Implementing Bottleneck Management Techniques and Establishing Quality of Sort Relationships to Improve Terminal Processing Capacity

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Abstract

The importance of classification terminals to railroad network performance is well established. As the key control points, each terminal's performance affects many aspects of network operations from freight car utilization to service reliability. The acceptance of scheduled railroading by all Class I railroad's in North America has heightened the interaction between terminal performance and network operations. Terminal performance is strongly affected by terminal capacity which is defined as the upper limit on the throughput of a production process. Due to constraints on capital, railroads need to harness as much capacity as possible from existing infrastructure. It is estimated that reducing terminal dwell time can result in a 15-30% terminal capacity improvement without a major capital investment.

Because classification terminals can be considered production systems, insight into the dynamics of a terminal system can be gained by adopting a manufacturing systems management approach. This enables use of production control tools that have led to significant capacity and performance improvement in the manufacturing environment. This work focused on improving terminal performance by adapting the Hopp & Spearman concept of "Factory Physics," Goldratt's Theory of Constraints (TOC) and tools from Lean Manufacturing.

The most important manufacturing process analog to improving terminal capacity is the bottleneck. In a production system the bottleneck is the process that limits its throughput. As such, the processing rate of the bottleneck sets the rate for the entire system. Improving the performance of the bottleneck is the best way to improve the performance of the entire terminal system. Value Stream Mapping and TOC were used to identify and understand the relationship between the bottleneck and the rest of the terminal system on two major North American railroads, CN and Canadian Pacific.

The pull-down process has been identified as the bottleneck in a majority of classification terminals, including those of CN and Canadian Pacific. Both railroads are engaged in efforts to improve terminal performance. Techniques that have proven successful in improving bottleneck performance at terminals on both railroads are discussed in the context of TOC and Lean Manufacturing.

The interaction between the hump and the pull-down process is discussed in the context of the factors that increase the workload of the pull-down crews. How well the cars are sorted in the classification yard directly impacts the performance of the pull-down process. Improving the Quality of Sort can translate into an increase in terminal processing capacity and is reflected in lower average dwell times. A metric for measuring the Quality of Sort in the bowl has been developed and its relationship to bowl volume established. Methods for implementing this metric at the production control level in a terminal are also discussed.

What's new?

Application of the manufacturing methodologies of Factory Physics, Theory of Constraints and Lean Manufacturing to railroad terminal operations and development of a metric to measure the quality of the sorting process. The relationship between that metric and bowl volume has been established and related to improving terminal performance.

Introduction

Previous studies have established the need for the railroad industry to improve service reliability in order to meet the increasing logistical demands of shippers [14]. These same studies have named the classification terminal as a key determinant in the service reliability of general merchandise freight. A majority of total trip cycle time (59%) is spent in terminals [12]. "This suggests that the reliability of car movements can be improved by reducing the time spent in those activities or by making them more reliable" [11]. The transition to scheduled operations by all of North America's Class I railroads has heightened the interaction between terminal performance and service reliability [9,10] because "efficient high-throughput classification yards are vital to scheduled railroading" [20].

Within a terminal, connections are made by classifying cars from inbound trains into blocks that will be assembled into outbound trains. The objective of a yard is to sort cars and reliably connect them to the earliest possible candidate outbound train, while minimizing cost [2]. Kraft has extensively studied the terminal connection reliability problem as it relates to dynamic car scheduling [7] and has developed a hump sequencing algorithm [8], a priority-based classification system [9] and a dynamic block to track assignment scheme with the goal of ensuring connections [10]. Kraft raises the issue of inadequate terminal capacity as a barrier to improved service reliability.

> "A very serious concern is the level of terminal congestion. Under the guise of operating 'efficiency,' some carriers may have reduced terminal capacity too much. Apart from the need to run trains on a reliable scheduled basis, the most important thing railroads can do to improve reliability is to invest in adequate terminal capacity." [8]

However, the availability of capital is constrained and it is prudent to harness as much capacity from extant infrastructure as possible. This has created the need for new management and operational methods that will increase the capacity of existing facilities.

Manufacturers face a similar need and this presents the opportunity for the use of selected techniques in the area of production management. Capacity can be improved an estimated 15-30% [12] by adapting methodologies that have been successfully applied at the production control level in manufacturing such as elements of "Factory Physics," developed by Hopp & Spearman [6], the Theory of Constraints (TOC), originally developed by Goldratt [5], and Lean Manufacturing [18]. In this paper we consider the classification terminal as a production system in order to demonstrate the theoretical importance of the bottleneck, identify the pull-down process as the bottleneck in hump yards, and discuss some current examples of bottleneck management methods. To better manage and understand the interaction between the pull-down process and its immediate upstream process (the hump), a Quality of Sort metric is developed and its relationship to bowl volume is established.

