An Analysis of the Effects of Interdependence and Variability on the Operational Control of a Five-Station Manufacturing Cell

Track: Operations Planning , Scheduling and Control.

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Abstract

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Introduction

Manufacturing Input/output control seeks to identify capacity problems resulting either from unworkable planned loads or from performance problems within the system. In either case, capacity problems are identified on the basis of deviations from planned performance. Inputs and outputs are monitored on a continuing basis to identify such deviations. Managers then can choose to take action to bring performance back into line with planned performance or to make other adjustments.

Such capacity management is based on short-term measurements of capacity. That is, available capacity under given conditions for a particular time period is specified, rather than theoretical or generally rated capacity for a system, which is usually based on long-term averages or on engineering specifications. The more accurately available capacity is estimated, the better input and output controls can fully exploit the manufacturing system and meet planned production goals.

The determination of available capacity is often based on empirical experience with a particular system. Variabilities in processing times and various other components of cycle time can lead to significant departures in demonstrated capacity from the long-term averages. In addition, interactions among subsystems of a production process may produce complicated patterns of output that are difficult or impossible to predict. The control actions that managers take – crash production schedules, widespread expediting, overtime scheduling and other expensive processes – have less to do with bringing a process back into control than with meeting production schedules *in spite* of that process.

A more accurate method to estimate available capacity and to describe system performance could lead to more stable production schedules and greater efficiency through

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input/output control systems. This paper describes a simple simulation experiment to determine the effects of variability and subsystem interdependence on the output of the system in order to detect any possible systematic method for accurately gauging output from input under given conditions, particularly as concerns the structure of variability present in the manufacturing cell.

The Basic Model

The model used in this study is described as a five-station manufacturing cell. Each station is identical to the others, each represents a single machine, and enjoys a unidirectional production flow without return paths or rework or scrap. The only difference among the stations is the position in the flow each of them occupies. Station 1 processes each unit of a 60,000-unit work order without blocking or starving. Each subsequent station processes each unit as it is fed from the upstream station. Station 5 feeds into a finished goods buffer of infinite size so that it is never blocked. Performance of the system will be measured by the total length of time required to process the 60,000 units. System parameters, such as throughput rates, cycle times, and average work-in-process inventories are based on that measurement of time consumed and units produced.

Initial Parameters

To establish a performance baseline, the model was operated with deterministic processing times identical at each station. Table 1 depicts the steadily increasing throughput rate for the manufacturing cell through the first 100 cycles for a uniform processing time of 10 units for each station. A steadily decreasing cycle times for the cell through the same period is a reciprocal of throughput rates. These curves depict the initial idle times for downstream station at start-up.

[Table 1 Throughput Rates Under Deterministic Conditions]

Under such conditions, no blocking or starvation takes place at any of the five stations. In addition, cycle times for station 4 and station 5 are perfectly correlated and correlation for throughput rates for station 4 and station 5 increases toward 1.0 as the number of cycles increases. The throughput rate difference between station 4 and station 5 is termed an "interdependent effect" because the difference exists solely because of the positional relationships of 4 and 5 in the manufacturing cell. The stations themselves are technically identical.

If there is a significant linear relationship between the capacity of a manufacturing cell under deterministic conditions and its capacity under variable conditions, then significant correlations between throughput rates for stations 4 and 5 and cycle times for 4 and 5 should exist. Such a linear relationship then makes possible accurate estimation of effective capacity under variable conditions based on effective capacity under average or stochastic conditions. If, on the other hand, there is no significant linear relationship, further research may reveal a non-linear relationship. If none can be found, then it may be speculated that a complex or chaotic relationship makes accurate estimates of effective capacity impossible in the long run.

Hypotheses

Hypothesis 1: There is significant correlation between stations 4 and 5 average cycle times under stochastic processing times at each station.

Hypothesis 2: There is significant correlation between stations 4 and 5 average throughput rates under stochastic processing times at each station.

