence has three Workstations, expends \$133/cycle and ties up \$347 in WIP in a Full Production Cycle. By combining Saw with Edge, and Dip with Drill, the minimum of 3 workstations is achieved, but by doing so the most expensive operation (Edge) is placed at the front of the assembly line. This goes against the previous “Rule of Thumb” and should have a negative impact on WIP Investment.

The Archer Tool’s *Assembly Line Tool* also has an option that will look for a *Cost-Efficient* sequence that minimizes cost/unit and then selects the sequence with the least Investment in WIP. The results of this search are shown below.

## Sequence 2

Four Workstations



Workstation	Champion
1	Saw, (CUM Total Cost=12.) (CUM WIP Invest.=12.) (CUM Time in Line=92.)
2	Drill, (CUM Total Cost=24.) (CUM WIP Invest.=36.) (CUM Time in Line=184.)
3	Edge, Dip, (CUM Total Cost=119.) (CUM WIP Invest.=155.) (CUM Time in Line=276.)
4	Paint, (CUM Total Cost=133.) (CUM WIP Invest.=288.) (CUM Time in Line=368.)

This sequence uses four Workstations, expends the same \$133/cycle but only has \$288 in WIP Investment. As a result of the four Workstations, each lot spends an extra 92 minutes in the assemble line. Although the WIP investment is lower, this line has several drawbacks as shown below:

<u>Management Concern</u>	<u>Sequence 1</u>	<u>Sequence 2</u>
<b>Extra Workstation Formation</b>	-	+1
<b>Idle Time (Utilization)</b>	-	+92 min
<b>Extra Startup/Shut Down Cycle (and Customer Responsiveness)</b>	-	+2
<b>Yield Losses</b>	-	-
<b>Production Costs</b>	-	-
<b>WIP Investment</b>	+ \$59	-
<b>Sequence Characteristic</b>	<i>Time-Efficient</i>	<i>Cost-Efficient</i>

The best way to differentiate between alternatives with differing cost and time structures is *Cash Flow Analysis*. A detailed cash flow analysis would probably reveal that Sequence 1 is preferable even though its Full Production Cycle has more WIP Investment. Instead of stepping through a Cash Flow Analysis (a little beyond the scope of this paper), the focus will be on tweaking the assembly line to improve performance based on the analysis of WIP Investment.

Notice: if it were possible to squeeze Sequence 2 into three workstations instead of four, it would be the best of both worlds – *Time-Efficient* and *Cost-Efficient*. For instance, by shifting processing times and costs among operations such that Saw and Drill could be combined into one operation, a better process can be created.

Consider this:

- Use better technology for Saw and Drill with some higher operational costs to improve processing times.
- Use lower technology for Edge and Dip, which, although it increases processing time, also lower costs.
- Slightly adjust cycle time.

For Saw and Drill, more expensive blades and bits and a higher speed are used. For Dip, a cheaper but slower etching chemical is used. For Edge, this machine does double duty on another product that shares its cost.

To accommodate these changes, a new Cycle Time of 93 minutes is required. Again using Archer Tool’s *Assembly Line Tool* to provide an effective sequence, we enter the data as shown below.....

**Example 3**

Operation	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXX
XXXXXXXXXX	Name	P-Time/OP (F)	P-Time/Unit (V)	Yield	Cost/OP (F)	Cost/Unit (V)
1 (Saw)	Saw	1	5	1.0	2	1.2
2 (Drill)	Drill	2	4	1.0	2	1.5
3 (Dip)	Dip	30	0	1.0	8	0.0
4 (Edge)	Edge	1	6	1.0	3	6
5 (Paint)	Paint	2	9	1.0	4	1

... and the resulting best *Time- and Cost- Efficient* sequence is:

Workstation	Champion
1	Saw, Drill, (CUM Total Cost=31.) (CUM WIP Invest.=31.) (CUM Time in Line=93.)
2	Edge, Dip, (CUM Total Cost=102.) (CUM WIP Invest.=133.) (CUM Time in Line=186.)
3	Paint, (CUM Total Cost=116.) (CUM WIP Invest.=249.) (CUM Time in Line=279.)

Three Workstations

Lower Cost & WIP Investment

By shifting technologies and a small tweak of the cycle time, the new example is not only less expensive to operate but less expensive to finance as well. This sequence is produced using either the **Minimize Workstations** or **Minimize Cost/Unit** options of Archer Tool's *Assembly Line Tool* and is indeed "the best of both worlds".

Now again, this was a simple example with convenient assumptions, but the underlying dynamics of time and cost apply to any serial line. And even lines with hundreds of operations and dozens of workstations can be easily examined for WIP Investment with inexpensive software like Archer Tool's *Assembly Line Tool*.