The Classification Terminal as a Production System

The idea of comparing a terminal to a production system is not new. Ferguson [4] used the analogy to contrast local decisions versus system decisions in a terminal control system.

> "This situation is analogous to a manager of an automobile assembly plant . . . In the railroad industry, the terminal superintendent is the plant manager and his function is to assemble inbound trains or parts of trains into completed outbound trains."

Classification terminals are factories that make trains and are subject to the same relationships observed in manufacturing systems.

Bottleneck Management for Terminal Production Control

Capacity is defined as the upper limit on the throughput of a production process [6]. Because every classification terminal has different design characteristics, operating practices and traffic mixes, management often experiences many challenges in accurately determining a terminal's processing capacity. Experienced managers will have a relatively good understanding of the maximum number of cars that their terminal can process per day using current methods. In order to improve the processing capacity, managers need to better understand how capacity is determined in a production system. Bottleneck management methods provide a means to understand processing capacity and guidance in improving terminal performance.

The Theoretical Importance of the Bottleneck

The bottleneck process limits the throughput of a production system. As such, the processing rate (throughput) of the bottleneck process establishes the capacity of the entire system over the long term [6].

The important relationship between the bottleneck rate and production system performance provides key insight into where improvement initiatives should be targeted. Because bottleneck rate and throughput have the same units (cars per day for terminals), Little's Law [6] can be used to quantify the benefits of improving the bottleneck rate:

$$\text{Bottleneck rate} = \text{Terminal throughput (cars per day)} = \frac{\text{Volume (car counts)}}{\text{Dwell time (days)}} \quad (1)$$

Increasing the bottleneck rate will reduce the dwell time for any given volume level in the terminal. Knowing this, management can reduce the complexity of managing a complex production system by focusing on improving the bottleneck process.

The Theory of Constraints (TOC) Approach

TOC provides a structured approach to improving production system performance by focusing on the system's bottleneck. Goldratt [5] has established the general process in the TOC approach. For any production system, the TOC approach is:

1. Identify the system's constraint
2. Decide how to exploit the system's constraint
3. Subordinate the remaining resources to the above decision
4. Elevate the system's constraint
5. If in the previous steps the constraint has been broken, go back to step one, but do not allow inertia to cause a system constraint

Terminals have few actual constraints (although many more are often perceived) but must have at least one. Step 1 means identifying the actual constraints and focusing improvement efforts on the one that impacts the objective (or The Goal in TOC parlance) the most. From the Factory Physics standpoint, the most important constraint is the bottleneck. Exploiting the bottleneck means managing it in a way that maximizes its throughput. This goes hand-in-hand with step 3 since the remaining resources (the non-constraints) should be managed so that they provide the bottleneck exactly what it needs and nothing more. Efforts should continually be made to elevate the bottleneck until it is broken and a new constraint becomes the most limiting to the system.

Lean Manufacturing Tools

The area of Lean Manufacturing provides several methods and tools for understanding and improving production systems. The focus of Lean Manufacturing is the identification and elimination of waste. Waste is defined as any step or process in a production system that, from the standpoint of the customer, does not add value to the product [17]. One tool that has found wide acceptance in manufacturing and other industries, because of its visual nature, is the Value Stream Map (VSM).

A VSM shows all of the processes and the related information flow that must occur in order to get the finished product to the customer. All of the processes are classified as either those that add value to the finished product (value-adding) or those that do not (non-value-adding). The total time that a product spends in the system is compared to the time that value is being added. Improvement efforts focus on reducing the total processing time by reducing the non-value-added time. At least two major North American Railroads are using VSM as part of their efforts to implement lean manufacturing methods in their organizations [1,13]. The procedures for drawing a current-state VSM, identifying opportunities for improvement and implementing those improvements are described by Rother & Shook [17]. Figure 1 shows an example current-state VSM for a classification terminal.