A Review of Some Past Research

Hillier & Boling described a "bowl phenomenon" in simulation studies of two, three and four-station production lines with variable operation times. The models demonstrated that a 3-station line with a fixed total sum of operating times would operate at a rate .5% faster on average when the operating times were distributed in a pattern of 1.09, .82, 1.09 than when the line was perfectly balanced with a distribution of 1., 1., 1. The authors also established that a 4-station line with a pattern of operating times of 1.14, .86, .86, 1.14 would operate .9% faster than a balanced line. They further demonstrated that a line as unbalanced as 1.28, .72, .72, 1.28 would produce overall at the same rate as a perfectly balanced line.

[Table 2 – Bowl-Shaped Phenomenon]

The authors were unable to advance a clear explanation for the observed phenomenon. They speculated that the slightly faster stations in the center of the line were able to have a positive effect on both preceding and subsequent stations, thus magnifying the influence of speeding these stations up and reducing starving and blocking. This was supported by the supplemental observation that the insertion of buffer storage between the stations lessened the positive impact of the imbalance on the production rate of the line. With a large enough buffer storage, the line eventually operated at the rate of its slower stations.

Hillier and Boling confirmed in the same simulation that these findings did not generalize to 2-station systems. Two-station systems operated at optimal production rates when in balance.

Rao (1975) demonstrated that there is an exception to the optimality of the 2-station balanced line when one station, although having an identical mean processing rate, is more variable than the other one. In that case, the author demonstrated that production rates for the line could be improved by shifting part of the workload to the less variable station.

For a 3-station system, Rao asserted that the effects of variability imbalance were considerably stronger than the bowl phenomenon. The author reported a maximum increase in the production rate of 6.79% for the variance-imbalanced line compared to just .5% for the production-rate imbalanced line of Hillier & Boling.

Hillier & Boling (1979) demonstrated in simulations that it is more desirable in production lines of more than two stations with highly variable processing time to unbalance the line according to the bowl phenomenon rather than to add buffer space or shift workloads to the less variable stations.

El-Rayah (1979) conducted a series of simulation studies to further explore the effects of line imbalance in 3- and 4-station lines. Specifically, the author looked at unbalanced allocation of buffer storage space in an otherwise balanced line (all stations with equal mean processing rates and coefficients of variation). No distribution of buffer space was superior to an equal distribution in terms of output rates. (The author did note a decrease in overall Work-in-Process (WIP) inventory when buffer space was allocated in an increasing pattern from station one to the end station. However, this was attained at the expense of a decrease in the production rate of the line relative to a perfectly balanced line.)

El-Rayah did report increased production rates when lower coefficients of variance (cv) were assigned to interior stations. In the 3-station simulation, the author tested lines with distributions of cv for one station of half the value assigned to the other two (cv =.3 and cv = .15), and reported a statistically significant positive difference for the .3, .15, .3 pattern over the other two patterns. This, along with similar results for the 4-station model, led the author to conclude that production lines react to imbalance of coefficients of variances in an analogous way to the bowl phenomenon.

Blumenfeld (1990) discovered an approximately linear relationship between buffer size and the ratio of utilization to idleness rates for N stations, each having equal mean production rates and cv. This permitted the development of an extension by analysis to earlier work by Muth and Alkaff & Muth, resulting in an analytic formula to predict throughput rates for the line.

Although Blumenfeld offered a general formula for the case in which stations have equal processing time but unequal variances, the formula was not tested. The author was unable to develop a formula for the case in which workstations have unequal mean processing times. Blumenfeld also discounted the value of the bowl phenomenon in understanding observed production line behavior, but offered no proof that the unbalanced line was not a significant factor.

Lau (1992) concluded from past research of Hillier & Boling, Rao, El-Rayah and others that the load of a station depended on three factors of its mean processing time, variance of the processing time and the size of the two adjacent buffers to the station. Lau conjectured that a higher load could be caused by a higher mean processing time, a higher variance or smaller buffer capacities assigned to a station. It was suggested as well that the ideal situation was one in which there was *not* a uniform set of values for these factors across all stations of the line.

