

Concept of Production Process Variation

PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

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*Corresponding author: S.C. Nwanya,
Department of Mechanical Engineering,
University of Nigeria, Nsukka, Nigeria;
Department of Mechanical Engineering,
Covenant University, Ota, Nigeria
E-mails: stephen.nwanya@unn.edu.ng,
snwanya@yahoo.com, stephen.nwanya@covenantuniversity.edu.ng

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Process variability analysis in make-to-order production systems

S.C. Nwanya^{1,2*}, C.N. Achebe¹, O.O. Ajayi² and C.A. Mgbemene¹

Abstract: Vehicle license number plate production in Nigeria faces high variability in terms of process times and inter-arrival times, resulting in poor production schedule reliability. This study aims to clarify the level of such variation and to provide process improvement strategies within plate production. The specific objectives herein include identifying assignable variables, estimating variability indices and minimizing variation by developing solutions to improve system performance. This study explores the variability pooling method in assessing potential cost-effective process improvements and a case study is conducted on four Nigerian vehicle license number plate production plants in order to demonstrate the applicability of the proposed technique. Structured questionnaires were circulated to plant workers and data collected from plant production records from 2012 to 2015 in seven production lines were analyzed. A preliminary study on the production lines revealed the coefficient of variation (CV) for the Awka, Gwagwalada, Lagos and Lagos State Plants, showing measured variability levels of 0.62, 0.67, 0.60 and 0.78, respectively. Comparatively, the results obtained after the variability pooling showed a significant improvement in performance characteristics, such as low CV levels, enabling a 68% increase in net annual income for each plant, as well as enhanced machine utilization.

ABOUT THE AUTHOR

S.C. Nwanya is a senior lecturer in Mechanical Engineering at the University of Nigeria, Nsukka and plays a key role in advancing the department's research and education mandate in industrial and management engineering. His research interests include industrial production systems design; production inventory control; scheduling operations; industrial energy modelling and management technology. He has attended many national and international seminars, conferences and workshops where he presented academic papers. Dr S.C. Nwanya has supervised successfully many postgraduate students and co-authored textbooks and journal articles of high repute. He has been involved in teamwork in professional, academic and community development groups. He has gained wealth of experience in academic and community work administration and is a registered engineer.

PUBLIC INTEREST STATEMENT

Vehicles in all countries of the world are required by traffic law to have license number plate for official identification purposes. In compliance to this rule, the plate production plants in Nigeria encounter problem of process time variability. Process time variability is considered to be the departure from the average time for production processes that affects delivery time in the plants. The paper describes how a cost-effective technique called variability pooling with structured questionnaire data provided solution to the problem. The technique assumes that postponing a supplier or a stage served by that supplier at a particular time will not severely affect other stages. Some of the benefits that can come from the technique are: suitability in situations of low product proliferation and lack of inventory characteristics.

Subjects: Industrial Engineering & Manufacturing; Manufacturing Engineering; Production Engineering; Transport & Vehicle Engineering

Keywords: capability indices; continuous improvement; make-to-order; variability pooling; vehicle license