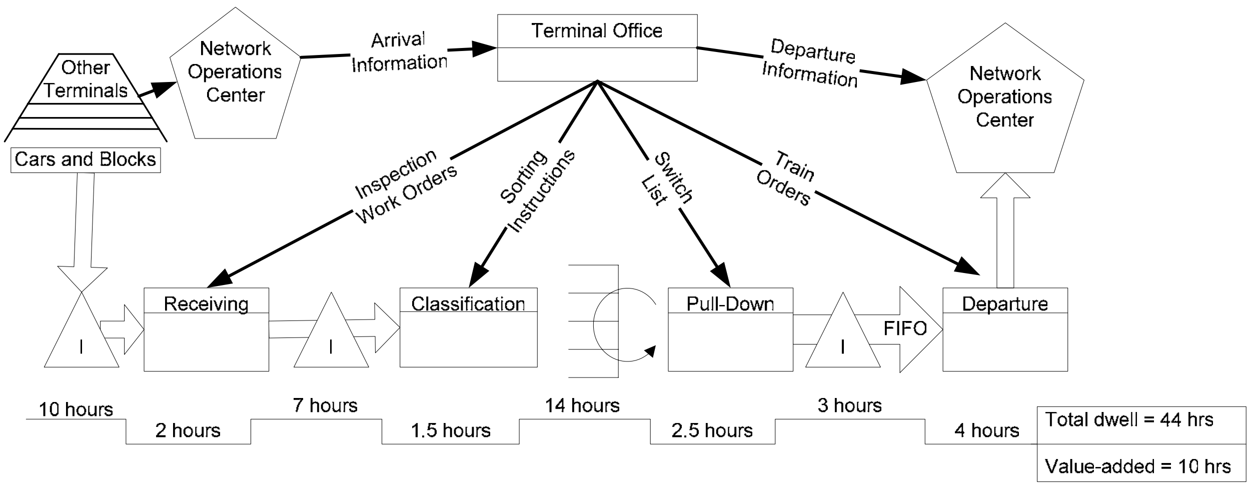

Figure 1: Example classification terminal current-state value stream map – simplified [1,13,17]

Identifying a Terminal's Bottleneck from the VSM

The total terminal dwell time (44 hours) and the value-added time (10 hours) are located in the lower right corner of the VSM. From the standpoint of the customer (the Network Operations Center), the products are the outbound trains and the value-added time is the time that the cars and blocks spend in processes that are required to build the outbound trains. These times are located in the lower sections of the timeline. Any other time spent in the terminal is non-value-adding (waste) and these times are located in the upper portions of the timeline. For this example, it is clear that a majority of time spent in this terminal (34 hours or 77.3%) is non-value-added idle time that the cars and blocks spend waiting for the next process to begin. A more detailed time-in-motion study by the GE Yard Solutions group provides a similar idle time figure of 71% of the 28.2 hour dwell time (Figure 2) and Logan [12] estimates that focusing on idle time reduction presents an opportunity for a 15-30% capacity improvement in terminals.

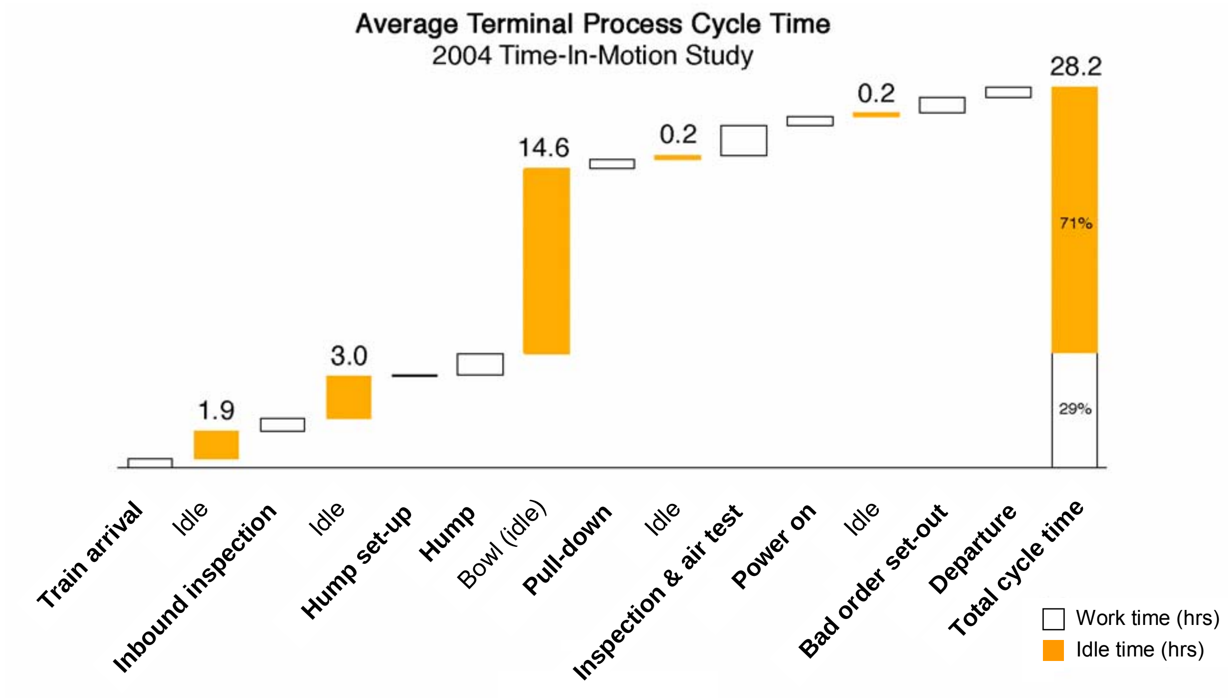

Figure 2: Average terminal process cycle time (2004 time-in-motion study) from GE [12]

The largest portion of the idle time (14 hours in Figure 1 and 14.6 hours in Figure 2) is spent in the classification yard (or bowl). A disproportionately long wait time immediately upstream from a production process is a good indicator that process is the bottleneck of the system. This leads to the conclusion that the pull-down process is the bottleneck. Past work by Petersen [15,16] and Kraft [9] has also identified the pull-down process as the most common bottleneck.

