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MEASURING MANUFACTURING THROUGHPUT USING TAKT TIME ANALYSIS AND SIMULATION

Jun Duanmu
Kevin Taaffe

Department of Industrial Engineering
Clemson University, 110 Freeman Hall
Clemson, SC 29634-0920, U.S.A.

ABSTRACT

This paper is motivated by a case study performed at a company that manufactures two main types of customized products. In an effort to significantly increase their throughput capability, the company created a new production scheme based on takt time calculations. To achieve a smooth flow of production, they desired low Work In Process (WIP) inventory in order to make all components move simultaneously. However, the order of operations in key shared resources implies that a simple takt time calculation cannot provide enough information in determining achievable throughput. The process includes several parallel assembly lines that "converge" to common resources. In certain cases, these components are joined into one unit; in other cases the components split again for further customization. We attempt to improve throughput using a combination of takt time and simulation by understanding how each stage of the system interacts with other stages.

1 INTRODUCTION

1.1 The production scheme

The company (referred to as "ABC") produces two types of Products; we call them Product 1 and 2 or P1, P2. Both of them are highly equipped for special purposes. The daily throughputs are 4 Product 1 and 16 Product 2.

In our simulation model, there are mainly 6 types of components flowing inside the production lines:

- Product 1 requires components 1a, 1b and 1c
- Product 2 requires components 2a and 2b

In addition, there are two types of component 1c, depending on the level of specialization equipped. Consequently, the time for 1c custom and assembly is based on the specialization content level of the component.

Components a, b, and c enter the production system from their own Pre-treat lines. They converge and are processed one by one in a serial sequence during the Common Stage. After the Common Stage, they are separated again to their individual custom stages. When they finish the custom stage, components a and b are assembled together for each respective product. The assembled ab components share the resources at the Check Stage, and then they continue to Custom 2 for their own product types. After Custom 2 stage, Product 2 completes a Final Check, while Product 1 is created in Assembly 2 by combining component 1ab with 1c. The assembled Product 2 then proceeds to the Final Check. Figure 1 depicts this process flow for each component and product type.

There are no queues between each stage and each station within the stages. It is a single flow process, where downstream tasks cannot be performed until a component finishes processing at an upstream station and moves forward. Using this as motivation, company ABC calculated appropriate station processing times based on Takt Time calculations.

Takt time is the available work time divided by the number of finished units required in that time period. This is often referred to as the "drumbeat" of the plant. Normally, it is a theoretical time that a factory must meet to achieve the planned throughput everyday. In ABC Company, the production planners used this takt-time framework for their production in an effort to eliminate any unnecessary inventory and operate with a smooth production flow.

Consider component 2b in the Pre-Treat Stage. According to the factory's data, its daily throughput is 16 and the total available time to process these 16 units each day is 586.67 minutes. This is exclusive of scheduled breaks during the shift. Thus, the takt time for each station is 586.67/16=36.67 minutes. This is the time used as an input to the model.

All the takt time concerning different stages are calculated by the same method. Table 1 summarizes the throughput requirements and takt time calculations for each stage in the production.