1. Introduction

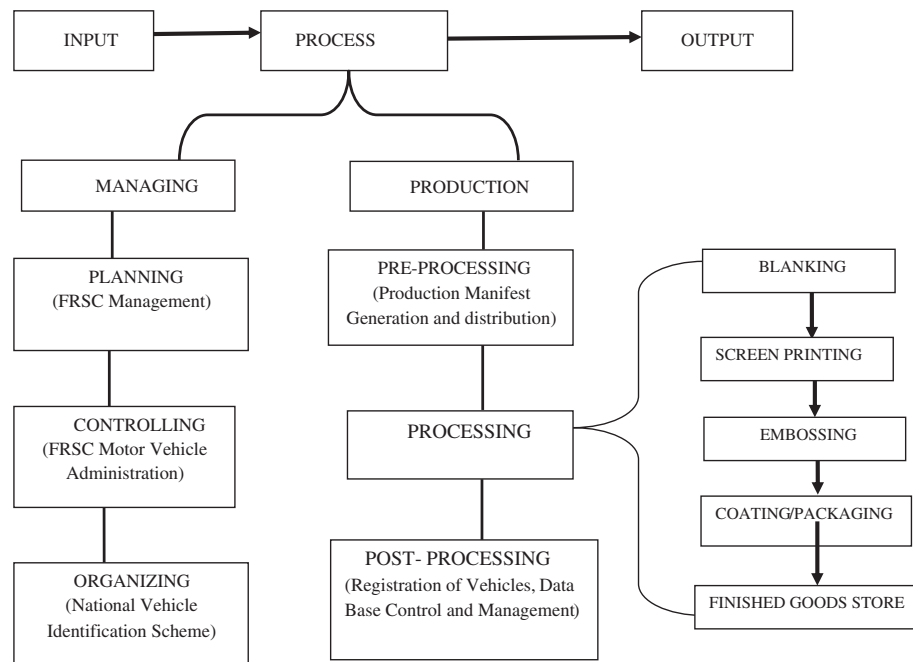
Production process variations caused by natural, random or assignable factors are inevitable. Although the effects of the variability on the throughput or output of lines can be mitigated, the continued success of production relies on tolerable process variability over a period of time. Worrisome effects are associated with prolonged high variability system performance, including the departure of manufacturing processes from uniformity and regular and predictable behavior (Hopp & Spearman, 2001), and the hindrance of on-time delivery (Kalir & Sarin, 2009). According to Harrison (2013), process variability arise as a result of unreliable equipment, unpredictable yields, glitches in human performance and numerous other sources (Kotz & Johnson, 2002; Villemeur, 1990). While it is important to discover sources of variation in order to assure control, it is also desirable in terms of improving the process that yields the product in terms of the sustainability of quality production.

In this study, we considered the plants to be serial production systems. Serial production systems are in a sense simpler forms of multistage production systems (Sadeghi, Makui, & Heydari, 2013). Thus, process time variability in the plants is considered to be a departure from the average time for production in the process steps of the plants. In recent times, such departures in license number plate production in Nigeria are on the increase and may be caused by a variety of factors. The most immediate and remote causes are assignable to any, or any group, of the following: setup, machine errors/failures, feeding the fingers during the coating, feeding and exchange of dies in embossing machines, glitches in human performance, type of number series, mesh leakages, and the re-preparation of mesh and re-working. Whatever the cause, there exists the potential for an impact on output. Identifying these causes and employing remedial solutions are thus important factors in relation to continuous performance improvement.

The monopoly to produce vehicle number plates in Nigeria is owned by the nation's Federal Road Safety Corps (FRSC). It employs a production process described by a multistep multiphase manufacturing configuration and each plant allows customers to apply for plate number from any part of the country without restriction. The application process is initiated by a customer request, which later translates into customer specifications. Over the past four years, the FRSC has been encumbered with the responsibility for new production and revalidation, encompassing 12.8 million old license vehicle number plates (Ananenu, 2012; Federal Road Safety Corps, 1993; Federal Road Safety Corps Establishment Act, 2007). The implication of this for the organization is that the production process has stultified, thus leading to increased process lead time variability between the production plants. The process design arrangement states that each job order is treated immediately upon arrival, if the system is not busy; otherwise, it joins a queue and is treated on a first in/first out (FIFO) basis. With this method, it is assumed that jobs are issued to production in the order in which they are received. The challenge facing organizations implementing the FIFO method is how to handle integrity issues, especially for operations utilizing a mechanical means of scheduling job orders to production. In the operations however, there is lengthy delay between ordering and delivery, which lead to production schedule reliability problem and increased process lead time variability in the production plants. The aforementioned challenge represents a production schedule reliability problem that is incompatible with the make-to-order philosophy espoused by the plants. A schematic of the production system of the FRSC license vehicle number plants is shown in Figure 1.

Previous studies have proven that standards do change over time and this similarly applies to specifications in production process steps. Various studies have been conducted on variability. The level of variation indicates the capability of the process to meet specifications (Kazmierski, 1995). Higher variability means added work-in-process and less predictability in output (Kalir & Sarin, 2009).

Figure 1. Production system for license vehicle number plate production.



In the context of this study, few studies are found to exist in connection with licensed plates. Nevertheless, the issue requires investigation, since its impact on production systems touch on the functional characteristics of the product.

