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Constraint identification techniques for lean manufacturing systems

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ABSTRACT

The first step in the Theory of Constraints (TOC) methodology is to identify the constraint. Several methods have been recommended in literature, such as looking for a backup of inventory (i.e., the operation that the inventory is waiting for is the constraint), or using linear programming or other analytical models. Yet, these methods may not be useful in a matured lean environment, which may have moving assembly lines where constraints are not obvious. This paper proposes three new methods for this purpose. The first method, Flow Constraint Analysis, takes a holistic view and evaluates whether the customer's demand is being satisfied. This evaluation is made by comparing the takt times and the cycle times of resources in the manufacturing system in order to identify the constraint(s). The second method, Effective Utilization Analysis, can be employed to pinpoint the location of the system constraint to a specific process or station. The actual production throughput is compared against the ideal capacity of the system to locate the bottleneck. This method is based on the relationship between WIP, bottleneck rate and lead time for a constant work in process (CONWIP) system. The third method, Quick Effective Utilization Analysis, can be used when there is little or no historical line performance data available. A case study of these methods applied to an actual production facility is presented.

1. Introduction

The manufacturing system output is a function of the whole system, not just individual processes. When we view our system as a whole, we realize that the system output is a function of the weakest link. The weakest link of the manufacturing system is the constraint. Consequently, there needs to be focus on the co-ordination of efforts to optimize the overall system, not just individual processes [1]. When a system matures in lean implementation, the production flows smoother and the main constraint becomes less obvious. However, the impact of performance of constraining resources in a lean system, especially one with moving assembly lines, is still evident. Because “every value stream has a primary bottleneck (constraint) that limits its ability to reach its goal” [2, p. 175], it is even more critical to be able to identify system constraints in a lean environment.

Theory of Constraints (TOC) is a well-known methodology for systems improvement that includes principles and practice guidelines that can be adopted by practitioners [3]. The famous novel for operations management, *The Goal*, written by Eli Goldratt [4] caught the attention of process improvement professionals and began the use of this methodology. From this book, the five focusing steps (5FS) were brought out: 1) Identify the System Constraint, 2) Decide How to Exploit the Constraint, 3) Subordinate Everything Else, 4) Elevate the Constraint, and 5) Go Back to Step 1, but beware of “Inertia”.

The concept of integrating Lean, Six Sigma and the Theory of Constraints is being explored more and more while simultaneously being applied to various industries [5]. The integration of Lean and TOC will be the focus of this manuscript. Constraint identification at a lean manufacturing plant using TOC will be the method of integration.

In mass production environments, constraints are usually easy to find; just look for large stockpiles of Work-In Process (WIP), backlogs, and frequent expediting [2]. But in a lean manufacturing environment, none of these conditions should exist; therefore a different approach has to be taken in order to identify the system constraint(s).

Currently there are four major constraint identification methods [6]:

1. The machine with the longest active state without interruption.
2. The machine with the greatest percentage of cycle time and fail state.
3. The machine with the longest average upstream queue length.
4. The machine with the largest percentage of utilization.

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Nomenclature

TOC Theory of Constraints. A management philosophy that stresses removal of constraints to increase throughput while decreasing inventory and operating expenses.

WIP or W Work in Process. Product or inventory in various stages of completion throughout the plant, from raw material to completed product.

CONWIP Constant Work in Process.

$CT_{avg.}$ Average Cycle Time. A time duration calculated by using the time weighted average process time.

$DT_{avg.}$ Average Downtime. A time duration calculated by using the total downtime for a given period divided by the number of products produced during the same period.

$CT_{process}$ Process Cycle Time. A time duration that is the summation of Average Cycle Time and Average Downtime.

CT_{pitch} Pitch Cycle Time. A time duration that represent the likely longest time the product will remain in that pitch.

r_b The assembly line bottleneck rate. Is the rate of the resource having the highest long-term utilization.

r_b^P Practical Production Rate. Is the anticipated throughput of the line.

T^P Practical Lead Time. Is the practical minimum time to traverse the line (no queuing).

T_e^P Effective Practical Lead Time. The summation of the assembly line pitch cycle time values.

T_q^P Quick Effective Practical Lead Time. The average of a sample of individual jobs' lead times.

U The Utilization. The utilization of a resource is the fraction of time it is not idle for lack of parts.

U_e Effective Utilization Rate. The resource utilization calculated using the Effective Utilization Analysis method.

U_q Quick Effective Utilization Rate. The resource utilization calculated using the Quick Effective Utilization Analysis method.

W_e Effective Work in Process. A constant work in process value calculated using the Effective Utilization Analysis method.

W_q Quick Effective Work in Process. A constant work in process value calculated using the Quick Effective Utilization method.

As can be seen from the above list, all of the major bottleneck detection methods are useful for individual machines.

For moving assembly lines, equipment failures and repairs are not the main reasons for line stoppages. Operators using the equipment, people maintaining the equipment, the people supplying parts to the assembly line and poke–yoke devices are the main causes. In most instances the assembly line stops only for seconds and in some cases it does not come to a complete stop but only slows down.

There are no major methods for identifying the constraint in systems with paced moving assembly lines. The question, “How do you identify the system constraint when the typical methods do not apply?” will be answered in this manuscript. This is important because continuous improvement is necessary for a company's survival and the gains of the blended methodologies have delivered results that were at least four times higher than any one approach alone.