Railroad management experience confirms this conclusion. For the classification terminals that have been analyzed as part of this study, management at several levels of Canadian Pacific (CPR) and CN have identified the pull-down process as the bottleneck [1,2]. The Union Pacific has also identified the pull-down process as the constraint as part of their work to apply TOC and Lean Manufacturing methods to rail operations [13].

Bottleneck Management Methods in Practice at Classification Terminals

The physical design of the pull-down end of a yard imposes a limit on the number of pull-down engines that can operate simultaneously and the length of pull-down moves. Adding new pull-down leads, lengthening existing leads and rearranging track layout are expensive solutions and are often limited by geographic and environmental constraints surrounding the yard. As TOC implies, developing management methods that exploit the bottleneck and subordinating the other resources is the preferred approach to large-scale infrastructure expansion. Railroad management is aware of the importance of improving the performance of the pull-down process and one solution is presented here.

Adding Pull-Down Capacity at the Hump End of the Yard

At Agincourt Yard (CPR) in Toronto, only two pull-down jobs can effectively operate simultaneously at the pull-down end. In order to increase pull-down capacity, yard management decided to use the hump pusher engine and build trains when the hump would otherwise be idle. This is done by placing the hump in trim mode (disabling the retarders and allowing the engine to enter the bowl from the hump end) and pulling blocks from the hump end while the two pull-down engines continue working on the trim end of the bowl.

This solution follows the TOC approach. Having identified the system's constraint, yard management was able exploit the pull-down process by subordinating one of the other resources in the yard (the hump) to it. Due to its lower utilization rate, the hump could be used in trim mode part of the time and still be able to sort enough cars to meet the needs of the pull-down process. By operating the hump in trim mode, management has increased the throughput of the bottleneck without adding any additional infrastructure. This translates to increased processing capacity and lower average dwell times for any given volume level. However, this solution is only practical in terminals with parallel receiving and departure yards (see Wong et al. [19] Ch 10) and the necessary track connections. Analyzing the immediate upstream process can provide solutions applicable to all hump yard designs.

The Interaction between the Classification (Humping) Process and the Pull-Down Process

As a production system, the classification terminal is a network of interacting parts. Changes made to one part of the system will affect the other parts. The TOC approach and the theoretical importance of the bottleneck dictate that changes should be made in a manner that benefits the bottleneck process. In other words, make the work of the pull-down process as easy as possible by modifying the classification process so that it provides the pull-down with exactly what it needs. The pull-down process needs certain blocks at certain times in order to build the right train at the right time. Factors that increase the workload of the pull-down process include:

1. The need to "cherry-pick" high priority cars that are "buried" behind other cars on a bowl track.
2. The need to remove misrouted or mis-sorted cars from a track before a block can be pulled.
3. Having to pull several different blocks from tracks that are widely separated in the bowl.
4. Variations in traffic flow patterns and volumes results in blocks being "split" onto two or more tracks in the bowl. These blocks will need to be reassembled during the pull-down process.

"Cherry-picking" is the most commonly accepted method of protecting connections that are in danger of being missed when outbound train capacity is exceeded. It "exacerbates the capacity bottleneck which already exists there, and reduces the throughput of the whole facility" [9]. Kraft analyzes Factor 1 [8,9,10] and all of his solutions (prioritizing inbound trains, re-humping and rescheduling low-priority cars) follow the TOC approach by subordinating the upstream processes to the bottleneck and eliminating the need to "cherry-pick" cars, effectively increasing the capacity of the pull-down process.

The impacts of Factors 2, 3 and 4 have been addressed by CN and CPR to varying degrees. A flow process chart for the hump operation was developed to identify when the events occur that result in Factors 2, 3, and 4 (Figure 3). MacMillan Yard (CN) in Toronto uses a static track allocation plan for Step 2. Each track in the bowl is assigned one destination block (composed of one or more yard blocks going to the same destination on the same train) to be built on that track. The plan also includes three tracks designated as swing tracks. Swing tracks are the buffers in the sorting plan and are used for overflow traffic from other tracks or when tracks cannot be used for whatever reason. They can also be used as re-hump tracks. A re-hump track is used for cars waiting for classification instructions, low priority cars and cars whose block is not being built at the time it reaches Step 4.