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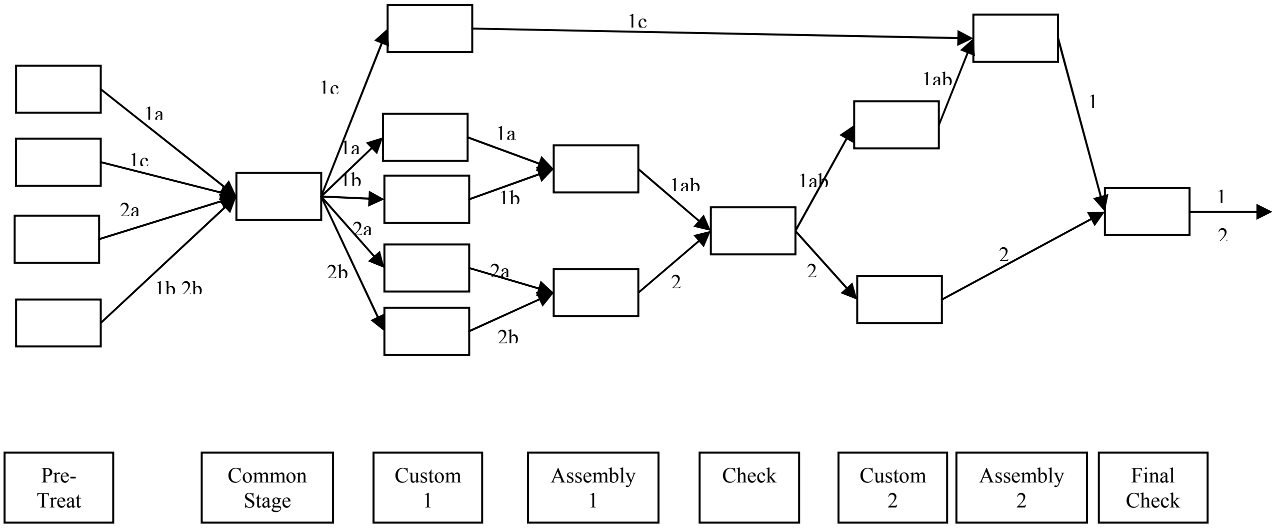

Figure 1: Flow chart for products and processes

Table 1: Throughput and takt time requirements.

Station name	Daily Throughput	Takt time	Item list
Pre-Treat	4 4 16 20	146.67 146.67 36.67 29.33	1b 1c 2b (4) of 1a, (16) of 2a
Common Stage	44	13.33	(4) of 1a, (4) of 1b, (4) of 1c, (16) of 2a, (16) of 2b
Custom 1	4 4 4 16 16	146.67 146.67 146.67 36.67 36.67	1a 1b 1c 2a 2b
Assembly 1	4 16	146.67 36.67	1ab 2ab (or just 2)
Check	20	25.88	(4) of 1ab, (16) of 2
Custom 2	4 16	146.67 36.67	1ab 2
Assembly 2	4 4	146.67 146.67	(4) of 1ab, (4) of 1c
Final Check	4 16	146.67 36.67	1 2

2 LITERATURE REVIEW

In this paper, we describe key aspects of Toyota Production System (TPS) Theory, takt time analysis, Factory Physics, and how these concepts can be combined with simulation to address complex manufacturing issues.

Womack et al. (1990) coined the term "lean production' in their book "*The Machine That Changed the World.*" Lean production (also know as 'lean manufacturing' or just 'lean') refers to a manufacturing paradigm based on the fundamental goal of continuously minimizing wasted material to maximize flow. This concept originated when Japanese manufactures realized that they could not afford the huge investments required to build facilities similar to those in the USA. The Japanese started questioning some of the basic business and manufacturing assumptions. Lean manufacturing initiatives, which are byproducts of the Toyota Production System (TPS), were originated by Ohno and Shingo at Toyota (Shingo 1989). Initially these initiatives were applied to remove wastes inside the organization and were oriented fundamentally to productivity improvement rather than quality. The main reason for applying TPS which was debated at that time, and is still valid today, is that 'Improved productivity leads to leaner operations which help to expose further wastes and quality problems in the system'. Thus, the systematic attack on waste is also a systematic assault on the factors underlying poor quality and fundamental management problems (Bicheno 1991).

The discussion of lean concepts is relevant in our work for several reasons. The case study company has a drive to improve production by increasing throughput, improving quality, and reducing waste. So it is important to include any process changes into the model to represent how the company is addressing lean manufacturing. In our case, this is primarily accomplished by the company using a takt time analysis.

