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VARIABILITY ANALYSIS USING PHASE-SPACE DIAGRAMS IN AUTOMATED TEST EQUIPMENT

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ABSTRACT

Integral to author's own PhD research is the investigation on the enhancements to variability in semiconductor industry Automatic Test Equipment's (ATE's) equipment maintenance time. Based on industry's case studies on product yields, ATE downtime, and ATE throughput time, ATE process variability is perceived as a real problem in semiconductor manufacturing industry. However, effective methods for addressing process variability is not available in the literature. The author proposed a relationship-based research where Independent variables (IV) designated as Production Time (PT), Idling Time (IT), Repair Time (RT), and Engineering Time (ET) with Production Yield (PY) as dependent variable (DV) are being used. A chaos theory four-quadrant phase space was plotted with coordinates in a chronological order. X-axis represents "PT changes", "IT changes", "RT changes" and "ET changes" signifying differences in factory shift ATE's time, while "PY changes" illustrated differences in output on y-axis in separate charts. Quadrant in the upper-right section embodies increase in factory output with increase in ATE's IV and DV. Quadrant in the lower-right section denotes ATE's increase in IV but decrease in DV where ATE participates in unproductive work. Quadrant in the upper-left section symbolizes decrease in IV but increase in DV in consequence of factory improvement activities. Quadrant in the lower-left section illustrates both decrease in IV and DV proving that ATE is shut down. Analysis shows positive linear PT-PY, negative linear ET-PY, while both IT-PY and RT-PY graphs as extremely erratic. Judging on the results, cumulative ATE time characteristics can be comprehended, which provide some clarity in predictable equipment performance for support maintenance prioritization and task management, and for future research directions on prediction capability for equipment capacity improvement. In conclusion, the chaos theory's phase space diagrams were successfully applied to simulate the chaotic characteristics and unpredictability in equipment performance in guiding maintenance teams to better prioritize maintenance tasks management, and for future research directions, to enable better prediction on equipment capacity improvement.

Keywords: *Chaos Theory, Manufacturing, Modeling Techniques, Phase-Space Diagrams*

1. INTRODUCTION

As one of the most important sector to Malaysian economy, semiconductor manufacturing contributed RM236.8 billion or 32.9% Gross Domestic Product (GDP) in 2013 [16]. With Malaysia's economic performance lagged against global competition by losing 0.3% in world market share from 1.5% (2000) to 1.2% (2013), manufacturing sector support for national export pie also diminished from 83.3% (2000) to 76.7% (2014) [6].

In connection to the Malaysian manufacturing sector productivity expansion, electrical and electronics (or E&E) manufacturing sub-sectors are among key strategic areas for National Key Economic Areas (or NKEAs). These areas are part of the effort to raise Gross National Income (or GNI) to achieve a high-income economy by 2020.

Malaysian government policy focused on the theme 'Towards Global Competitiveness,' the nation's Third Industrial Master Plan (or IMP3) which is in alignment with this research. One of IMP3's critical objectives for the Manufacturing Sector Strategic Thrust is to promote knowledge-based activities and supports applications for leading-edge technologies [30].

This objective is achieved by 'facilitating industries in the adoption and diffusion of advanced manufacturing technologies and processes' as well as 'developing and improving technological

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capabilities. The targeted fields of expertise are microelectronics, nanotechnology, automotive engineering, and biotechnology' [30].

The fact that Malaysia's competitive position is being corroded by emerging economies [30] is validated by the 2013 Global Manufacturing Competitiveness Index [31]. It demonstrates that Malaysia currently ranked 13th with 5.94 Competitiveness Index score, whereas in five years' time (2018), Malaysia will drop to 14th position with 6.31 rating.

A phenomenon in any arbitrary production process where variation or discrepancy to planned operations is happening is called process variability. As an accepted fundamental aspect of manufacturing, execution uncertainty is expected as there is no assurance for zero misexecution [13].

Figure 1: Automatic Test Equipment (ATE)

Current research theories dealing with production process analysis, some of them include Continuous Models [2], Synchronous Models [3] [8] and Asynchronous Models [20], [9], [18], did not take variability into consideration due to lack of methods for evaluating process variability [5].