1.1. The use of Theory of Constraints

The effectiveness of TOC has been reviewed extensively over time. For example, the extended literature survey by Naor et al. [7] provides a great insight into the theoretical foundation of TOC. Furthermore, the second evolution is taking place now. Pretorius [8] has identified several shortcomings with the five focusing steps (5FS). To address these shortcomings, the 5FS are transformed into a decision map that includes all five steps and two prerequisites, this allows decision points to guide the user through the process. The answer to the first decision point, “Is the constraint physical?” is yes. Therefore to analyze the manufacturing system being studied, the first two steps of the five focusing steps do not change.

When exploiting the constraint, we should wring every bit of capability out of the constraining component as it currently exists. In other words, TOC urges us to rethink what we can do to get the most out of this constraint without committing to potentially expensive changes or upgrades and be able to implement the changes in a short period of time [5]. Constraints can be both external and internal. External constraints are often beyond the control of management because they are market driven. External or market constraints affect demand, they influence product mix, which in turn affects resource utilization [10]. The product mix for the manufacturing system being studied in this paper is 60% of product A and 40% of product B. Internal constraints come in many forms, e.g., management philosophy, labor skills, inflexible work rules and limited capacity at various resources [10]. During this study only limited capacity will be considered.

Two major benefits are achieved by following the TOC methodology: (1) realizing the maximum system improvement from the least investment in resources and (2) learning exactly how much effect improving a specific system component has on overall system performance [5].

1.2. Overview of the literature

The literature search for this paper began with the publication period from 2000 to 2014. The following list of journals were selected as a field of candidates that could provide potential reference material:

- *Journal of Operations Management;*
- *Production and Inventory Management;*
- *International Journal of Production Research;*
- *Industrial Engineering;*
- *International Journal of Operations & Production Management;*
- *European Journal of Operational Research.*

These selected journals did not provide any articles directly related to the industry and manufacturing system being studied; therefore a second mini literature search as performed with the primary focus being constraint detection and production assembly lines. The time period was widened and several applicable articles surfaced. Books and websites on TOC were also reviewed during the literature search.

1.3. Three new methods

In this paper, three new methods are proposed to pinpoint constraints in matured lean systems. The first method, named Flow Constraint Analysis, is a holistic approach that evaluates whether the customer's demand is being satisfied. This evaluation

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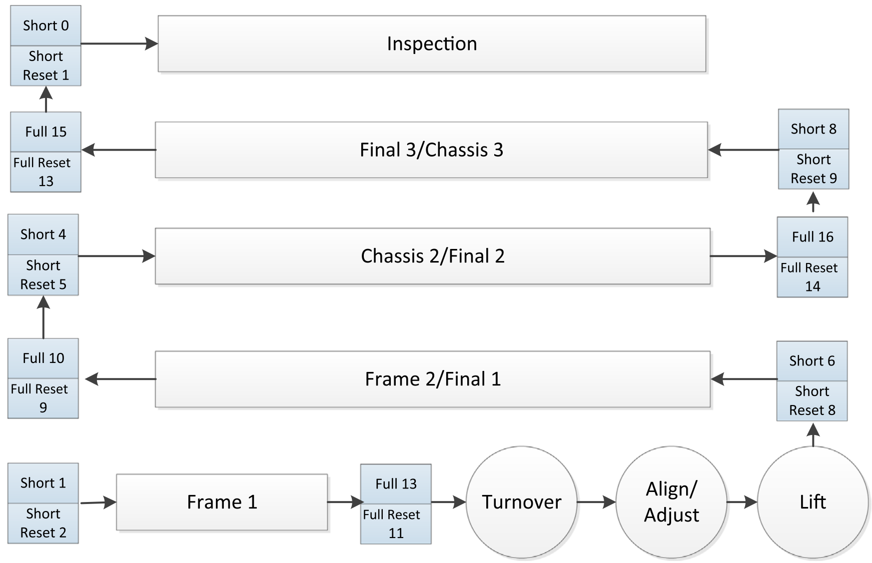

Fig. 1. Manufacturing system layout.

is made by comparing the takt times and the cycle times of resources in the manufacturing system. Cycle times will come from one of two sources, i.e., a moving assembly line or an automatic station. Resources with cycle times higher than a calculated target value are likely to be the constraints.

The second proposed method is the Effective Utilization Analysis. It can be employed to pinpoint the location of the system constraint to a specific process or station. The actual production throughput is compared against the ideal capacity of the system. This method is based on the relationship between WIP, bottleneck rate and lead time for a constant work in process (CONWIP) system. Resources with low effective utilization values are likely to be the constraints.

Imagine being able to work into a manufacturing facility and identify the primary constraining resource in a short period of time with only real time data. That is the greatest strength of the third method, Quick Effective Utilization Analysis.

All three of the methods can be used to identify the constraint where resource time is constant or random. The methods can be used independently or in conjunction depending on the situation. Each of the methods provides valuable insight into the performance of the enterprise under analysis.

1.4. Case description

A case study of the three methods applied to an actual production facility is presented in the paper. The value stream under consideration consists of tandem assembly lines separated by a work in process (WIP) buffer. The buffer holds enough WIP to allow the assembly lines to temporarily run at different speeds without affecting (blocking or starving) one another.

This facility produces vehicles. There are two models, and they are transported down the assembly line on a carrier. There is a main assembly line which is fed by a sub-assembly line. The main line is made up of five moving assembly lines. The names of the lines are Frame 1, Frame 2/Final 1, Chassis 2/Final 2, Final 3/Chassis 3 and Inspection. The name of the sub-assembly lines are Trim 1, Trim 2 and Chassis 1. Fig. 1 shows the manufacturing resources and various buffer capacities for the main line.