Another approach to analyzing manufacturing processes uses "Factory Physics" concepts. Researchers have used many methods in identifying the interrelationship between resource, machine, components and stochastic processes. In queuing theory, the most fundamental relationship is "Little's Law." It is expressed as:

$$WIP = TH * CT, \quad (1)$$

where WIP is work in process inventory, TH represents the throughput of the system, and CT represents the cycle time per unit processed in the system. To provide a simple explanation, the models described in this paper show that the throughput in a Limited WIP model actually achieves a higher throughput than what we call the MRP model, due to the relationship between WIP and cycle time. Consider the relationship expressed in terms of throughput:

$$TH = WIP / CT.$$

Even though one system may have higher WIP, if each unit requires a longer cycle time, then the system loses any benefit of the increased WIP. The outcome results in unchanged or even lower throughput.

When a factory tries to apply TPS theory, if the manufacturing system is very complex and it is hard to use Factory Physics to analyze it directly, simulation might be a good alternative way. Since the manufacturing problem is very complex, researchers normally focus on one specific phenomenon instead of presenting a "heal all". It is true that concerning different products, we are not able to apply one success experience directly on another problem without any modifications; in some environments, one advantage might be a drawback for other companies.

Many researchers have investigated topics such as Takt time analysis, the TPS, and lean production. However, there is significantly less research on the combined topic of Takt time and simulation in complex production systems.

Czarecki et al. (2001) present the application of simulation in Lean Assembly Line for High Volume manufacturing. They covered some main issues when simulating a lean production system, such as one piece flow, takt time calculation. They also gave a simple example about two different models based on traditional and lean system. However, there are no detailed examples for these two models, and it is difficult to determine exactly how beneficial any new policies or changes to process flows would be.

Adams et al. (1999) introduced how simulation can be used as a tool for Continuous Process Improvement. In his case study, he presented several model structures to represent different improvement plan and compared their effects. More than data analysis, he emphasized simulation methodology in Lean and continuous improvement.

Schroer et al. (2004) also used simulation to understand lean manufacturing. Using software named "Modular Manufacturing Simulator" to build the Lean Production Model, it illustrates a simple work process with 6 stations. They showed the relationship between cycle time, WIP and resource numbers. He didn't analyze the problem with the theory of Little's law, but his work indicates the relationship between these these variables and why lean is so effective. Their approach to WIP as similar to a Kanban also provided inspiration in our model development.

Lian et al. (2002) wrote a paper about the comparison between pull and MRP system based on two simulation model created with Arena. They demonstrated the throughput, WIP and Lead time. It is a good example of using an Arena model to analyze the Lean and traditional production.

Park et al. (1998) presented a simulation model of Mercedes Benz AAV production facility. Through hybrid coding in C++ and SIMAN, they evaluated the maximum throughput based on the current structure. It also collected the buffer size information and gave a bottleneck analysis., however knowledge of Factory Physics and Lean on their model was not directly applied.

From the literature review we see that much research has been carried out in the individual areas such as TPS, Lean production, Factory Physics, and data analysis with simulation; however, combining these issues in greater detail has been less explored. Moreover, little documented research exists in combining these topics with an optimization approach, i.e., to determine appropriate input parameters in the manufacturing process. In fact, simulation is a powerful tool for understanding how these various tools and concepts work together.

3 BASE MODEL OUTCOME AND ANALYSIS

3.1 Model with Takt-time-based Processing Times Only

The simulation model is constructed strictly according to the production system as we described before. We just want to see if the takt time plan can be fulfilled as what we have hoped. We simulate the production for 1000 hours and cut off the first 100 hours as the warm-up time. Since all the process times are takt time, there are no variance of these takt times, the whole system is a decisive system. Thus, we only need to run this model for one time.

After simulation, we found the performance of the new design is not ideal. If we strictly simulate the production according to the takt-time-based processing times and buffer sizes as ABC planned, the throughput is almost 0; in fact, the entire production process gets stuck after 70 hours. By watching the simulation animation, work-in-process components cannot move forward to the next station, and new orders cannot begin since the facility is full.