Alyth Yard (CPR) in Calgary implemented a similar static track allocation scheme last year that designates tracks for specific traffic with added flexibility by designating groups of tracks based on the design of the pull-down area. The pull-down jobs are scheduled access windows and work only one group. The blocks that each job will need to build its assigned trains are contained within that group. This limits both the interference between the pull-down engines and the distance traveled to gather the necessary blocks [1]. These static track allocation plans provide the initial guidance on how to sort the cars in a manner that reduces the workload of the pull-down jobs. However, a hump controller could make a better decision at Step 7 if he/she knew how much extra work would result at the pull-down end from placing a car on a particular track based on the current state of the bowl. This information would also be helpful in determining whether to "clean" a misroute at the hump end or leave it for the pull-down end (Decision D). A metric to determine how well the cars have been sorted would aid in both tasks.

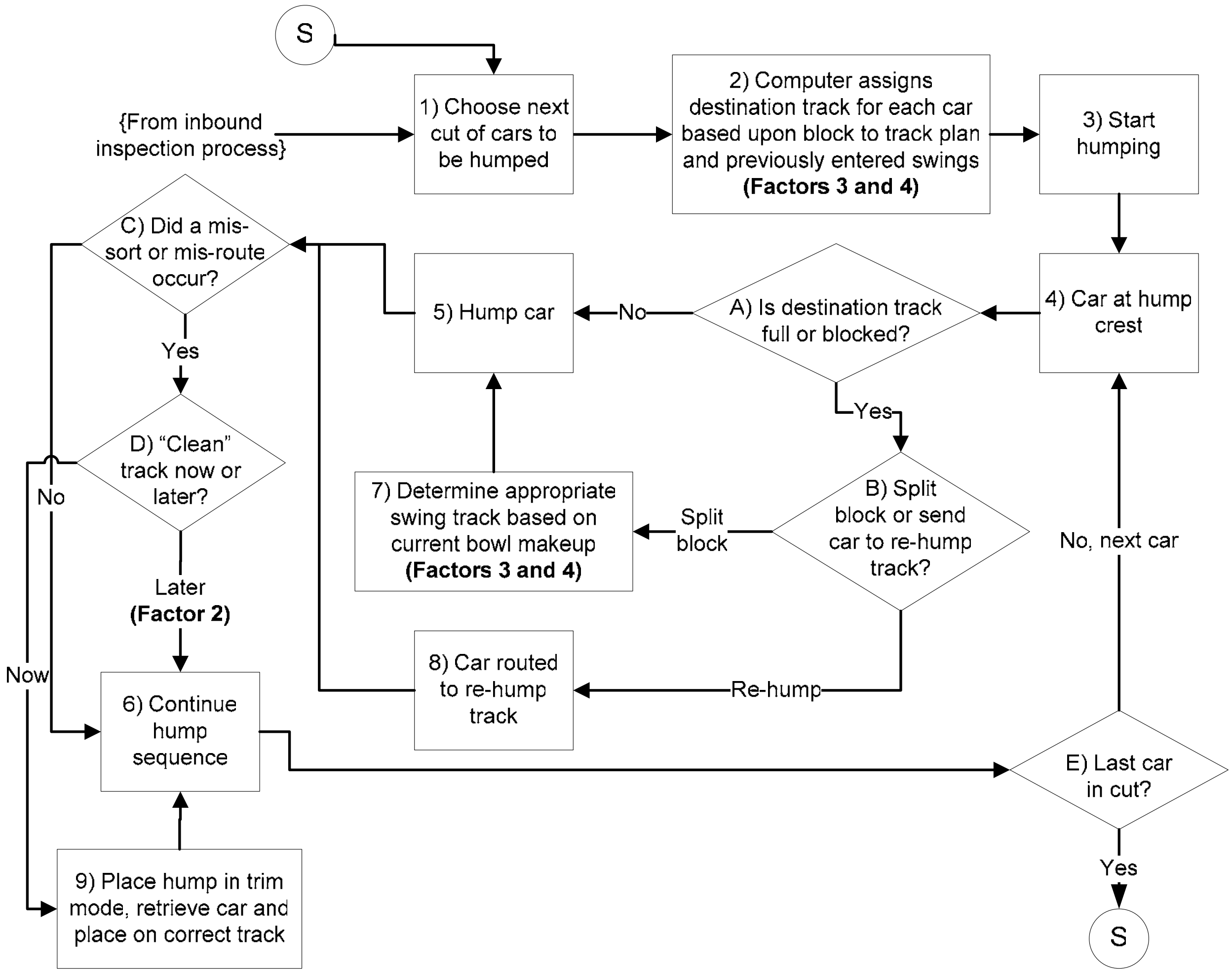

Figure 3: Hump operation flow process chart

The Quality of Sort Metric

In order to better manage the interaction between the hump and the pull-down process (particularly during periods of high yard congestion), a measurement of how well the cars are being sorted was needed. The Quality of Sort metric seeks to measure the impact of Factors 2, 3 and 4 on the workload of the pull-down process.