2. Method #1: constraint identification using Flow Constraint Analysis

The Flow Constraint Analysis method involves a two-step process. The first step of the analysis is to determine if a true constraint is located in the manufacturing system. The second step is to identify secondary/tertiary constraints. In the first step, the existence of a constraint is determined by calculating and comparing the takt times and the cycle times. If the takt time is greater than the associated cycle time for each resource in the manufacturing system, the system is capable of meeting customer demand. The system constraint is then defined as being external. If demand exceeds the capacity of any of the resources of the manufacturing system a true bottleneck is said to exist [10], which means the constraint is internal. Another method of defining an internal constraint resource is through spare capacity. Spare capacity is the difference between cycle time and the takt time [2]. The resource with the least amount of spare capacity is the primary bottleneck for manufacturing systems with resources that have varying cycle times.

The manufacturing facility under analysis has an Andon system which collects the time and duration of events that occur. The Andon system also states a takt time for each assembly line in the manufacturing facility. This given takt time will be used during the analysis.

Another type of constraint resource also exists. These constraint resources have sufficient capacity when managed and scheduled carefully, but they could adversely affect the system's performance when managed inappropriately [10]. That is the purpose of the second step in the flow constraint method of analysis. The second step is to identify secondary/tertiary constraints by comparing individual times against each other.

When applying the flow constraint method, the process time for resources falls into one of four categories based on two characteristics. The first of the two characteristics is if the process time is dependent on the model mix, while the second is if the process time remains constant or varies from job to job.

- The first category is a process time that is independent of the model mix and constant. Resources that fall into this category process all jobs at a consistent rate and the process time is a single value.

- The second category is a process time that is dependent on the model mix and varies, which results in a group of process times for the resource.
- The third category is a process time that is independent of model mix and varies. For this category the resource is the source of the variability and thus produces a process time that is a random variable. The random variable results in a single distribution that can be either discrete or continuous.
- The fourth category is a process time that is dependent on model mix and varies. The process time for each model type is a random variable. The random variables result in multiple distributions that again can be either discrete or continuous.

2.1. Moving assembly lines

2.1.1. Evaluation

Statistical fluctuations apply to the performance of all resources [11]. One of the most prevalent sources of fluctuations is “natural” variability. Natural variability includes minor fluctuation in process time due to differences in operators, machines, and material [12]. Natural variability is ignored in the flow constraint method. Also, there are no effects on the assembly lines due to model complexity. The assembly lines are assumed to operate at a deterministic cycle time. Usually, the cycle time can be obtained from the control panel. For this analysis the average cycle time was calculated for the resources and assumed constant. Continuous moving assembly lines process times can be categorized as non-model dependent and constant.

2.1.2. Results analysis

The point chart below, Fig. 2, shows the takt time and cycle time for each assembly line. The first three lines are the sub-assembly lines, while the remaining lines are part of the main line. One interesting characteristic of the Fig. 2 point chart is the variability of the takt time among the assembly lines. In academic literature, takt time is calculated as a single value for the entire manufacturing facility. The methodology of how and why the takt times are different values was a managerial decision and the reason was not explained. Therefore the values are considered a given value which was recorded from the assembly line control panels.

The cycle time for the Frame 2/Final 1 assembly line is greater than the takt time for the line. Therefore the system is not able to meet customer demand and a true bottleneck exists, which is the Frame 2/Final 1 assembly line.

Chassis 2/Final 2 and Final 3/Chassis 3 assembly lines cycle times are the same which means the system has potential dual constraints. Since both assembly lines have the same cycle time there is not a sufficient amount of spare capacity.

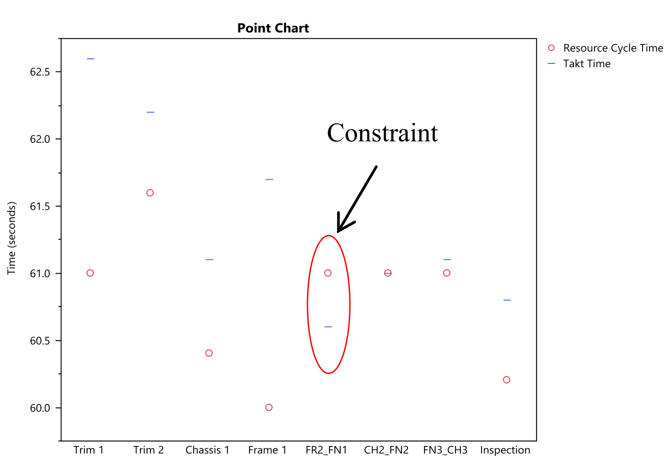

Fig. 2. Takt time vs. cycle time.

The resources upstream of the inspection assembly line have higher average cycle times. The inspection assembly line therefore is not the designed constraint. This fact is being mentioned because this is a plant management philosophy.

The sub-assembly products are assembled to the main line products on the Frame 2/Final 1 assembly line. Comparing the cycle time for the sub-assembly lines with the Frame 2/Final 1 cycle time shows that two thirds of the sub-assembly lines have a higher cycle time. The sub-assembly lines could potentially starve the main assembly line of parts.

2.2. Individual stations

2.2.1. Evaluation

Additional resources are located between Frame 1 and Frame 2 assembly lines. These resources will be added to the discussion to demonstrate the use of the flow constraint method to automatic stations. There is a turnover, two transfers, two alignment/adjust work stations and a belt elevator.