Advanced Topic

## 5. "What about WIP Investment in unpaced lines?"

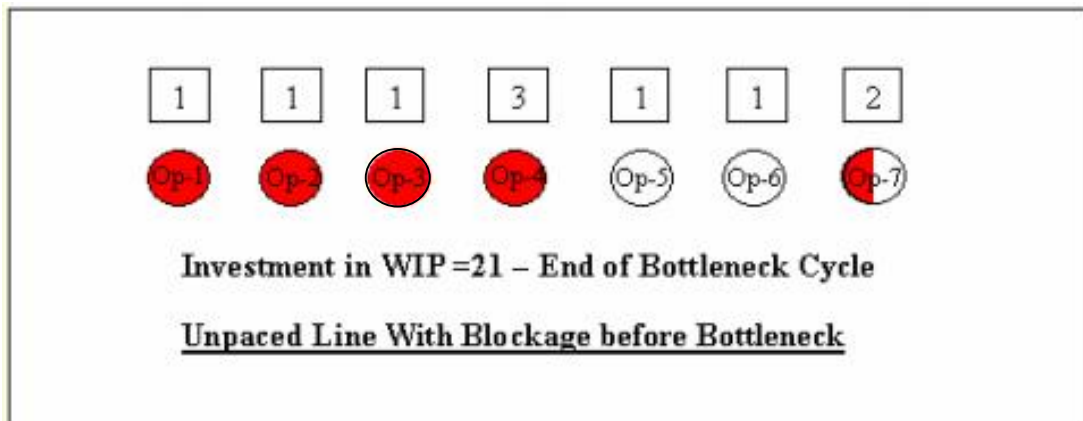
Unpaced lines are lines where units move from one operation to another whenever the unit is ready and the operation is available. There is no Cycle Time, although the line's bottleneck operation will constrain the maximum production rate. The purpose of using an unpaced line in the first place is to shorten the time that units stay in the line.

WIP Investment in unpaced lines is difficult to analyze because accumulation of costs to units are not synchronized to a specific period. It is possible to take a "snapshot" of the WIP Investment at a particular time (Archer Tool's *Assembly Line Tool* does this at the end of the bottleneck operation and the metric is denoted "WIP Invest. [B]"). While this gives some information of line performance relative to a specific period, a snapshot doesn't capture costs that exit during the time in question. The exact amount and duration of capital required for any arbitrary period requires analysis of every event within the period, a tedious task for large problems. Simulation tools are useful

(provided the WIP Investment metric is properly defined and the maximum WIP Investment can be captured within a cycle).

If the “snapshot” metric – “WIP Invest. [B]” can be calculated, it can be used to estimate the maximum WIP Investment in a line. The maximum WIP Investment varies from the WIP Investment [B] metric of the bottleneck cycle by, at most, the cost of one completed unit (or lot), so the analyst can make some approximations as to what the capital requirements might be for an unpaced line by noting other metrics such as the size of the WIP, cost per unit (or lot), which operations are vacant at the end of the bottleneck cycle, and which unit is closest to the end of the line.

Regardless of the challenges of unpaced lines, the importance of WIP Investment is still applicable and sequencing to move expensive operations away from the front of the line is still a good “Rule of Thumb” particularly in true unpaced lines where WIP accumulates before a bottleneck operation. Consider this example.



If this line were input into Archer Tool’s *Assembly Line Tool*, it would look like this. (Note: Time=Cost for this simple line.)

**Time and Cost Data**

Operation	XXXXXXXXXX	XXXXXXXXXXXXXX	XXXXXXXXXXXXXX	XXXXXXXXXX	XXXXXXXXXXXXXX	XXXXXXXXXXXXXX
XXXXXXXXXXXXXX	Name	P-Time/OP (F)	P-Time/Unit (V)	Yield	Cost/OP (F)	Cost/Unit (V)
1 (OP-1)	OP-1	1		1.0	1	0.0
2 (OP-2)	OP-2	1		1.0	1	0.0
3 (OP-3)	OP-3	1		1.0	1	0.0
4 (OP-4)	OP-4	3		1.0	3	0.0
5 (OP-5)	OP-5	1		1.0	1	0.0
6 (OP-6)	OP-6	1		1.0	1	0.0
7 (OP-7)	OP-7	2		1.0	2	0.0

### Precedence Data

Operation	1	2	3	4	5	6	7
XXXXXXXXXX	OP-1	OP-2	OP-3	OP-4	OP-5	OP-6	OP-7
1 (OP-1)	+++++						
2 (OP-2)	X	+++++					
3 (OP-3)		X	+++++				
4 (OP-4)			X	+++++			
5 (OP-5)				X	+++++		
6 (OP-6)					X	+++++	
7 (OP-7)						X	+++++

### WIP and WIP Investment [B] Metrics

Workstation	Champion		
1	OP-1, (CUM WIP=1.) (CUM WIP Invest.[B]=1.)	5	OP-5, (CUM WIP=4.3333) (CUM WIP Invest.[B]=12.)
2	OP-2, (CUM WIP=2.) (CUM WIP Invest.[B]=3.)	6	OP-6, (CUM WIP=4.6667) (CUM WIP Invest.[B]=12.)
3	OP-3, (CUM WIP=3.) (CUM WIP Invest.[B]=6.)	7	OP-7, (CUM WIP=5.3333) (CUM WIP Invest.[B]=21.)
4	<b>OP-4,</b>  (CUM WIP=4.) (CUM WIP Invest.[B]=12.) (MAX Production Rate=0.33333)		

The operation in red denotes the bottleneck. Notice the WIP Investment [B] increases in operations 1-4 and 7. This means there is a unit sitting in each of these operations at the end of the bottleneck cycle. In operations 5 and 6, the WIP Investment does not increase. This means operations 5 and 6 are empty at the end of a bottleneck cycle.