Lau then based a series of simulations on this reasoning to explore the effects of unbalanced variances on a series of 3-, 5-, 7-, 9- and 19-station lines. Analytically, Lau showed that some past research in variance-unbalanced lines, in calculating coefficients of variation, violated the principle of ‘conservation of variance.’ For lines with a constant total sum of coefficients of variance (c) and varying cv at individual stations, the total variance (v) is actually increased for some imbalances. This discovery complicated interpretation of the results of some of the previous experiments in that increased total variances in and of themselves can lead to a decrease in system throughput rates independent of an imbalance effect (Lau, 1992).

Lau obtained evidence in his simulations that three desirable patterns of variance allocation existed, which he named, ‘bowl-shape’, ‘symmetry’ and ‘spike-shape’. In addition, he identified ‘box-shaped’ as an extreme of the bowl-shape. Lau further asserted that the magnitude of the phenomenon is very small. The author’s contention is that perfect balancing of unpaced production lines is the most advantageous goal, and that both Hillier & Boling’s bowl phenomenon and the variance imbalance phenomenon can safely be ignored in production line design.

Baker, Powell & Pyke (1994) developed a distribution-free approximation procedure to estimate the throughput rate for an asynchronous, unbuffered unbalanced serial line. Building on the previous work of Muth & Alkaff, Hillier & Boling (1966), Hillier & So, Rao, and others, the authors present an algorithm which they asserted to be accurate to within 2% of simulation modeling and more exact methods for known types of distributions.

Erlebacher & Singh (1999) extend Lau’s work by analytically identifying two desirable variance patterns or structures for synchronous assembly lines (Lau 1992 had modeled asynchronous lines) – a uniform configuration in which variability is distributed equally across all stations (See Table 2, Uniform Variance Structure), and a spike-shaped configuration (See Table 3, Spiked Variance Structure) in which all, or almost all, variability is assigned to one station while the other stations have little variability. They further identify through analysis the conditions under which each pattern is better.

This the authors refer to as the variance allocation problem in which they seek the optimal variance structure for a synchronous assembly line as a solution to the more general variance reduction problem. In their reasoning, reduction of variance is always desirable in a production line, but not all variance can be gotten rid of through managerial action. If residual variances remain after an attempt to reduce variability is conducted, the pattern of that remaining variance may be shaped to produce the best line performance under those conditions.

This provides managers with an indication as to how to allocate resources to reduce variability. If total variability cannot be reduced below a certain critical level, it may not be optimal to equalize variability across the production line. Likewise, the station with the greatest variance may not be the optimal one to target for variance reduction efforts. A spike-shaped pattern of variances, with the large-variance station located at the end of the production line appears to be the optimal solution for a line with large total variability.

The Experiment

The experiment consisted of the simulation of processing of 60,000 units of production through a 5-station manufacturing cell with variable processing rates according to an Erlang distribution. Variability of processing rates are tested at 3 levels, corresponding to low variability, medium variability and high variability. Each level was tested with interstation buffers set at 0 capacity and 1-unit capacity to signify two levels of degree of coupling of the subsystems of the manufacturing cell. Each experimental unit was iterated 30 times and the resulting measures of throughput rates for station 4 and station 5 and cycle times for station 4 and station 5 were subjected to analysis (ANOVA) to detect and characterize linear relationships, including simple correlation.

Summary

Input/Output control of a manufacturing system requires an accurate determination of effective capacity of the system under current conditions. Proven capacity may often seem to bear little relationship to long-term or theoretical capacity of the system, or to engineering specifications of subsystems of the manufacturing cell, particularly under variable or probabilistic conditions. Inaccurate benchmarks or standards result in over- or under-estimation of system capacity and inefficiency in the control process. An understanding of interactions between subsystems induced by variability could clarify the relationships.

These experiments were conducted to determine if linear relationships could be detected in a simulated 5-station manufacturing cell with balanced long-run capacities between workstations of the cell.