To aid in understanding the function of the resources, the sequence of operations will be described. The product is removed from its skillet (pallet) and rotated 180 degrees. The first transfer removes the product from the turnover equipment and places it into one of two alignment/adjust stations. The alignment/adjust stations are dedicated resources, which means only one type of product is processed by each. Next, transfer #2 removes the product from one of the alignment stations and places it on the belt elevator. The elevator lowers the product onto its skillet where it travels through the rest of the manufacturing system. The definition of station cycle time presented by Hopp and Spearman [12] will be used to determine the cycle time for the automatic stations.

$$\begin{aligned} Cycle\ time &= move\ time + queue\ time + setup\ time \\ &\quad + process\ time + wait-to-batch\ time \\ &\quad + wait-in-batch\ time + wait-to-match\ time \end{aligned} \quad (1)$$

The system follows single piece flow and first in first out rules. The alignment/adjust station that services Part B has an automatic changeover process which starts prior to the part's arrival, therefore the setup time will be assumed to zero. Queue time will not be considered in the analysis using the Flow Constraint Method. Move time will be called process time for the transfers since this is their only job function; Eq. (1) reduces to,

$$Cycle\ time = process\ time \quad (2)$$

The turnover and belt lift fall into the independent and constant category. The transfers process time (move time) fall into the dependent and constant category. While the alignment/adjust stations have independent and variable process times. As before with assembly lines, the first step of the analysis is to calculate and compare the takt times and cycle times. For stations with random cycle times the maximum cycle time values are compared against the takt time. If only one station has maximum cycle time values that exceeds the takt time, then that station is the constraint. If multiple stations have maximum cycle time values that exceeds the takt time, a different comparison method is required. A comparison of the probability of the cycle time exceeding the takt time should be performed.

2.2.2. Results analysis

There is no takt time given for the automatic stations from the Andon system. For demonstration purposes, the cycle time for the

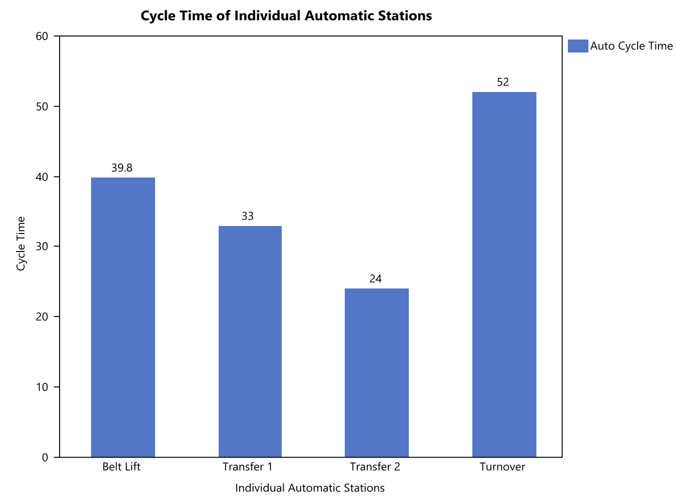

Fig. 3. Automatic stations cycle times.

upstream assembly line, Frame 1, will be used as the reference time value the equipment should be operating below. This value, 60 s, has been selected to reduce the effects of blocking the Frame 1 assembly line.

The turnover and belt lift follow the same type of analysis as the moving conveyors. After the data collection process, the average cycle time for the turnover station was 52 s and the maximum cycle time value observed on the belt lift was 39.8 s. Therefore these stations were eliminated from consideration as a possible constraint.

The next resources, the transfers are analyzed by considering the effects of model mix. The processing time for transfer 1 is the longest for Part A, with a value of 33 s. While processing time for transfer 2 is longest for Part B, with a value of 24 s. These stations are also eliminated as a possible constraint, see Fig. 3.

The cycle time data for the remaining two pieces of automatic equipment is random and therefore a histogram has been created for the sets of data. The Part 1 alignment/adjust operating range (see Fig. 4) is well below the target value and is not a system constraint. The Part 2 alignment/adjust histogram shows that the cycle time data is bimodal, see Fig. 5. Since we are concerned with constraint identification, the first mode is not considered during the analysis. The second mode, is also well below the target value. None of the automatic equipment is a system constraint.

If both of the histograms had contained the target cycle time value, a probability distribution would have been fitted to the data. Next, the probability of the resource running at a cycle time greater than the target value would have been calculated and the resource with the highest probability would be the constraint resource.

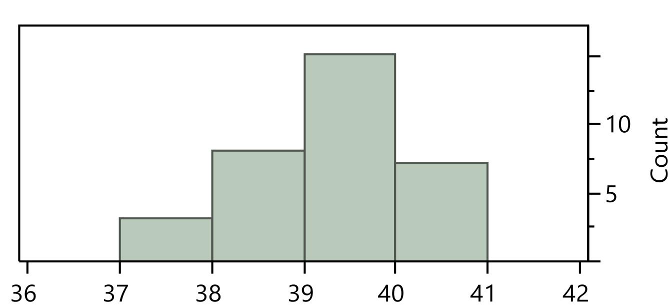

Fig. 4. Part 1 Alignment/adjust cycle time histogram.

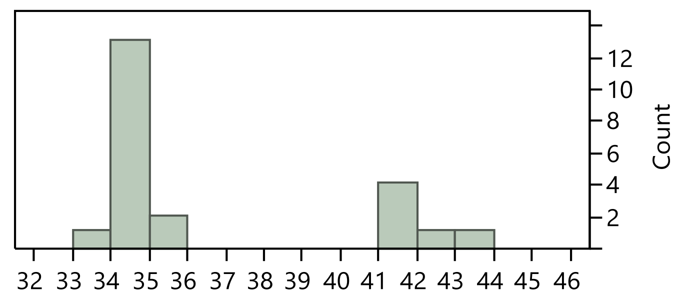

Fig. 5. Part 2 Alignment/adjust cycle time histogram.