When a production system is subjected to the stress of process variability, the resultant waiting times can become extensive compared with actual processing times (Harrison, 2013). Jacobs, Etman, van Campen, and Rooda (2003) reported on the consequences of increasing variability such as the congestion of orders, increased cycle time, low capacity utilization and increased optimal batch size. Many authors have reported the effects of queuing on the performance of a production system (Aurand & Miller, 1997; Chen & Hsu, 2004) and process performance (Kotz & Johnson, 2002). In order to monitor process variability, Raiz and Saghirr (2007) proposed Gini's mean difference (G-Chart), in contrast to the R-Chart and S-Chart, because it is less affected by departures from normality. The applicability of measures of process performance, such as standard deviations, the coefficient of variation (CV), and the variance, arrival and service times applied to evaluations of variability, have inspired extensive research studies (Colledani & Matta, 2010; Mahesh & Prabhuswamy, 2010), Jacob et al. (2003) in the area of process variability. Also, multivariate process capability indices have been used to show how manufacturing process can meet specification limits, when quality characteristics are correlated (Raissi, 2009). All of these authors share the opinion that these parameters are adequate to ascertain levels of process stability. For example, CV is emphasized as a tool for measuring process reliability (Harr, 1987; Li & Meerkov, 2000).

Although extensive literature exists on the issue of process variability, a great many of these studies address multistage systems and inventory related issues (He, Wu, & Li, 2007; Kalir & Sarin, 2009). Very few suggest the desensitization of the process in order to reduce variability, by making the process more robust to the variability inherent in process input (Mackay & Steiner, 1996). The Use of Taylor series expansion and probability generating function techniques to analyze the throughput of serial production lines with unreliable machines, finite buffers and quality inspection machines can be found in Han and Park (2002). Nair (1992) reported on the use of parameter design and Kalir and Sarin (2009) developed a strategy denoting the last-station method to reduce the inter-departure time variability of a serial production line, using a simulation model to visualize the behavior of the system. However, studies on non-inventory cases are scarce, while a negligible percentage of these

studies have been identified with parameter design as a means of improving process performance, more so when the forcing factor is a casual policy. In this study, variability pooling is used as an important aspect of parameter design because it reduces the time a job has to wait in a line before it is served. Four factors that determine the magnitude of benefit from variability pooling, according to Cattani and Schmidt (2005), are average service time, utilization of the servers, variability in arrivals and services, and number of servers being pooled. Natasha and Lilly (2009) observe that the potential advantages of pooling will be greatest in situations with high variability.

In order to achieve the overall aim of improved process performance, the specific objectives of this study include: identifying assignable variables and job process stage critical to variability improvement, determining process time variability parameters for number plate production in the four plants and measuring the performance of the plants using process capability indices. As a departure from traditional practice, the economic cost was calculated as an illustration for improved fiscal performance. Until now, the plants have coped with the situation by engaging on routine inspection to no avail.

2. Materials and methods

Various methods have been implemented in order to acquire the reliable data and information required for this study. However, few relevant studies exist, in part because this information and data are very difficult to locate. Major source of data for this study is the production records, which includes customer surveys, employee surveys, process surveys, productivity reports, internal operational cost analyses and amount of machine downtime by cause code. The customer and employee surveys were conducted using structured questionnaires. The process surveys were carried out in the four plants in Nigeria. Also, personal interviews granted by plant staff were applied. Time series data were obtained and analyzed for patterns of change using the least squares method. For cost-effective process improvement, the variability pooling technique is selected for this study. Using the above-mentioned methods, critical information in relation to this work has been obtained and segmented, following the order below.

2.1. Calculations: Arrival of job orders

Data in connection with the arrival of job orders was obtained from the plants' production records for 2012–2015. The term “arrival rate”, is used to denote the average number of jobs that arrived per hour on a given day for the three-year period considered for the plants; this process variable was used as an indicator for monitoring any changes that occurred in the average service or waiting time. Only approved job orders arrived at the plants and were produced.

$$\text{Arrival rate, } \lambda = \frac{\text{Total average daily arrival}}{3 \times 9} \quad (1)$$

where λ = arrival rate of jobs (pairs/h), nine (operational hours) = one day and plant production year = 261 days.

2.2. Mean process time and cycle time

Mean process time by operation is considered in this work. It includes the average set-up and run times of the production lines. Process Time by operation (PT) of N steps in a production line is such that

$$PT = \sum_{i=1}^N (ST_i + RT_i) \quad (2)$$

where PT = process time, ST = set-up time and RT = run time (includes infrequent short human and machine errors).