The underlying cause is that the system is unbalanced, such that the arrival of one component does not always result in immediate processing of the component. Since each station is waiting on output from a prior station, any imbalance in product flow will result in lower throughput than would be expected using a theoretical calculation. For example, at the shared Common Stage, it is impossible that when one component arrives, it will be processed immediately, since the interarrival times of each component are not evenly spaced to match the Common Stage's process time. This results in either the Common Stage waiting for the arrival of a component or the arriving component waiting for the resource to become free. This delay and wait will decrease the output of the whole system, and for this reason, we will also denote the Common Stage as the bottleneck stage.

We also observe that there is an imbalance in the presentation of components as they reach any of the Assembly 1 or Assembly 2 stations. One component is often waiting at the assembly station for its counterpart to arrive. This is partially due to the imbalance in how components are processed in the Common Stage, but there are other reasons as well. For example, if Component 1a is waiting for Component 1b at Assembly 1, and the imbalance has resulted in an additional Component 1a being held in the Common Stage, then there will be no further movement until Component 1b can be matched with the Component 1a at Assembly 1. If there are no Component 1b's in Custom 1, then the system will remain in a gridlock state.

3.2 Modified Base Models

To overcome this problems, we identify two choices. Either we monitor the WIP level throughout the facility or we create a planning sequence that restricts the order in which components are introduced into the system.

3.2.1 Control the WIP – LimWIP Base Model

In this case, we ensure that the total number of components can be held inside the whole production line for each stage without obstructing the shared production lines.

We added counters for each component to limit the maximum WIP number in each stage. The control variables are the maximum number of each components. Then, we perform simulation optimization in order to maximize throughput while managing the WIP level. One key reason that WIP must be controlled is that the system may experience gridlock without WIP limits in place. The results are shown in Table 2. From the data we see that the "takt time" model can only produce approximately 70% of the plan.

Table 2: LimWIP base throughput

Base Limited WIP model	Product 1	Product 2
Throughput per hour	2.91	11.89
Cycle Time	54.14	17.28
WIP	16.69	21.30
Theoretic WIP=CTxTH	16.17	21.07

3.2.2 Control Item Sequencing – MRP Base Model

The second method is to control the sequence of the components that enter the system and, ultimately, the Common Stage. Components are kept on a cycle as follows:

Step 1: 1 Product 1a, 1 Product 1b, 1 Product 1c,
Step 2: 1 Product 2b, 1 Product 2a,
Step 3: 1 Product 2b, 1 Product 2a,
Step 4: 1 Product 2b, 1 Product 2a,
Step 5: Go back to step 1.

This cycle can help all items merge quickly at the assembly stations without the need to limit the maximum WIP number. This is similar in concept to pushing an properly sequenced set of parts through the manufacturing line, and we denote this model as the MRP Base model. For this case, the results are provided in Table 3

Table3: MRP base throughput

Base MRP model	Product 1	Product 2
Throughput per hour	2.10	8.54
Cycle Time	59.17	25.02
WIP	13.16	22.24
Theoretic WIP=CTxTH	12.75	21.92

As shown above, observed throughput is much lower than the throughput achieved using the Limited WIP model. Recall that each stage actually can contain multiple stations, and it is imperative to keep each station busy and operating in order to maintain a high level of throughput (or at least for the case when all processing times are exactly equal to takt times). Figure 2 depicts a snapshot of an animation of this model. Note the gaps resulting within one stage. Another reason for such an occurrence is the unequal number of stations within each component's stage.