3. Method #2: constraint identification using effective utilization analysis

Before expounding on the effective utilization method a brief definition of some of the method's terminology is required. There is a design reference line that is theoretically located through the center of the front axes of the vehicle. This line is known as the L10 line. The distance between the L10 lines is constant and is known as the assembly line pitch.

The work performed by an individual operator is known as a process. The process should begin and end within a designated area on the plant floor. This area is known as the process pitch. All the processes do not have the same work content. Because of the differences in work content, the process pitch is not the same for all the processes. The start of the process pitches could also be different. In some rare instances the process pitch is greater than the assembly line pitch (Fig. 6).

3.1. Moving assembly lines

3.1.1. Evaluation

For assembly lines analyzed using the effective utilization method, model complexity and downtime effect the determination of the constraint resource. The effect of model complexity is captured in a variable named average cycle time. The processes performed by an operator are product model dependent. Since there is process time variability, the time weighted average is calculated for each process pitch and recorded as the average cycle time. Downtime durations are recorded in a variable named average downtime. First, the total downtime is calculated by summing up the downtime across all shifts over several days for each pitch. Next, the total downtime is divided by the number of products produced over the same time period. This calculation is performed for each process pitch. The average cycle time and average downtime values are summed. The summation is called process cycle time. This value will typically not be analyzed by itself. The reason is because of manpower allocation. There are typically two operators, one on each side of the product on the moving assembly line.

A comparison has to be made among all the operators working in a process pitch to ensure that the maximum time seen by the product in the process pitch is recorded. Logic is used in the next step of the method to determine the correct value to be recorded. The name of the recorded value is *pitch cycle time*.

Pitch cycle time can be assigned one of three values. The first logical decision is to determine if there are any processes in the pitch. If there are processes in the pitch, then the maximum *process cycle time* is compared against the inverse of the bottleneck rate for the assembly line. If the *process cycle time* is greater than the inverse of the bottleneck rate, then the maximum *process cycle time* is recorded as the *pitch cycle time.*

The next scenario occurs is if there are no processes in the pitch. In this case, the summation of the average downtime(s) for the pitch is compared against the inverse of the bottleneck rate. If

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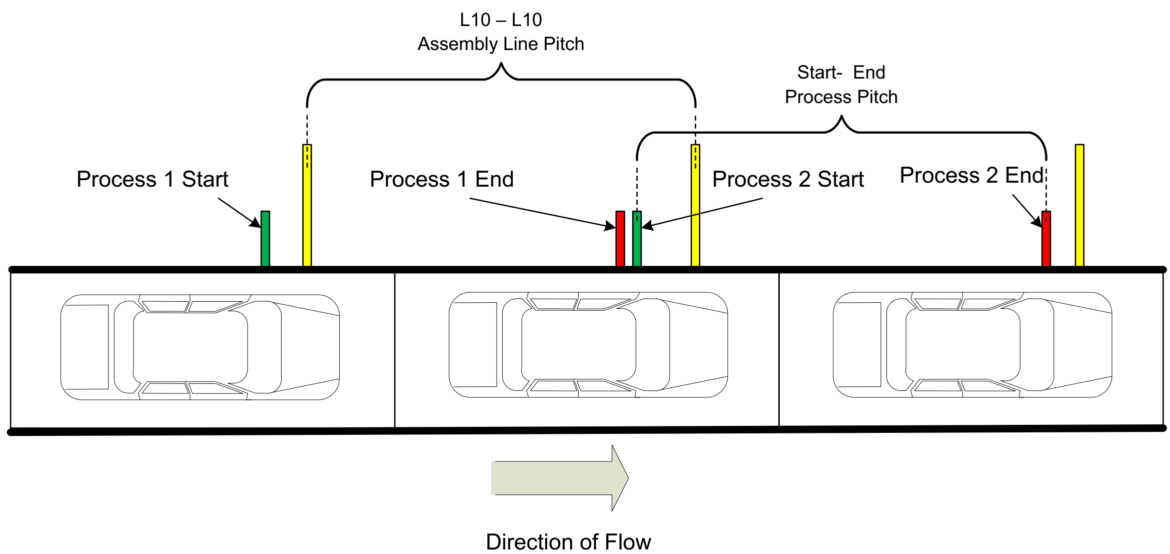

Fig. 6. The relationship between assembly line and process pitch.

the summation of the average downtime(s) is less than 1% of the inverse of the bottleneck rate, then a value of 0 is recorded as the *pitch cycle time*. The 1% value is based off of historical system performance data for the manufacturing system being studied. In theory if there are no processes taking place in a pitch, then that those pitch should not produce any downtime. Even though the product still has to physically travel through the pitch, a value of 0 is recorded because the only other acceptable value would be the inverse of the bottleneck rate. Recording the inverse of the bottleneck for pitches tends to improve the utilization value for the assembly line, therefore 0 is recorded instead.

Let us now discuss the third and final value that the *pitch cycle time* can assume. For the third possible value to be valid, two events can occur and produce the same result. The first event is; yes, there are processes in the pitch but no, the maximum *process cycle time* is not greater than the inverse of the bottleneck rate. The second event is; no, there are no processes in the pitch and no, the summation of the average downtime(s) is not less than 1% of the inverse of the bottleneck rate. If either of these events occurs, the *pitch cycle time* is calculated by summing the inverse of the bottleneck rate and the maximum average downtime value for the pitch.