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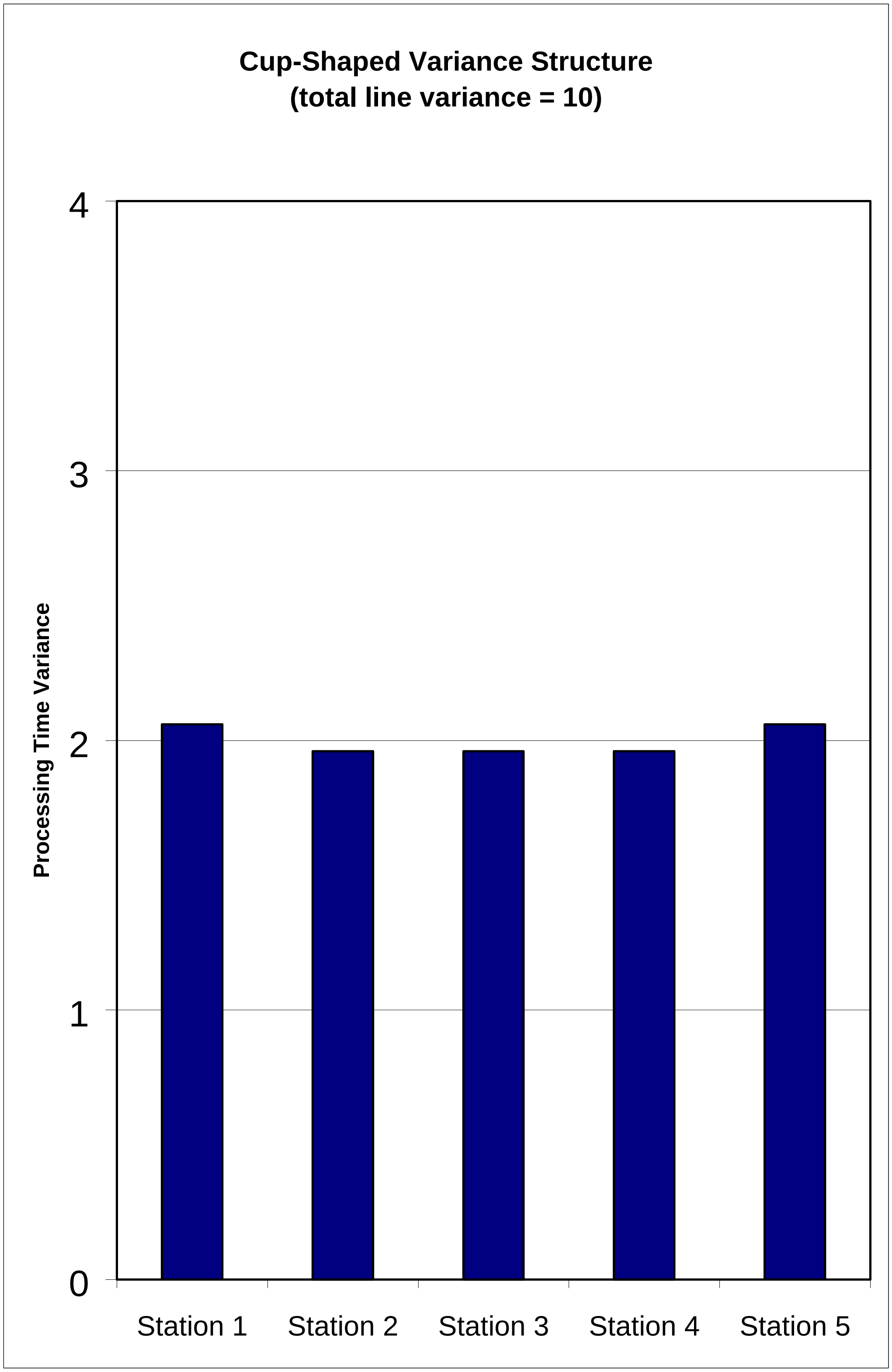