2.3. Mean cycle time

This is the average value of Cycle Time (CT) of N production lines in a plant, expressed as:

$$FF = \frac{CT}{RPT} \quad (3)$$

This is a ratio of the cycle time (CT) to raw process time (RPT) and measures process flow in plants.

$$CT = \sum_i^N CT_i \quad (4)$$

2.4. Rated capacity (actual capacity)

Capacity based on the highest production rate established by actual trials is referred to as rated capacity. Actual capacity is even lower than system capacity since many factors affect output, such as actual demand, downtime due to machine/equipment failure, unauthorized absenteeism, etc. The plant efficiency was estimated as expressed in Equation (5).

$$\text{Plant efficiency} = \frac{\text{Rated capacity}}{\text{System capacity}} \quad (5)$$

2.5. Measurement of process time variability

From the collected data, variability parameters were evaluated based on existing equations and were used to measure, prioritize and classify the process time variability of the production lines of the plants. These variability parameters are:

- Mean effective process time of a job = \bar{X} .
- Standard deviation = σ .
- Coefficient of variation, $C_v = \frac{\sigma}{\bar{X}}$.

The signal factor is the coefficient of variation, C_v , as its value can be used to measure and qualify the systems variability in terms of: *low variability* (when the coefficient of variance is between 0 and 0.75 mostly, natural variability), *moderate variability* (when the coefficient of variance is between 0.75 and 1.33) and *high variability* (when the coefficient of variance is from 1.33 upwards).

The coefficient of variation is the ratio of standard deviation (δ) to mean effective process time of a job at the production lines. It can be obtained from the collected data through Equation (6) expressed as:

$$C_v = \frac{\sigma}{\bar{X}} \quad (6)$$

2.6. Performance measures of the plants using the m/g/1 queuing model

Waiting occurs in systems with multiple stages. The plants have production lines that produce plates in successive steps, where each step is performed by a single machine workstation. This is an example of serial production. Therefore, analytical modeling (using existing formulas) of the m/g/1 queuing model was used to evaluate the performance measures (or indicators) of the plants, including:

- Machine utilization (ρ).
- Cycle time (CT).
- Average number of pairs of number plates in a queue at a particular utilization (L_q).
- Average number of pairs of number plates in the plant at a particular utilization (L).
- Average waiting time per pair of number plate in a queue at a particular utilization W_q .

These indicators were calculated so as to help the authors understand and quantify the effect of process time variability in the plants.

2.7. Variability pooling

The essence of variability pooling is to ensure that the variability of combined random processes is less than the variability of individual random processes. In applying the pooling technique, an assumption was made that the plants run multistage production lines and involve a network of suppliers, which means that postponing a supplier or a stage served by that supplier at a particular time may not severely affect other stages. The strength of pooling lies in its wide applicability in situations of low product proliferation and lack of inventory characteristics, both of which define license plate production.

With the aid of the pooling method, the variability of individual random processes of the screen printing line was pooled in the blanking line. Costs and other implications were also considered, in order to understand fully the economics of pooling.

3. Data analysis and results

The daily approval reports for the Gwagwalada plant (as shown in Table 1) were used as representative for the analysis of the mean arrival rate of job orders.

The process time variability parameters of the plants were evaluated based on time-dependent data already obtained from existing plants and variations in the process steps are shown in Figure 2.

3.1. Variability pooling

From Figure 2, it was observed that the mean process time of the screen printing section at all the plants was high. Pooling this section to the blanking section was considered and evaluated. Table 2 shows the variability parameters before variability pooling, which is a useful benchmark for comparative process analysis.

After pooling, it was observed that the Gwagwalada plant experienced less relative variation while Lagos experienced the greatest degree of relative variation with a higher level arrival rate in terms of job orders. It shows Gwagwalada plant has highest throughput while Lagos has the least throughput because there was more arrival rate in job orders. Also, it implies that process time variability in these plants was assignable to non natural causes since low variability levels are adjudged to be mostly natural variability.

Table 1. Arrival rate (λ) vs. process rate (μ) of jobs at the plants

Plant	λ (pr/h)	μ (pr/h)
Awka	111	222
Gwagwalada	158	222
Lagos	383	444
Lagos State	114	167

Figure 2. Process time of the production lines.