3.1.2. Results analysis

The analysis begins with the calculation of the practical lead time for the assembly line. This is accomplished by summing the *pitch cycle time* values. The assembly lines maintain a constant work in process (WIP). The actual WIP value has to be reduced to account for pitches with no processes and very little downtime. Therefore, only non-zero *pitch cycle time* values are counted to determine the WIP value for the assembly line. With the practical lead time and WIP calculated for the assembly line, the practical production rate can be determined from Eq. (3).

$$r_b^P = \frac{W}{T^P} \tag{3}$$

The utilization for the assembly line is determined by evaluating the ratio of the practical production rate with respect to the assembly line bottleneck rate, see Eq. (4). The bottleneck rate will be larger than the production rate because the bottleneck rate does not assume any losses due to model complexity or downtime. This property can be used to verify calculations while performing the analysis.

$$U_e = \frac{r_b^P}{r_b} \tag{4}$$

The flow chart shown in Fig. 7 will aid in following the steps required to perform the various calculations. Unlike traditional thinking where high utilization rates are associated with constraint resources, the opposite is true using this methodology. High utilization rates are desired, low utilization rates represent assembly lines that are constantly stopping. Among the sub-assembly lines Trim 1 has the lowest value, while Frame 1 has the lowest value for the main assembly lines, see Table 1.

3.2. Individual stations

3.2.1. Evaluation

Now the utilization method will be used to determine the constraint for individual automatic stations. The method of calculating a utilization value for independent stations presented here is borrowed from Hopp and Spearman [12]. They did an excellent job of explaining the concept and developing the applicable equations (see Eq. (5)). This section of the paper will apply those concepts and equations to the manufacturing system under study.

Instead of analyzing all the automatic stations, only the alignment/adjust stations will be reviewed. These stations were selected because of their more frequent stoppages.

$$\textit{Utilization} = \frac{\textit{Arrival rate}}{\textit{Effective production rate}} \tag{5}$$

Model complexity and downtime effects will be considered in this analysis method. The effective production rate, in the denominator, will capture downtime effects.

3.2.2. Results analysis

When calculating the utilization for individual stations using this method, a lower utilization is preferred. In the case of completely reliable stations connected as a serial production line, the station with the largest cycle time (the most utilized station) is the constraint station. The station dedicated to product A had the higher utilization (Table 2).

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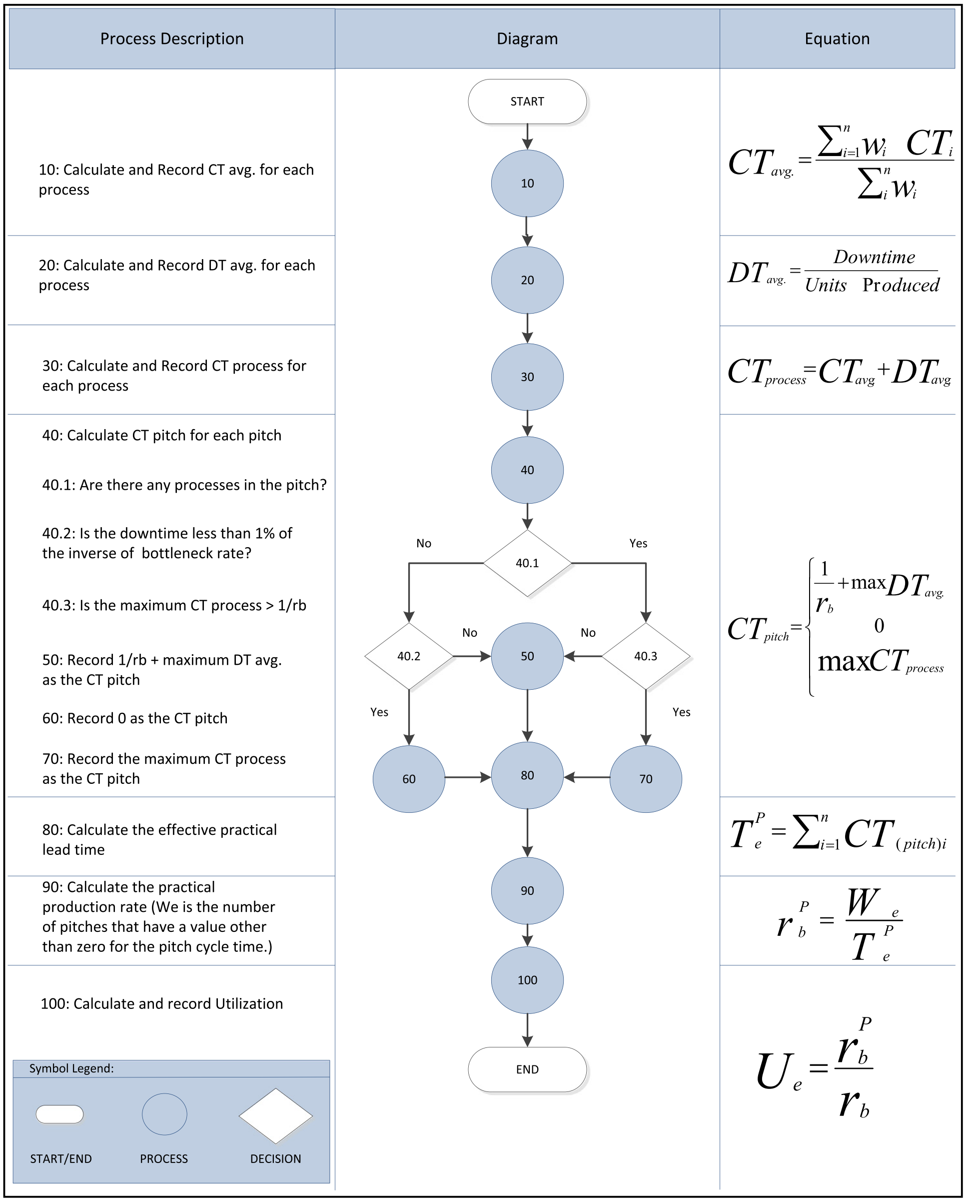