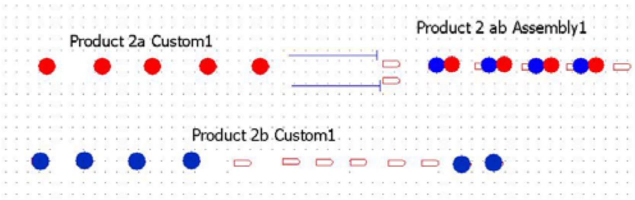

Figure 2: The animation of gaps

When a component 2a arrives at Assembly 1 or matching stage, component 2b is still on its way since this component needs to traverse more stations; this also implies that shorter chains of stations will typically be fully occupied. It is also easy to understand that the sequencing limit included in the operation reduces the ability to maintain a "continuous" production, thus causing lower station utilizations. We can overcome some of this assembly waiting issue by adding an offset time for releasing component 2a and 2b into the system. However, since all stages have different numbers of stations, this kind of wait cannot be completely avoided

Do we have chance to improve our performance? The answer is Yes, in the coming sections we will apply some method to do the test with our simulation model.

4 ALTERNATIVES MOTIVATED BY FACTORY PHYSICS CONCEPTS

4.1 Overview

The relationship between WIP and Cycle Time (CT) as shown in Little's Law (see equation (1)) is nonlinear since they have a complex interaction with throughput. All of these three factors affect each other. For example, if we improve WIP to two times higher than before, the CT may not increase two times since throughput will be changed as well. Any changes to WIP will have repercussions on the resulting CT. Whether throughput increases or decreases is hard to say; the change is contingent upon how WIP and cycle time interact with each other. We can check the change and interaction by simulation.

In setting up the alternatives, we manipulated WIP and cycle time by either adding buffer areas or reducing station processing times. Of course, each of these factors must be weighed against the actual system. If the reduction in processing times is not possible, then that particular scenario would never be feasible. However, the motivation here was to identify how much processing time reduction is associated with a particular throughput level. Then, the company can determine whether the reduction is possible.

The method we use to see the effects is that we provide a relatively wide range of the concerned parameter and let Arena run the optimization engine OptQuest to find the Maximum throughput. We then have a means of comparing each alternative.

Below are the five scenarios we tested based on each of these two models: LimWIP and MRP.

4.1.1 Add buffer

We can add buffer between each stage, thus product is always available whenever it is required at the Common Stage or any assembly station. This may result in higher throughput, but it is opposite the rule of the Toyota Production System (TPS). In Arena, we define the range of buffer from 2 to 10.

4.1.2 Reduce Processing Times at and before Common Stage

If TH = WIP/CT, shortening the cycle time could, in theory, improve throughput. Two possible ways to reduce cycle time are to (1) decrease the process time for the work station, and (2) lower the WIP as we can see from Little's law. We first consider only processing time reductions before and including the shared resource, Common Stage, otherwise known as the bottleneck stage. The range of timings we allow Arena to select is from 50% to 100% of the current processing time values.

4.1.3 Reduce Processing Times after Common Stage

This is an effort to compare the effect of obtaining processing time reductions before and after the shared resource, Common Stage. The range of timings we allow Arena to select is from 50% to 100% of the current processing time values.

4.1.4 Combine WIP and Cycle Time Factors before Common Stage

In this scenario, we let the model select the optimum combination of buffer size and process time before bottleneck to see how good our performance can reach.

4.1.5 Simulation Optimization of all Parameters

Here, we now leave all options open to the model and let Arena combine all these settings. We want to see whether we could have a 100% throughput (based on the amount of orders being sent through the system) using either the limited WIP model or MRP model.

4.2 Summary of Results

Table 4 presents the results from all five scenarios from the Limited WIP model and MRP model. For easier comparison, Figures 3 – 5 provide a graphic comparison of throughput, WIP, and cycle time for all scenarios. There are many interesting phenomena, which will be discussed for each scenario.

Table 5 presents the comparison of each scenario's utilization range and whole system's production rate. Production rate is calculated by (Type1throughput + Type2 throughput)/(16+20).