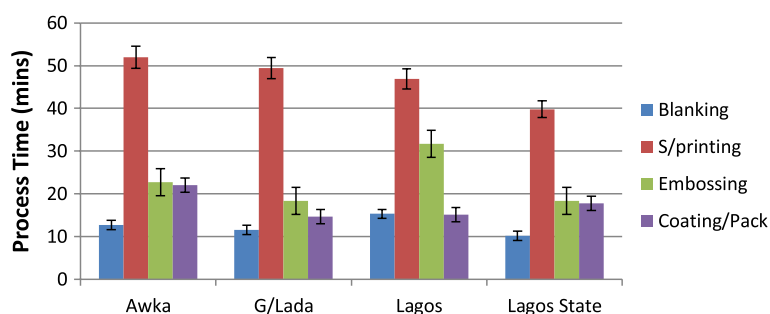


Table 2. Variability parameters of the plants

Plant	\bar{x} (h)	σ (h)	C_v	Variability level	Implication for performance case
Awka	0.46	0.29	0.63	Low	Between best case practical worst case
Gwagwalada	0.39	0.29	0.74	Low	Between best case practical worst case
Lagos	0.46	0.25	0.54	Low	Between best case practical worst case
Lagos State	0.36	0.21	0.58	Low	Between best case practical worst case

Table 3. Expected performance measures of the plants after pooling

Plant	λ (pr/h)	μ_p (pr/h)	\bar{x} (h)	σ (h)	C_v	ρ	P_0	$L_{q(pr)}$	$L_{(pr)}$	Wq (h)
Awka	111	475	0.32	0.10	0.31	0.23	0.77	77	78	0.72
Gwagwalada	158	535	0.25	0.06	0.24	0.30	0.70	66	67	0.41
Lagos	383	769	0.34	0.10	0.29	0.50	0.50	1,478	1,479	3.82
Lagos State	114	341	0.26	0.08	0.31	0.33	0.67	60	61	0.55

3.1.1. Performance measures of the plants after variability pooling

The performance measures of the plants were re-evaluated after variability pooling, by the application of analytical methods using the operating characteristics. Table 3 shows the results of the performance measures of the plants after variability pooling.

The performance measures presented in Table 3 are designated as follow: arrival rate, λ ; process rate = μ ; machine utilization, $\rho = \lambda/\mu$; probability of zero job order in the plant = P_0 ; mean process time variability = \bar{x} ; \bar{x} standard deviation of the process time, σ ; coefficient of variation of the process time = C_v ; average number of pairs in the queue at a particular utilization = L_q ; average number of pairs of number plates in the plant at a particular utilization (L); and L average waiting time per pair in the queue at a particular utilization, W_q .

The effects of average number of pairs in the queue after pooling for two plants are shown at Figures 3 and 4, respectively. In these Figures, the variability levels of the plants are low as measured by the coefficient of variation (C_v).

3.1.2. Economics of variability pooling for the plants

The economics of the variability pooling were evaluated by considering the variable cost of pooled and non-pooled processes, with the Gwagwalada Plant being used as a case study. For reasons of information confidentiality, specific characteristics of the enterprise and its product costs are not be detailed.

3.1.3. Cost measurement for variability pooling

In line with the objectives of reducing variability, the cost measurement contributes to the decision to pool screen printing operations. For the purpose of unit cost measurement, net income is given by Equation (7a) as:

Figure 3. Effect of variability reduction by pooling on average number of plates on queue for Gwagwalada plant.

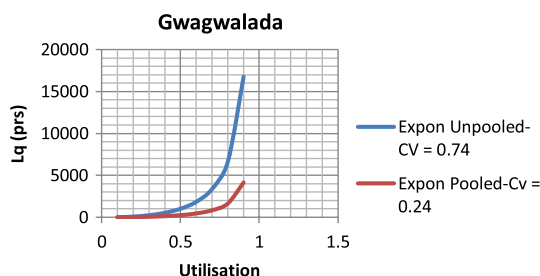
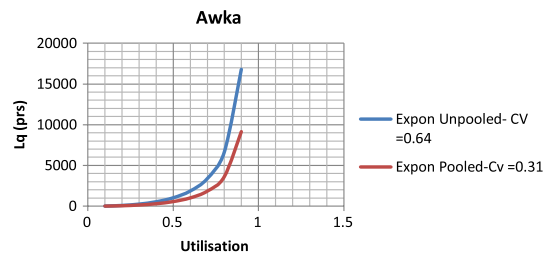


Figure 4. Effect of variability reduction by pooling on average number of plates in queue for Awka plant.



$$\text{Net income} = SP(X) - FC - VC(X) \quad (7a)$$

where X = average annual production of the plant in pairs of number plates, SP = selling price, FC = fixed cost and VC = variable cost per pair of number plates.