Process variability has become a centerpiece in semiconductor manufacturing: unpredictability in equipment performance producing critical customer-ordered products, vital factory staff out on unscheduled leave, intermittent delays in availability of essential factors of production, missteps in processing urgent jobs, and a plethora of issues which affect manufacturing goals [13].

An industrial classic case study showcased factual ATE downtime (non-operating machine time for producing output) 16 weeks' hourly data for ten ATEs (Fig. 2). Observations were made for Repair Time (machine time for technician repair) and Awaiting Time (machine time awaiting for technician repair) from the lowest stated goal in Week 26 of 4 hours/week to Week 28 until Week 40 exceeding 12 hours/week. The auspicious 4 hours/week/system downtime objective was never attained except in Week 26 during the study period. The data indicates that manufacturing objectives are affected by variability in ATE production time which is a major predicament for the industry [3].

[14] hypothesized that most manufacturing processes are implemented based on a considerable number of constraints-based assumptions. In real-life situations, due to unanticipated factors, some of the earlier held assumptions are no longer true during the time of execution. The likelihood is that the factory will need to be flexible and adjust accordingly to reality, hence **process variability.**

Consequently, a hypothesis is being proposed: As process-dependent variability significantly affects production throughput, delivery, quality, costs, and customer satisfaction, leading to high production costs, the unpredictable equipment performance behavior needs to be investigated as a non-linear dynamic system. The proposition is that the unpredictability in a complex system of mutually interacting elements can be characterized as overall behavior, suggesting some measure of predictability to help understand, control and manage equipment performance.

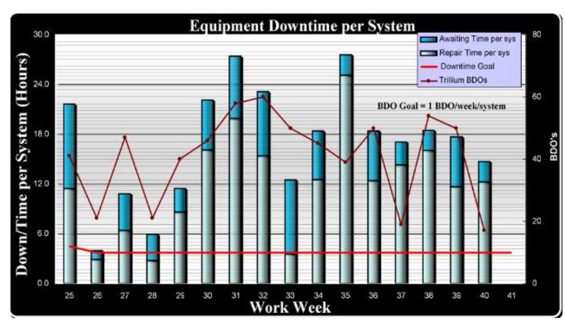

Figure 2: Actual ATE industry downtime data [3]

To this end, the research objective is to propose and develop a phase-space diagram technique to visualize the apparent chaotic represention of equipment performance.

This paper is constructed as undermentioned: the consequent section endeavours to enlighten readers with existing research on process variability, with focus on the use of phase-space diagrams to predict patterns of equipment performance. In section three, a phase space diagram is proposed and described for use with equipment time. Section four concentrates on the experiments and discussion of the findings. The last segment

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encapsulates the conclusions and perspectives derived from this paper.

2. LITERATURE REVIEW

'Lean manufacturing' is one key technique implemented by semiconductor manufacturing with the objective to drive down production steps variability and accomplish cost reduction. As part of continuous improvement, it is a method to rigorously recognize and remove all unproductive and wasteful activities [1] and cut all factors of production by fifty percent [26].

One essential sector in lean manufacturing that is given priority is equipment support [17] as adequate production time is expected to churn out products as per customers' requirements. It is understood that in consequence of unscheduled ATE downtime, factory lines would not be able to operate and complete critical customer orders. Delays in customer orders delivery might also result in lines down at the customer end. For that reason, it is imperative for the process where ATEs are in operation that an extremely dedicated maintenance workforce provides round the clock support to ensure equipment uptime and minimize process variability [24], [22].

It has been a marching order for the factory to pursue ongoing process of variability minimization to guarantee, in clockwork precision, that exact quantity to be fabricated with the exact quality completed at the exact time and delivered to the exact place [19].

There have been research in modeling simple physical systems using linear system theory. However, in reality, almost all physical processes available have nonlinear attributes or too complex to be transformed into algorithmic form [21].

A number of methods to measure and manage the equipment productivity and performance is mentioned in the literature. The measurement technique must comply with the following criteria: it continues to be applicable in different production scenarios, be able to provide analytical data capability, and designated as the consistent standard for the manufacturing entity [32].