The metric is called the Incorrect Sort Rating (ISR) and is built in three levels: car, track and bowl. It is measured in number of cars and a low ISR indicates fewer incorrectly sorted cars. At the car level, every car that is humped into the bowl is rated according to three components. Each component is weighted according to the impact that it has on the pull-down workload.

$$\text{Car ISR} = RT + RG + BI \qquad \text{s.t. } RT = 0 \text{ or } \alpha;\ RG = 0 \text{ or } \beta;\ BI = 0 \text{ or } \mu;\ \alpha + \beta + \mu = 1 \qquad (2)$$

The first component (RT) in Equation 2 is used to measure the adherence to the static track allocation scheme used in the yards studied and is called Right Car-Right Track. The second component (RG) recognizes the need for flexibility of the static track allocation scheme and is called Right Car-Right Group. The third component (BI) is called Block Integrity and takes into account the extra workload caused by a car having a different block than the previous car on that track.

An example from Alyth Yard (CPR) will be used to illustrate Equation 2. Car ICE 70512 has classification code 4850MA1 (St. Paul Manifest Block) and that block is assigned to track CT12 (Central Group) in the bowl. CT12 is the destination track. If the actual track that ICE 70512 is humped to equals the destination track (CT12), then RT=0 and RG=0. If actual track does not equal destination track, then RT=α and RG=0 if the actual track is in the Central Group; otherwise, RG=β. BI=0 if the previous car on the actual track is from the same block (St. Paul Manifest) as ICE 70512. BI=μ if the previous car on the actual track is from a different block.

The track level reflects the fact that the pull-down process works by track. It is based on a metric used by CN at its MacMillan Yard called bowl integrity. It is used by local managers to asses the current state of the bowl and plan future humping and pull-down operations accordingly. Bowl integrity is defined as the percentage of classification tracks that are "clean." A clean track is a somewhat subjective term. A track that contains cars from only one block is definitely counted as a clean track. A track with cars from three or more blocks is definitely "dirty." A track with cars from two different blocks may be considered clean if the blocks are departing on the same train [2]. Kraft provides a more objective definition of "clean" and "dirty" tracks by comparing the number of separations to the number of blocks. "A separation is a group of cars *in standing order* all having the same block. . . If there are more separations than blocks, then at least one car must be out of place on that track" [8] (Figure 4).

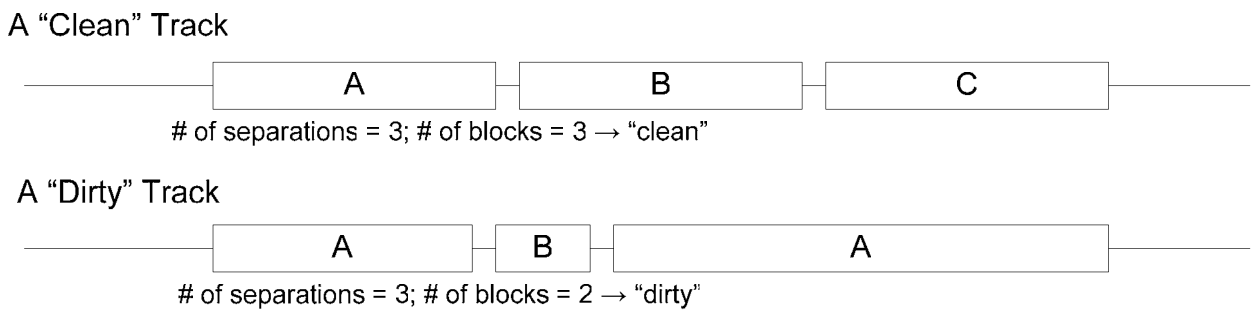

Figure 4: Kraft's definition of "clean" and "dirty" tracks [8]

The ISR values for every car on a track are summed and a multiplier reduces the total if the track is "clean" (δ), or increases the total if the track is "dirty" (η).

$$\text{Track ISR} = \{\textstyle\sum_{\text{all cars on track } n} \text{Car ISR}\} \times \text{TF} \qquad \text{s.t. TF} = \delta \text{ or } \eta \qquad (3)$$

The Track ISR value for designated mechanical and re-hump tracks is not multiplied by TF because they are supposed to be "dirty" and subjecting them to the multiplier would artificially inflate the ISR.

The bowl level of the metric is the highest level and reflects the overall performance of the hump controller in maintaining a "clean" bowl. The bowl ISR is the sum of the Track ISR values for every track in the bowl except the designated mechanical tracks. The mechanical tracks are ignored because they are subject to a different pulling process.

$$\text{Bowl ISR} = \textstyle\sum_{\text{for all non-mechanical tracks}} \text{Track ISR} \qquad (4)$$

Before the Bowl ISR can be used to gauge a hump controller's performance, the expected Bowl ISR over a range of bowl volume levels needed to be determined. In order to build this relationship, a Bowl Replay program was developed to analyze yard event data.