3.1.3.1. Cost measurement for un-pooled operation. The relevant costs were evaluated from Equations (7a–c);

$$\text{Average annual production } (X) = \frac{\text{GPDRC}}{4} \quad (7b)$$

where GPDRC = grand total production over four years,

$$X = 370,587 \text{ pairs}$$

$$\text{Variable cost per unit} = \frac{\text{annual variable cost}}{\text{average annual production}} = \text{₦}1056.12 \quad (7c)$$

$$\text{Fixed cost} = \text{₦}500,000,000$$

$$\text{Selling price per unit} = \text{₦}5000$$

$$\text{Net income} = 5000 (370,587) - 500,000,000 - 1,056.12 (370,586)$$

$$\text{Net income} = \text{₦}961,551,713.70$$

3.1.3.2. Cost measurement for pooled operation. Annual production after pooling was estimated using Equation (8):

$$\text{GPDRC} = \mu_p \times \theta (\dot{\eta} \times \dot{p})$$

where μ_p = expected process rate after pooling = 535 prs/h; θ = nine operational hours per day; $\dot{\eta}$ = number of years time series record (4); \dot{p} = plant operational days per year (261).

$$\text{GPDRC} = 5,026,860 \text{ pairs}$$

$$\text{Average annual production} = \frac{5,026,860}{4} = \text{₦}1,256,715 \text{ pairs}$$

$$\text{Variable cost per unit} = \frac{\text{annual variable cost}}{\text{average annual production}} = \text{₦}317.65$$

In order to evaluate net income earned due to variability pooling, the incremental costs in connection with the fixed cost and selling price per unit were estimated and used.

Table 4. Cost benefit of pooling

Type of operation	X (pairs)	SP (₦)	FC (₦)	VC (₦)	Annual variable cost (₦)	Annual net income (₦)
Pooled operation	1,003,023	5,000 (\$25)	500,000,000 (\$2.5 m)	398 m (\$1.99 m)	399,200,000 (\$1.99 m)	4,124,939,050 (\$20.62)
Un-pooled operation	436,788	5,000 (\$25)	500,000,000 (\$2.5 m)	896.05 m (\$1.95 m)	391,383,405 (\$1.95 m)	1,292,556,113 (\$6.4 m)
Profit						2,832,382,937 (\$14.16 m)

Note: Exchange rate \$1.00 = ₦200.00.

Summary of cost measurements and benefits for un-pooled and pooled processes were obtained and are compared in Table 4. The estimated cost in Table 4 aids in exercising judgement and making decision. The surplus annual net income accruing after variability pooling amounted to ₦2,832,382,937.00, a 68% profit to sale, as shown in the cost benefit of pooling data presented in Table 4. This further justified the removal of screen printing lines from the plants as a major variability reduction strategy for better operation.

The significance of the result in Table 4 is that elimination of assignable variability by pooling can yield 8.25% returns on invested capital. In heavily loaded systems, the percentage cost reduction becomes insignificant and a pooled system offers no relative advantage over a distributed system. Nevertheless, there remains value in pooling, as indicated by the positive absolute cost savings (Benjaafar, Cooper, & Kim, 2005).

3.2. Process capability

It is clear that the variability found in the case study process is a measure of the uniformity of output (Montgomery, 1985). The implementation of process pooling is essentially for performance improvement. Thus, determining the process capability is an important step for evaluating how efficiently the process can satisfy the customer's requirements. For that reason, capability indices related to the process parameters are used (Kane, 1986). In processes where a reduction in process variability is a priority, two main criteria: process capability ratio, C_p and capability index, C_{pk} —are widely recognized as adequate indices for the measurement of quality standards (Chien-Wei, Pearn, & Kotz, 2009). The former criterion is expressed in Equation (9) (Kane, 1986):

$$C_p = (\text{CPU} + \text{CPL})/2 \quad (9)$$

where CPU (CP upper) or USL = upper specification limit and CPL (CP lower) or LSL = the lower specification limit.