4.3 S1: Add Buffer

In LimWIP model, we add buffers at each interface between two stages, the range of buffer is 2-10. We found that adding buffers helped the system achieve a slightly higher throughput, while WIP increased as well (from 20 to 29 for Product 2). However, the effect of buffer is limited, which leads us to consider alternate methods for throughput improvement.

Table 4: Results by Scenario

	MRP Model		**Limited WIP Model**	
S1 Add buffer only	**Product 2**	**Product 1**	**Product 2**	**Product 1**
Throughput	13.60	3.34	14.65	3.61
Cycle Time(hr)	20.93	55.79	25.54	64.36
WIP	29.64	20.93	38.79	24.43
Theoretical WIP	29.18	19.11	0.85	28.85
S2 Short Time Before Bottleneck				
Throughput	8.68	2.14	15.35	3.77
Cycle Time(hr)	24.83	58.83	16.34	45.49
WIP	22.33	13.23	26.01	18.10
Theoretical WIP	22.03	12.84	25.65	17.55
S3 Short Time After Bottleneck				
Throughput	13.65	3.39	14.68	3.62
Cycle Time(hr)	13.24	25.77	13.32	37.55
WIP	18.75	9.12	20.23	14.23
Theoretical WIP	18.47	8.93	20.00	13.90
S4 Add Buffer and Short Time Before Bottleneck				
Throughput	15.30	3.76	15.39	3.79
Cycle Time(hr)	21.25	55.17	22.56	51.87
WIP	33.82	21.95	36.03	20.72
Theoretical WIP	33.24	21.23	35.48	20.11
S5 Simulation Optimization				
Throughput	15.84	3.94	15.86	3.90
Cycle Time(hr)	12.24	24.03	7.73	37.11
WIP	20.02	9.83	12.64	15.18
Theoretical WIP	19.81	9.68	12.52	14.80

Table 5: Utilization and Production Rate

	MRP Model	**Lim WIP Model**
S1 Add Buffer Only		
Utilization Range	42%-99%	46%-99%
Production Rate	0.85	0.91
S2 Short Time Before Bottleneck		
Utilization Range	26%-99%	47%-99%
Production Rate	0.54	0.96
S3 Short Time After Bottleneck		
Utilization Range	12%-99%	35%-99%
Production Rate	0.85	0.92
S4 Add Buffer and Short Time Before Bottleneck		
Utilization Range	47%-99%	47%-99%
Production Rate	0.95	0.96
S5 Simulation Optimization		
Utilization Range	12%-99%	12%-99%
Production Rate	0.99	0.99

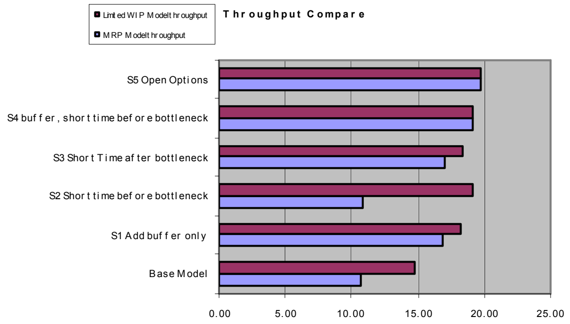

Figure 3: Throughput comparison (Product 2)

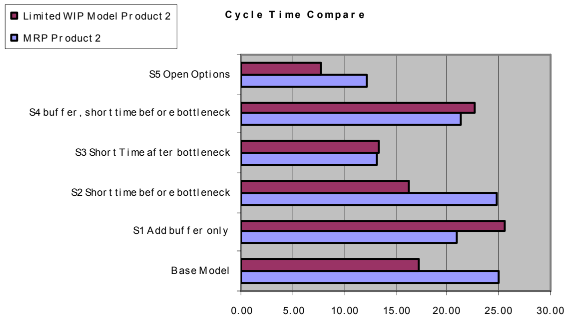

Figure 4: Cycle time comparison (Product 2)