The Bowl Replay Program

The Bowl Replay Program is an Excel VBA program that utilizes event data that are normally captured by the terminal control systems of CPR coupled with information gathered during site visits. The first operational version was completed for Alyth Yard and a second version was developed for Bensenville Yard (Chicago).

CPR provided starting bowl count/car location, hump, pull-down and class-track-to-class-track movement event data from its Train Yard Enterprise System (TYES). TYES obtains the hump event data from the PROYARD™ hump control system. The Bowl Replay is a discrete-event program with four main types of events: hump, pull-down, hump-end trim move and pull-down-end trim move. These events come directly from the TYES data with additional events added manually to reflect movements not captured by TYES. The bowl is populated with all of the cars at midnight on the day in question and the program runs for the number of events as entered by the user. The main interface screen shows the current state of the bowl with each row representing a track and each colored cell representing a car in the bowl. The coloring scheme is based upon the previously described "dirty" vs. "clean" track definition (Figure 4) and allows for quick identification of the separations on each track. See Dirnberger [3] for a detailed description of the program.

To facilitate the program development, weighted values were assigned to the ISR components based upon management feedback. Breaking block integrity was unequivocally considered the greatest detriment to pull-down throughput; therefore, μ was assigned a value of 0.50. The wrong track and wrong group components were rated equally with α and β assigned values of 0.25. For the TF component of the Track ISR level (Equation 3), "clean" track values are multiplied by δ=0.5 and "dirty" tracks by $\eta = S - B$ where: S = number of separations and B = number of blocks. These values are arbitrary but time studies are being conducted to make them more quantitative. When cars are pulled from the bowl, their ISR values are removed from the totals. The impact of trim events is also reflected in the ISR subject to the three quality components but with an added penalty for the extra work. The program continually records the bowl volume and bowl ISR for use in the development of the relationship between those two parameters.

Bowl ISR vs. Bowl Volume

Based on their experience, management at both CN and CPR intuitively knew that bowl volume was the primary driver behind Factors 2, 3 and 4.

- Factor 2 – A misrouted car is one sent to a different track than the hump controller designated because of mechanical error (switch not realigning) or safety (over-speed or fouled track). As bowl volume increases, pressure to keep humping coupled with more full tracks tends to increase the occurrence of misroutes. Mis-sorts are operator or operator-control system interface errors and also tend to increase as bowl volume increases for similar reasons.
- Factors 3 and 4 – "The more cars in a yard, the more difficult it tends to be to find track assignments of sufficient capacity to start new train blocks when needed. Under congested conditions, blocks tend to be split more often than when the yard is fluid" [10].

As the primary driver behind factors 2, 3 and 4, knowing the expected ISR at a particular bowl volume level would allow for terminal management to gauge the performance of a hump controller and, coupled with the relationship between Track ISR and pull-down throughput, provide a tool for improved management of the interaction between the hump and the pull-down. To develop the relationship presented here, a bowl replay for Alyth Yard using event data from September 13 to 17, 2005, was built. A total of 9,300 observations of bowl volume and corresponding ISR were recorded. The observations were grouped by volume level and any volume level with less than 10 observations was discarded. Averages for the remaining observations were calculated and plotted (Figure 5) and the expected trend of a higher volume resulting in a "dirtier" bowl is seen.