Fig. 7. Flow chart of effective utilization analysis method (drawn by: Trumone Sims).

4. Method #3: constraint identification using quick effective utilization analysis

During the effective utilization method discussion, utilization rate was used as the key process indicator for constraint identification. Utilization was calculated and interpreted two different ways. In order to distinguish the two utilizations, an "*e*" suffix was added to the *U* term to identify when the effective utilization rate referenced in Section 3.1.2 is being discussed.

The quick effective utilization method will introduce yet another method of calculating utilization. The suffix "*q*" will be added to the *U* term to identify the use of this method (see Eq. (6)). U_q, quick utilization rate, will only apply to continuous moving conveyors. Eq. (3) will also be used to calculate the practical production rate. Even though the terms from Eq. (3) are identical, the method of calculating the CONWIP and minimum practical lead time values that the terms represent is different. When using the quick method, the CONWIP term is the actual number of jobs on

Table 2
Alignment/adjust stations utilization.

Station	Utilization (%)
Product A	55
Product B	45

Table 1
Assembly line utilization rates.

Assembly line	Trim 1	Trim 2	Chassis 1	Frame 1	Frame 2/Final 1	Chassis 2/Final 2	Final 3/Chassis 3	Inspection
Utilization	93%	97.5%	97.6%	96.2%	96.7%	97.8%	98.1%	99%

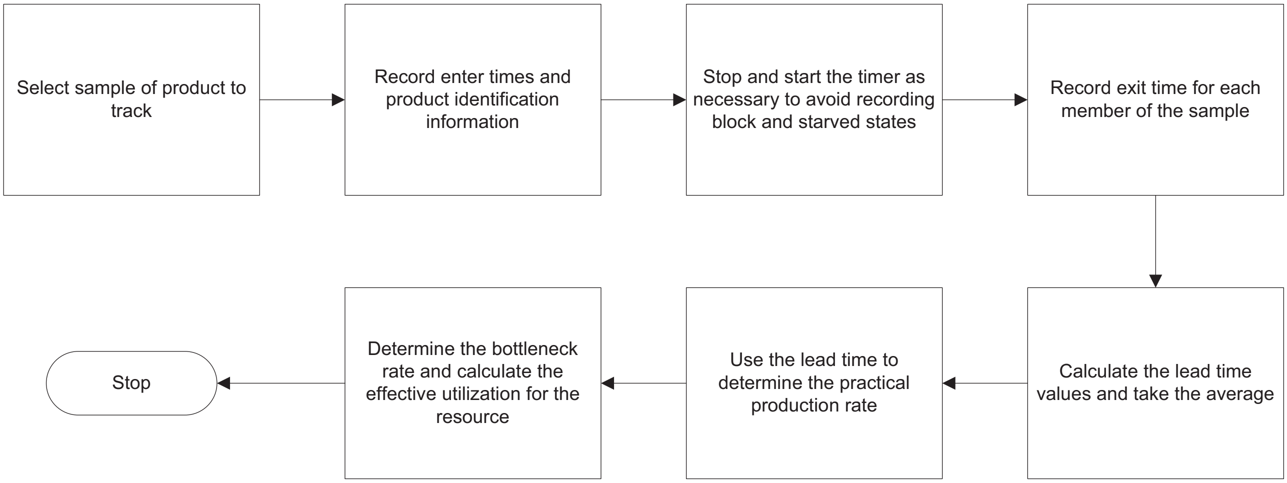

Fig. 8. Quick effective utilization flow chart.

the assembly line conveyor, while the minimum practical lead time is the average lead time of a sample of observed jobs (Fig. 8).

$$U_q = \frac{r_b^P}{r_b} \tag{6}$$

4.1. Moving assembly lines

4.1.1. Evaluation

A quicker and rougher technique for calculating the practical production rate is to use the Quick Effective Utilization Method which will now be presented. From Eq. (3), which is Little's law, we are able to calculate the practical production rate r_b^P. The CONWIP level, for the production line is obtained by waiting for a planned stop to occur, such as a break or lunch period, and then counting the number of parts on the line. To determine the minimum practical lead time, a small sample size of parts is selected to track through the production line. Start at the beginning of the line and record the time the part enters the line and the sequence/job number associated with the part. Walk the part through the production line and record the time the same part exits the line. Subtract the start time from the stop time to calculate the lead time. The goal is to include the time durations for minor stoppages on the production line in the lead time. The time durations that the production line spends in a blocked or starved state should not be included in the lead time calculation. Then calculate the sample set average lead time; this value is the minimum practical lead time, T_q^P. Table 3 shows a data sheet for the Frame 2/Final 1 production line. Several columns in the table are left blank. The blank columns would have been used if the production line stopped for long durations of time (i.e. breaks, lunch, and excessive downtime).