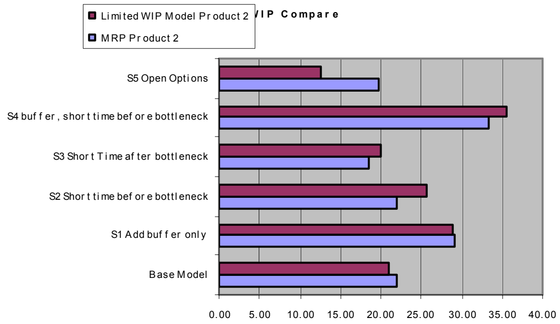

Figure 5: WIP comparison

In the MRP model, we took the same approach. However, to let the planning module have more capacity to hold the ready components, we added buffer sizes from 2 to 20. The throughput did increase, as the "gaps" in the line have been effectively reduced.

However, there seems to be an "unseen" ceiling for both of these models. It is true that in a serial system, an interaction exist when one component stops, thus, it will never reach the theoretic throughput based on takt time definition. The upper limit can be attained when there are no "matching" and "converging" spots. When these conditions exist, all these individual stages will be affected and some delays invariably occur.

An interesting point also arises here. It may seem counterintuitive that stages after the Common Stage are underutilized when the Common Stage utilization is near 100%. Why can the system not maintain its 100% performance? Where are those components that are supposed to go out…are they absorbed by the system?

Given the same amount of WIP, throughput will be diminished as components spend more time in the system. The system can achieve near 100% throughput when a constant takt time system exists, where every station is always busy and occupied, and throughput is equal to the input. If there are some idle stations at any time, the system has no way of achieving 100% utilization if takt times are used at each station. Thus, reduction in processing times (below the takt times) is necessary to increase throughput, and this is what is shown in the next section.

4.4 S2: Reduced Processing Times at and before Common Stage

This approach results in a good outcome since the system provides almost 95% of the planned throughput. As we can see, the fast process time before bottleneck presents a good preparation for a quick motion. Whenever a component is needed, a finished one is ready. The cycle time and WIP are also not very high since there is no additional buffer and no queue. We can regard this system as a lean and PULL system, because the moving forward of any component will cause new production. Orders wait (if necessary) at the very beginning, so in essence these orders have not begun processing and are not counted in the system. Aside from this beginning queue, orders move forward in the system every time an event occurs that moves forward an individual order. It is a good model for Toyota Production System, Lean and Pull, yet the company must be aware of how long an order is waiting prior to initial processing. Assuming the facility can achieve the desired throughput level, and they do not induct more orders than the throughput rate, there should never be an extended queue prior to initial processing. There is still inefficiencies at the Common and Assembly stations since the wait time can not be eliminated completely unless it is a pure balanced production.

As we can see, if we do not lower the process time to an extreme, the system improved very little concerning the throughput. In the planned or MRP system, the sequence of components that enter the production line are pre-defined and can not be changed. Thus, if the speed of stages after the bottleneck remains unchanged, the quickly finished component must wait until the downstream stage is available. Consider that a downstream station is available but the quickly finished upstream component is not the one that can enter this available downstream stage. The upper part must stop and wait until its downstream station is ready. On the contrary, in the limited WIP model, there are no specific sequences or cycles of components entering the system. The Optimization process has taken into account the factors like Total WIP and process time. By controlling each component's Maximum WIP, the system can address minimizing the total wait time, so, after optimization, almost always the correct one is waiting for the downstream station whenever a downstream station is available. So, the wait times decrease significantly. In Limited WIP model, the optimization has balanced the upper and down stream process and make the wait time keep in a minimum level. In contrast, for MRP model, the whole production line's speed is only decided by the assembly at downstream stages. No matter how fast components are processed in early stages, without further process adjustments, we can not reach a higher throughput.