[33] reviewed the original Overall Equipment Effectiveness (OEE), giving birth to permutations like Total Equipment Effectiveness Performance (TEEP), Overall Factory Effectiveness (OFE), Overall Throughput Effectiveness (OTE), Overall Line Effectiveness (OLE), and Overall Equipment Effectiveness of a Manufacturing Line (OEEML).

OEE is the landmark metric based on availability, performance, and quality with some derivatives devised to suit diverse factory requirements. TEEP, which is a striking resemblance to OEE, makes use of Calendar Time to assess equipment utilization. OFE is OEE index expansion to the manufacturing plant level, however the metrics are not available in the literature. OTE is a metric analogous to OEE utilizing simulation analysis. Line availability and line production quality performance are the measurement components of OLE. The bottleneck of machine performance efficiency is a focus measurement component of OEEML [33].

A number of these ecosystems exhibit unpredictable or chaotic characteristics which can be described by Chaos Theory, an Artificial Intelligence (AI) technique originally proposed by [15]. Two unique properties have been observed [7]: subtle dependence on initial conditions [18], [10], and a long term volatility or unpredictability [4].

As described by the Chaos Theory, an attractor bear a resemblance to coordinates plotted in a chronological order. Its path is similar to a geometric orbit in a theoretical multidimensional phase space, with a long-term system characteristics [18], [4]. There are four categories of attractors listed in literature: being relatively simple **point**, **pendulum**, **torus** (which is a kind of orbit), and the vastly complex **strange** attractor.

Phase space, as it is called, will be the medium for phase space diagram, developed by plotting variables. [2] noticed that an apparently chaotic time series pattern might harbor a hidden trends or structure by moving to a different perspective, through phase space. Current work in this area includes investigation into mechanical systems performance using position and velocity in phase space, as well as study on ecological systems dealing with the size of the species' population.

As discussed in previous sections, the problem statement can be formulated. Based on the industry's case studies on product yields, ATE downtime, and ATE throughput time, ATE process variability is perceived as a real problem in Malaysian semiconductor manufacturing industry. However, as discussed, effective methods for addressing process variability is not available in the literature.

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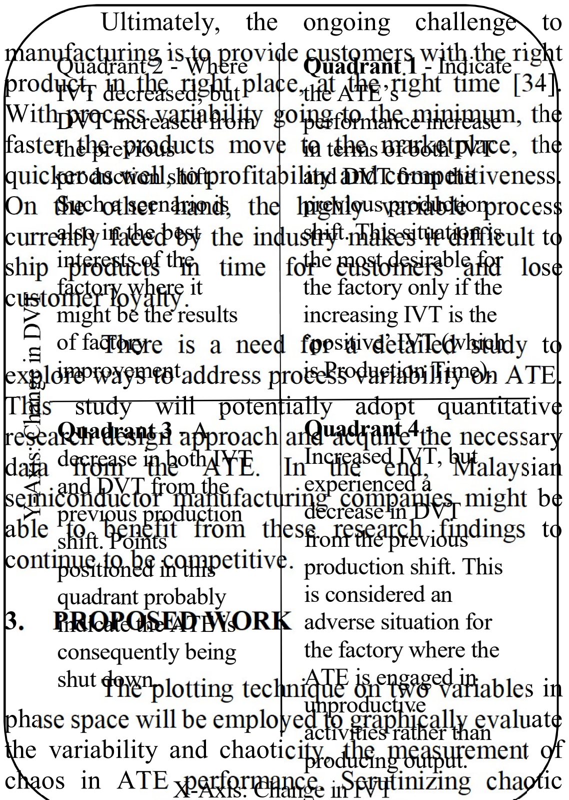
Ultimately, the ongoing challenge to manufacturing is to provide customers with the right product, in the right place, at the right time [34]. With process variability going to the minimum, the faster the products move to the marketplace, the quicker as well, to profitability and competitiveness. On the other hand, the highly variable process currently faced by the industry makes it difficult to ship products in time for customers and lose customer loyalty.