4.1.2. Results analysis

Using the data from Table 3, the practical production rate can be calculated.

$$r_b^P = \frac{W_q}{T_q^P} = \frac{26\text{ units}}{28\text{ min}}$$

$$r_b^P = 0.929\text{ units/min}$$

Referring to Fig. 2, we see that the cycle time for the FR2_FN1 assembly line is 61.0 s. Since minutes were used as the base time unit when calculating the practical production rate, the bottleneck rate will be converted to minutes also.

$$r_b = \frac{60.0\text{ s/min}}{61.0\text{ s/unit}} = 0.983\text{ units/min}$$

With the practical production rate and bottleneck rate known, Eq. (6) can be used to calculate the quick effective utilization of the production line.

$$U_q = \frac{0.929}{0.983} = 94.5\%$$

As before high utilization rates are desired. One of the advantages of using the Quick Effective Utilization Method is the ease of accounting for the production lin's downtime in a simulation model. The conveyor's speed can be obtained by simply multiplying the r_b^P, with the assembly line pitch. The conveyor's speed can directly be entered into a simulation data module without the need for additional modules to model production line stoppages.

Table 3
Data sheet.

FR2_FN1	Seq. #	Start T1	Stop T1	Start T2	Stop T2	Time 1	Time 2	- Lead time
1	17	8:42	9:10	–	–	0:28	–	0:28
2	9	8:43	9:11	–	–	0:28	–	0:28
3	10	8:44	9:12	–	–	0:28	–	0:28
4	38	8:45	9:14	–	–	0:29	–	0:29
5	8	8:46	9:15	–	–	0:29	–	0:29
6	7	8:47	9:16	–	–	0:29	–	0:29
7	12	8:48	9:17	–	–	0:29	–	0:29
8	5	8:49	9:18	–	–	0:29	–	0:29
							Average	0:28
W_q=26 units (frames)							T_q^P=28 min	

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Table 4
Comparison of methods.

Analysis approach	Application
Flow constraint	• Provides the users with the ability to determine the location of the enterprise constraint and determine if multiple system constraints are present. Use for early planning phases, such as before the manufacturing system has been installed or when there are plans to increase the capacity of an existing facility. The system constraint is identified through the use of plots and graphs.
Effective utilization	• Requires more computations and data. Use as part of a continuous improvement program. A lower utilization rate is used to identify the system constraint when comparing continuous moving conveyors. In contrast, a higher utilization rate is used to identify the system constraint when comparing individual automatic stations.
Quick effective utilization	• Requires very little computation and data. Real-time data is collected and analyzed. Use in situations where downtime data is not available for the production line, during verification of a simulation model or to model other resources of the manufacturing system after the primary constraint has been identified. A lower utilization rate is also used to identify the system constraint.

4.2. Individual stations

4.2.1. Evaluation

Kuo et al. [13] stated that a resource can be identified as the primary constraint by comparing the production rate of all the resources. Instead of calculating the production rates, an indicator was derived that permits the identification of the constraint resource by using real time data. An example of a two resource-one buffer system was analyzed, which is a similar system to the automatic stations being studied in this case study.

The real-time data being collected or observed is the frequency of blockages and starvations of the resources. This leads to the following rule for constraint identification;

> Bottleneck Identification Rule: *If the frequency of manufacturing blockage of machine m_i is larger than the frequency of manufacturing starvation of machine m_{i+1} (either measured or calculated), the bottleneck is downstream of machine m_i. If the frequency of the manufacturing starvation of machine m_i is larger than the frequency of the manufacturing blockage of m_{i-1}, the bottleneck is upstream of machine m_i. If, according to this rule, there exist multiple bottlenecks, the primary one is the bottleneck with the largest Severity* [9, p. 251].

4.2.2. Results analysis

The constraint can be identified by just observing blockages and starvations of the machines. If the time spent in the blocked state is larger than the time spent in the starved state, the constraint is downstream of the buffer, otherwise the constraint is upstream.

5. Discussion and conclusions

In this paper, three methods have been proposed to locate constraints in matured lean systems, especially with moving assembly lines, which usually do not have obvious bottlenecks. A case study on a real production system shows that three methods can be used for analysis at both system level and component level. The uses of the three methods are slightly different as discussed below (Table 4).

The Flow Constraint Method provides the users with the ability to determine the location of the enterprise constraint. If the there are multiple system constraints they can be quickly identified. The flow constraint method can also be used to evaluate if the design intention of the manufacturing system is being met. The Flow Constraint Method is more suitable for early planning phases, such as before the manufacturing system has been installed or when there are plans to increase the capacity of an existing facility.

The Effective Utilization Method requires more computations and data. This means the user of this method will have to spend more time and effort implementing this method. The users of this method will have the ability to narrow the focus of changes to an actual process. The users will also have deeper understandings of the manufacturing system and the effects model complexity and downtime have on the system. The Effective Utilization Method is more applicable for use as part of continuous improvement program.

The Quick Effective Utilization method requires very little computation and data. Real-time data is collected and analyzed. The analysis method can be used in situations where downtime data is not available for the production line, during verification of a simulation model or to model other resources of the manufacturing system after the primary bottleneck has been identified.

The presented case study covers only a portion of a production system. For future study, the method can be applied to the other areas of the system as well as other cases. This research can be further extended to include other aspects of the TOC methodology. After the constraint is identified, appropriate decisions can be made on exploiting the constraint to further improve the system. Insights into the system constraints can also facilitate redesigning a segment of or the whole system to be compliant with the concepts of TOC.

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