The increase in WIP Investment [B] in operation 7 is only 9 units; a completed unit has 10 units of cost in it. Therefore, the unit in operation 7 is incomplete and will not exit the line until one more unit of cost accrues. In the next bottleneck cycle, operations 1,2,3,4,5, and 7 will accrue 1 unit of cost before the unit in operation 7 can exit. (Operation 6 will still be empty because operation 5 was empty.) At this time, the total WIP Investment will be 27. This is the maximum cost tied up in the line during a bottleneck cycle.

This simple example illustrates how an unpaced line's exact required WIP Investment can be determined solely by examining the WIP Investment [B] metric and calculating resources needed to exit the last unit and the resulting expenditures in every other operation during the time it takes to expel the last unit - straight forward but tedious.

A simpler method to estimate the required capital of a line is to:

1. Set Maximum WIP Investment estimate to WIP Invest. [B]
2. Take the Cumulative WIP and multiply it by  $\frac{1}{2}$  the cost of a completed unit.
3. Check result:
  - a. If the result is greater than previous Maximum WIP Investment estimate, set Maximum WIP Investment estimate to the result.
  - b. If the result is less than previous WIP Investment estimate, Maximum WIP Investment estimate remains equal to WIP Invest.[B].
4. Since unpaced lines often have some variability in them anyway, add a 5%-10% safety margin to the Maximum WIP Investment estimate.
5. Stop

In our example, WIP Invest.[B]=21; WIP=5.3333, Cost per unit is 10.

1. Max WIP Investment = 21
2.  $(5.333)(1/2)(10)=26.665$
3. Max WIP Investment = 26.67
4. Max WIP Investment =  $(26.67)(1.05) = 28$
5. Stop

The exact answer was 27. This estimate is about 3% higher than the exact value, but it is well within the target safety margin of 5% (with a heck of a lot less work!)

This method should work fine in most planning instances for well behaved lines. However, if you need an estimate down to the exact cent, use simulation or a more complex analytic approach.

For more information on WIP investment analysis, email me at [info72@theindustrialanalyst.com](mailto:info72@theindustrialanalyst.com). To download a free copy of my *Assembly Line Tool*, go to [http://www.theindustrialanalyst.com/analysis\\_software/assembly\\_line\\_software.htm](http://www.theindustrialanalyst.com/analysis_software/assembly_line_software.htm) .

## 6. “So, what are the key points to remember?”

The key points to remember are:

- WIP Investment occurs in any serial line.
- Managing WIP Investment is important to efficient utilization of capital resources.
- Operational sequencing can minimize WIP Investment.
- Generally, sequencing operations in ascending order by cost will minimize WIP Investment and improve your bottom line.
- When selecting an efficient sequence, choices may arise between *Time-Efficient* sequences and *Cost-Efficient* sequences with competing management concerns.
- Analyzing WIP Investment in competing *Time-* and *Cost-Efficient* sequences can lead to improved processes.
- WIP Investment analysis in unpaced lines can be challenging but there are easy ways to estimate capital requirements using analytic tools or simulation.

One final thought:

We are usually obsessed with *Time-Efficiency* especially in start-up operations where we are simply trying to get product out-the-door. *Time-Efficiency* is important, but it is only half the battle in your assembly line design. You have only achieved “Doing the right things right and in the right sequence” when your line is both *Time Efficient* and *Cost Efficient*. WIP Investment analysis can help your bottom line. Try it!

I am also available for WIP Investment consultations; please contact me for more information – [info72@theindustrialanalyst.com](mailto:info72@theindustrialanalyst.com).

Any questions or comments on this paper can be addressed to the author.



*About the author: Mr. Tim Archer is the current Managing Member of The Archer Tool Company, LLC. He holds a B.S. in Systems Engineering from the University of Arizona and an M.S. in Industrial Engineering from New Mexico State University. He has over 20 years of experience in Systems and Industrial Engineering and has been a staff engineer for a number of high-tech organizations including Learjet, National Semiconductor, and White Sands Missile Range. He makes his home in Las Cruces, New Mexico in the beautiful Mesilla Valley.*

**Comments or Questions? You can contact Tim at [info72@theindustrialanalyst.com](mailto:info72@theindustrialanalyst.com)**