The role of C_p is to indicate how close the process mean is to the specification limits relative to six sigma spread throughout the process. Thus, the C_{pk} is considered the standard measure used to express process performance and is related to C_p by Equation (10).

$$C_{pk} = \min\{(\text{CPU}/3\sigma), (\text{CPL}/3\sigma)\} \quad (10)$$

where σ = process standard deviation expressed as $\sqrt{\frac{\bar{R}}{nd_2}}$ (Kazmierski, 1995), \bar{R} = mean of process range, d_2 = control limit factor and n = sample size.

The data collected from screen printing lines and evaluated for capability indices are shown in Table 5. The results of process capability analysis indicate that C_p is 1.0048 and is the same value as C_{pk} , which implies an in-control process. According to Kane (1986), if C_{pk} is close to C_p , then process

Table 5. Data from screen printing lines

Sample no.	Awka plant	Gwagwalada plant	Lagos plant	Lagos State plant
1	12.45	11.92	11.58	12.79
2	12.12	12.02	12.12	13.50
3	11.93	12.10	11.93	12.44
4	15.81	12.02	11.88	12.54
5	12.71	11.97	12.71	12.16
6	11.88	11.54	14.81	12.26
7	14.98	11.21	12.11	12.16
8	12.11	12.01	12.17	12.57
9	12.58	12.16	12.30	12.16
10	12.17	12.02	11.23	12.27
11	12.30	12.65	12.00	13.27
12	12.23	11.22	12.23	12.33
13	12.03	11.78	12.03	13.38
14	12.51	12.27	12.51	12.15
15	12.66	11.67	12.66	12.89
16	12.79	11.58	12.43	12.30
17	13.50	12.28	11.88	12.15
18	12.44	12.19	11.92	12.14
19	12.54	11.99	12.02	11.59
20	12.16	12.11	12.10	12.00

location is not a problem. From the foregoing analysis, the proposed variability pooling as a design parameter change is justifiable.

3.3. Discussion of results

The arrival rate (λ) of jobs to each of the plants was evaluated using Equation (1). Table 1 shows the arrival rate of job orders per hour to the plants and indicates that the Lagos plant has the highest rate, followed by the Gwagwalada, Awka and Lagos State plants, respectively. The significant implication of the approval and arrival rate is that, as the variability of either arrival or processing time increases, waiting time increases.

The production system in place at the four plants is a serial system that consisting of four production lines. Hence, the manufacturing machines form a queuing network. Every number plate has to pass through each of the production lines before its production process is completed. Therefore, the machines are treated as single machines with production progressing from one production line to another.

The mean process times of the production lines were evaluated, and the results prioritized, according to the process time variability of the production lines of each plant. The screen printing line was found to have the highest lead time in processing the mean arrival per hour at all plants. The process times of the screen printing line are 52, 49.4, 46.9 and 39.8 min for the Awka, Gwagwalada, Lagos and Lagos State plants. Figure 2 charts the processing times of the production lines of the plants.

All the plants: Awka, Gwagwalada, Lagos and Lagos State have moderately high variability level with CVs of: 0.63, 0.74, 0.54 and 0.58 respectively. The assignable causes included fluctuation of job order, plate type (private, commercial, fancy, government and diplomatic plates), frequent policy changes and unpredictable yields.

The performance of each plant was analyzed prior to pooling. The average number of number plates in pairs in the queue and the plant overall at a particular utilization, and the average waiting time in the queue in the plants, were obtained, in addition to other performance measures previously evaluated. It was found that, if the machines at the Awka plant were to be utilized to 59%, the average number of plates in the queue would be 1,760 pairs with an average waiting time of 13.33 h. This means that any job order arriving at the plant would wait 13.33 h or more before being processed; similar conditions apply to the other plants in terms of their utilization and queuing. The utilization, average number in queue and average waiting time in queue values for the other plants are: Gwagwalada plant (84%, 8,711 prs, 49.69 h), Lagos plant (98%, 295,851 prs, 679.74 h) and Lagos State plant (45%, 226 prs, 3 h).

The effect of process time variability and utilization on average number of plates in the queue and waiting time in the queue at the plants was evaluated. It was observed that, as variability increases with expected increases in cycle time and utilization, the average number of plates in the queue increases, as does the average waiting time in the queue.