4.5 S3: Reduced Processing Times after Common Stage

In the LimWIP model, a quick process time after the Common Stage contributes less than Scenario 2. In this case, we did not increase the bottleneck production rate. The downstream stations are easily starved by their own faster processing times. Unlike S2, the pull system, when one component is finished and moved out, another one can not arrive and start working right away. We observe that both WIP and cycle time dropped significantly, leaving the resulting throughput unchanged (and even slightly lower).

In the MRP model, Arena selected all processing times after bottleneck at their lower bound, resulting in a 50% processing time reduction. We can see that the cycle time dropped a lot, about 60% as before, however, the WIP also dropped since we do not allow any additional WIP. Throughput increased from 8.7 to 13.7 units. It seems that in a MRP platform, an accelerated production rate can help the system reach a higher throughput, although the efficiency drops.

4.6 S4: Combined WIP and Cycle Time Factors before Common Stage

If we add WIP storage plus reduced processing times before the Common Stage, we observe similar performance from both the pull model and the planned sequence model. However, we point out a key observation concerning th pull model. In comparing against Scenario 2, total throughout only increased by 0.1 units, yet the WIP and cycle time increased significantly. Given an operation running smoothly, adding WIP storage is really redundant and there is no need.

We find that the model with planned sequence reached a high level of throughput, although it is still slightly lower than the pull system. This scenario provided another throughput improvement over either Scenario 2 or 3.

4.7 S5: Simulation Optimization

In the pull model, we define the range of processing times and buffer sizes, and then provide these as input to OptQuest to search for a good solution. It seems the system find some good options. However, all the time are close to the lower bound, which we define as half of the current time. The system works in a low utilization status, from 12% -99%. The "Pull" system is not truly lean any longer, since it sacrifices this objective to gain a high throughput.

In the MRP model, we achieved nearly 100% throughput.

The WIP and cycle time are very low, mostly due to the fact that the process times have been decreased substantially. The actual buffer size is not very large since the process time is very short. However, the efficiency is not so ideal, since the overall production operation works very quickly and has a lot of idle time. In fact, even though the results from this case are very desirable, there is no indication that we can truly achieve these reduced processing times in the real system. A major point of future work is to identify achievable station processing times, which, in the case of company ABC, means determining an improved method for assigning workers to tasks and allocating workers across neighboring workstations.

5 CONCLUSION

Simulation is a good tool for parallel and continuous flow manufacturing research. As we can see, by simulation, we found that a theoretical takt time plan can not be fulfilled under a situation of complex structure and manufacturing flow, and such systems ultimately require a combination of simulation and takt time analysis for throughput improvement.

Little's law helps us understand the outcomes from different scenarios. Adding buffers provides a throughput improvement, however, a lean and pull system can do much better, provided that we have a fast process time before and including the Common Stage. Buffers increase WIP and appear to aid in increasing throughput, but in a pull system and lean system, additional buffers help very little. The MRP-based system relies more on the buffer than the pull-based system, plus, acceleration in the speed after the Common Stage has a better effect in MRP system.

Both the MRP and Limited WIP models are good simulations for ABC's production plan. With the help of simulation and Factory Physics, ABC is on the path to realizing its facility's intended capabilities.

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AUTHOR BIOGRAPHIES

JUN DUANMU is a Ph.D. student in the Department of Industrial Engineering at Clemson University. He finished his masters degree in Industrial Engineering at Chalmers University of Technology, Sweden. His research area includes logistics systems analysis as well as production, inventory optimization and simulation. His email address is <jduanmu@clemson.edu>.

KEVIN M. TAAFFE is an assistant professor in the Department of Industrial Engineering at Clemson University. His primary research interests include transportation and logistics systems analysis as well as production, inventory, and demand management. He is a Senior Member of IIE, as well as a member of INFORMS, Transportation Research Board, and Decision Sciences Institute. His email address is <taaffe@clemson.edu> and his Web address is <http://people.clemson.edu/~taaffe/>.