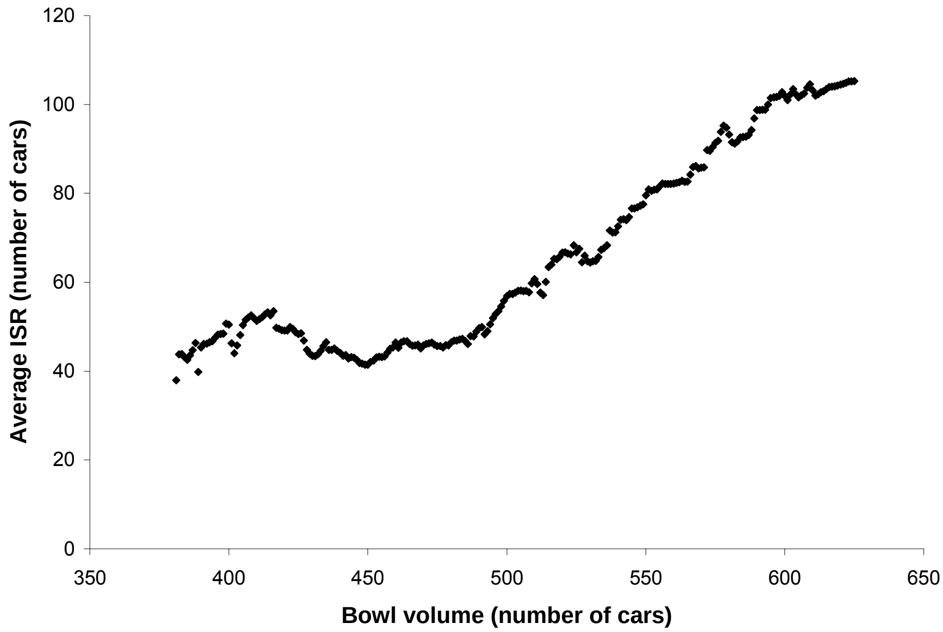

Figure 5: Average ISR vs. bowl volume for Alyth Yard, September 13 to 17, 2005

Data for an additional time period in November when CPR management considered Alyth to be congested were analyzed to determine how the Bowl ISR changed as volume approached 752 cars, the capacity of Alyth's bowl [1] (Figure 6). Note that while the Average ISR tends to increase as bowl volume increases, distinct spikes are observed with the ISR actually decreasing after a volume of approximately 650 cars. A likely factor behind this is the level of hump controller experience with more experienced controllers able to maintain a "cleaner" bowl. Additional observations are being conducted to develop a more robust understanding of this relationship, the effect of controller experience, and an acceptable range of Bowl ISR as a function of volume level.

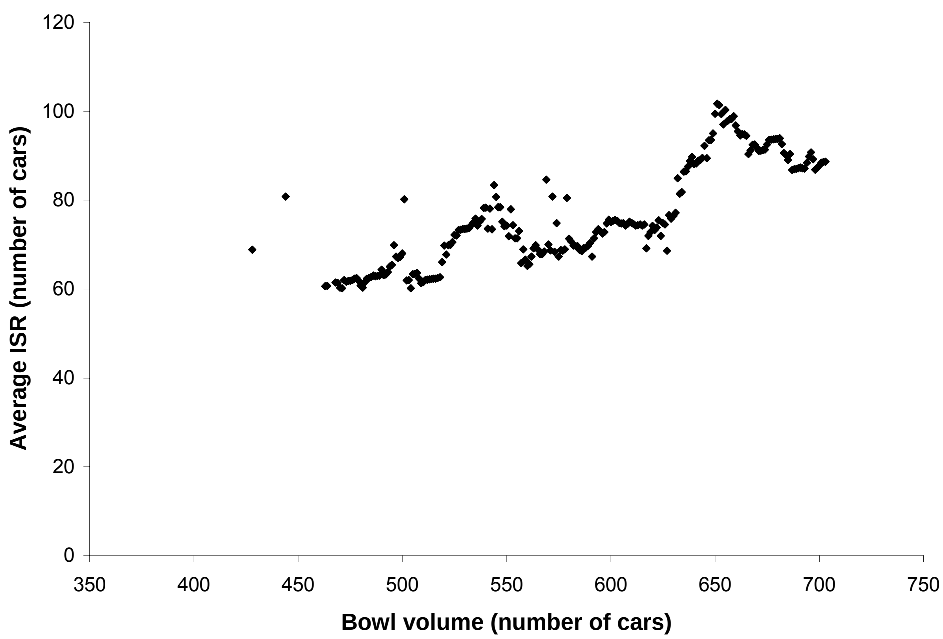

Figure 6: Average ISR vs. bowl volume for Alyth Yard, November 15, 19 and 20, 2005

Next Steps

This research is on-going at the time of submission. Focus has shifted from Alyth Yard to Bensenville Yard in Chicago because its proximity allows for the direct observation necessary to establish the additional time required to “clean” tracks that are “dirty.” Basing the weighted components of the ISR on management feedback has provided the framework for a metric that will enable better management of the bottleneck. The components will be adjusted to reflect the results of the time study and statistical regression methods are being developed to model the relationships. A natural extension of this work is an optimization method using the Quality of Sort metric to aid the hump controller in Step 7 of Figure 3. These steps will be found in Dirnberger [3] and forthcoming papers.

Conclusions

Production systems often focus too much on quantity and not enough on quality. Hump yards are no exception. Hump controllers are rated primarily on the number of cars humped during their shift with little emphasis placed on how well they have sorted those cars. The Quality of Sort metric should be used in a yard management system to emphasize the importance of preventing and correcting defects at the hump end of a yard. Sustaining this quality emphasis will require management focus to shift from the hump to the pull-down process.

The insights of “Factory Physics” and TOC indicate that focusing more attention on the productivity of the pull-down process will result in increased terminal capacity. The Lean Manufacturing emphasis on reducing idle time in all terminal processes will further increase capacity. By combining scheduled railroading with a version of Lean Manufacturing in their yards, CPR reports average terminal dwell fell from 30.4 hours in March 2005 to 20.7 hours in March 2006 [1]. Assuming a constant terminal volume of 1,500 cars, this results in an estimated average terminal capacity increase of 555 cars per day (Equation 1), a 46.9% increase.

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