Having analyzed the process time variability and prioritized it in the earlier result, the process time variability of the plants was found to be mostly natural. As such, variability pooling was found to be suitable as the major variability reduction strategy for the process time variability situations found in the plants. The idea behind process time variability pooling is that the variability of combined independent random processes is less than the variability of individual processes. Therefore, pooling the screen printing line with the blanking line was considered an option as, which improved the CV by 50, 67, 46 and 46%, respectively for the Awka, Gwagwalada, Lagos and Lagos State plants.

After process time variability pooling, the process time variability parameters of mean process time ($\bar{\mu}$), standard deviation of process times (σ) and coefficient of variation (C_v) were evaluated, respectively, for each plant. The results obtained are shown in Table 3. A marked decrease in the CV of the plants is evident from 0.63 to 0.28, 0.74 to 0.24, 0.54 to 0.46 and 0.58 to 0.31 for the Awka, Gwagwalada, Lagos and Lagos State plants, respectively. The variability levels became lower and the implication of this in terms of the performance case is also adjudged best for all the plants.

The average waiting time in the plants also dropped from 13.33 to 0.76 h, 49.69 to 0.57 h, 679.74 to 12.65 h and 3 to 0.32 h for the Awka, Gwagwalada, Lagos and Lagos State plants, respectively. The expected significant benefits of variability pooling were evident in the variability reduction by pooling on average number of plates in the queue (L_q) and effect of variability reduction by pooling on average waiting time in the queue (W_q), respectively, for the plants, as plotted in Figures 3 and 4. The economics of variability pooling was however considered for the plants using the Gwagwalada plant as a case study, in order to determine the cost effects of variability pooling over un-pooled operations. The surplus annual net income accruing after variability pooling amounted to N2,832,382,937.00. This further justified the benefit of pooling the screen printing lines in the plants, as a major process improvement strategy for enhanced performance. Again, the capability test showed that C_p and C_{pk} have equal values of 1.0048 and as a result, the process performance is adequate to meet customer satisfaction. Customer goodwill is intangible benefit of variability pooling that can be difficult to quantify.

4. Conclusion

A process variability analysis of vehicle license plate number production has been carried out on plants in Nigeria. The study has provided useful information concerning levels of process variability in the plants.

The long queues and waiting times experienced within the plants, which affect production schedule reliability, are assignable to non-natural factors. Long process time variability contributes to the long queues and waiting times, as seen in the performance measures of the plants. The screen printing operation is the unit pooled with the blanking operation. We must conclude that the

prevailing level of variability is not only likely to lead to the counterfeiting of plate numbers, but may also lead to gross inefficiencies in performance or the outright degrading of the system. This risk is particularly significant, considering the security implications of counterfeited plates.

In conclusion, results obtained showed a significant reduction in process time, cycle time, machine utilization, queue length and waiting time, increased production rate (capacity) and reduced cost, at all the plants. The significance of the changes in the performance measures after pooling is that it confirm the suitability of variability pooling technique in tackling the plants' scheduling issues. These results are key to attaining acceptable due-date deliveries, which is a significant performance indicator, expected of the plants. This reduction in variability allows make-to-order manufacturing. This work has significantly contributed to existing knowledge in the field of study; as the first analytical work conducted on vehicle number plate production plants in Nigeria, it has revealed how long queues for number plate production in these plants can be reduced. The study has eliminated assignable factors as the main causes of long queues and determined variability indices as helpful process improvement measures. Hence, the pooling strategy can be applied in related manufacturing plants. The application, if appropriately implemented, could yield cost benefits, both tangible and intangible, that add billions of income.

The valuable contributions of this work would lead to the development of effective and efficient vehicle number plate manufacturing plants because the delivery performance shortfalls in production capacity, production and quality control, productivity and product delivery responsibilities due to process time variability are addressed by its results. With these prospects complaints by customers against vehicle licence plants would drastically reduce.

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Author details

S.C. Nwanya^{1,2}

E-mails: stephen.nwanya@unn.edu.ng, snwanya@yahoo.com, stephen.nwanya@covenantuniversity.edu.ng

C.N. Achebe¹

E-mail: achebe4real@yahoo.com

O.O. Ajayi²

E-mail: oluseyi.ajayi@covenantuniversity.edu.ng

C.A. Mgbemene¹

E-mail: chigbo.mgbemene@unn.edu.ng

ORCID ID: <http://orcid.org/0000-0002-2641-3394>

¹ Department of Mechanical Engineering, University of Nigeria, Nsukka, Nigeria.

² Department of Mechanical Engineering, Covenant University, Ota, Nigeria.

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