Table 1 – A Cup-Shaped Variance Structure

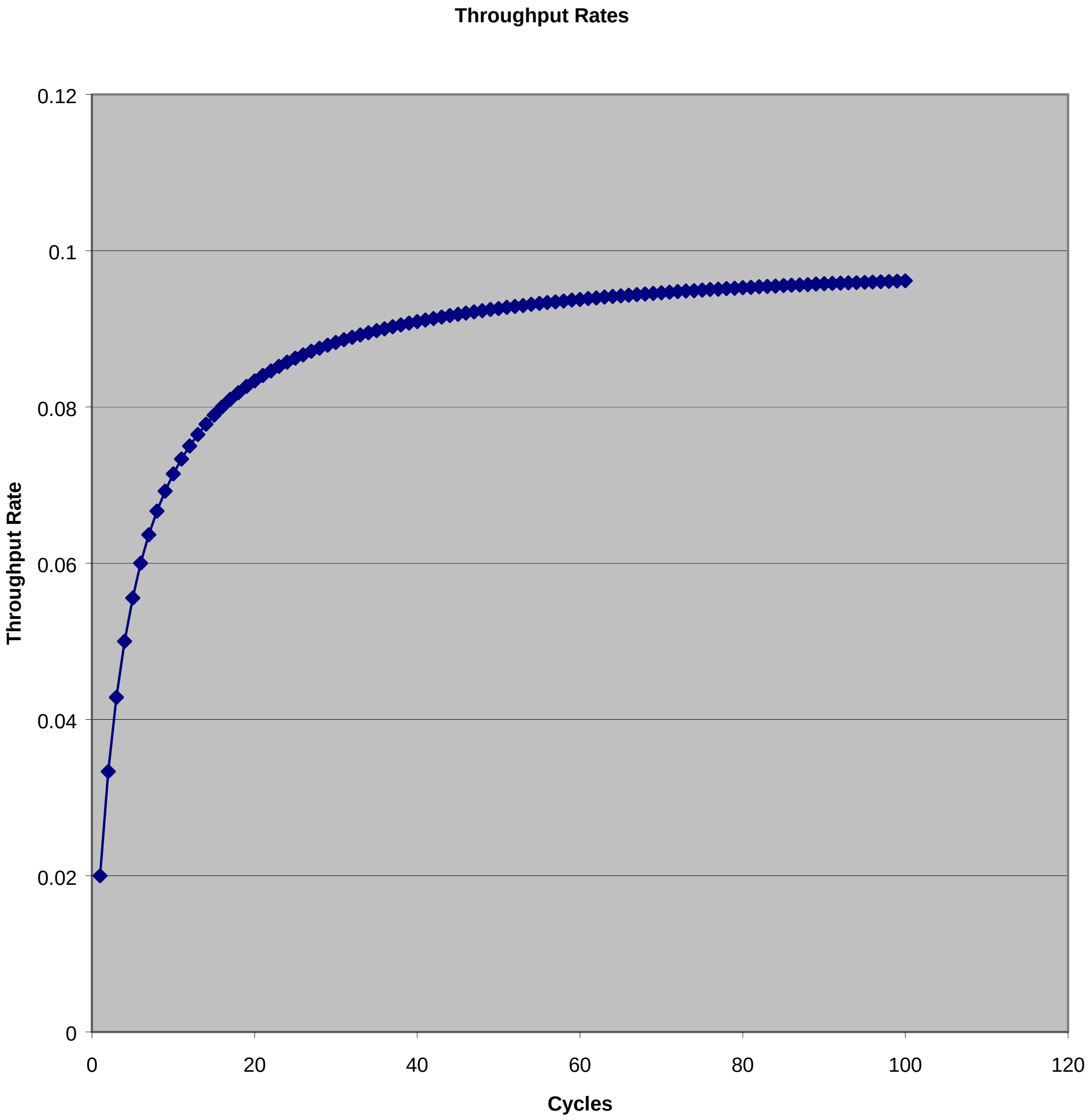

Table 2 – Increasing Throughput Rates in a 5-Station Manufacturing Cell