There is a need for a detailed study to explore ways to address process variability on ATE. This study will potentially adopt quantitative research design approach and acquire the necessary data from the ATE. In the end, Malaysian semiconductor manufacturing companies might be able to benefit from these research findings to continue to be competitive.



3. PROPOSED WORK

The plotting technique on two variables in phase space will be employed to graphically evaluate the variability and chaoticity, the measurement of chaos in ATE performance. Scrutinizing chaotic behavior in phase space requires time series data [11]. The raw data sets has been endorsed for the appropriate production shift time sequencing. Some number of missing production shift data is expected due to system downtime.

[14] defined 384 data points sample size requirements for any population size greater than 1000000. Therefore, the extracted 650 cumulative data points of 130 shifts from 5 ATEs of construct type 'equipment time' should exceed the requirement. This 6-months of collected dataset should be more complete than similar four weeks dataset taken by [12], as well as comparable work by [25] for the automotive industry.

Some adjustments are required to use phase space diagram method applied for operations research by [4]. To comply to this requirement, the independent variable pairs (Production Time (PT), Idling Time (IT), Repair Time (RT), and Engineering Time (ET), shown in Table 1) will be transformed as the "PT changes", "IT changes", "RT changes" and "ET changes" respectively, to be captured individually in separate charts on the x-axis.

Depicted on the y-axis, the dependent Production Yield (PY) will be transformed into "PY changes" variable pair to be together with each of the variable pair in their own respective charts.

Table 1: ATE Variable Name and Operational Definition

Common Name	Operational Description	Variable Unit Of Measure
Production Yield (PY)	Production output for the shift	1000's (quantity of microchip units)
Idling Time (IT)	Time the machine is idle & not generating productive output	Hours
Repair Time (RT)	Time the machine under repair by a technician	Hours
Engineering Time (ET)	Time the machine being used for engineering analysis	Hours
Production Time (PT)	Time the machine being used for generating productive output	Hours

The discrepancy between the prior shift and the current shift PT, IT, RT, and ET correspondingly (together denoted as IVT, abbreviated from Independent Variable Time), are calculated to acquire the change in respective IVT at the x-axis coordinate. Fig. 3 shows a four-quadrant graph with two study variables representing IVT changes for x-axis, and DVT changes for y-axis.

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Figure 3: Phase Space with Four Quadrants (Adapted from [4])

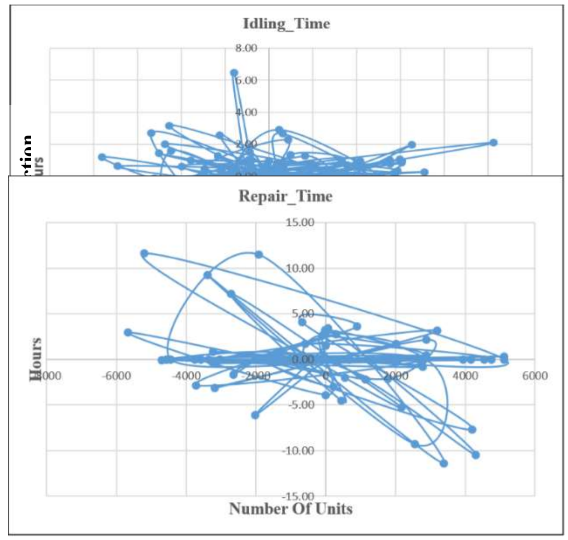
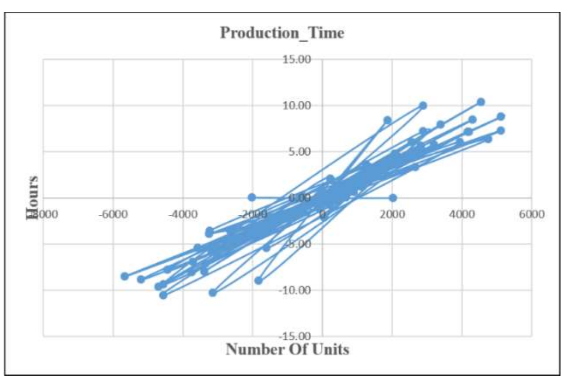
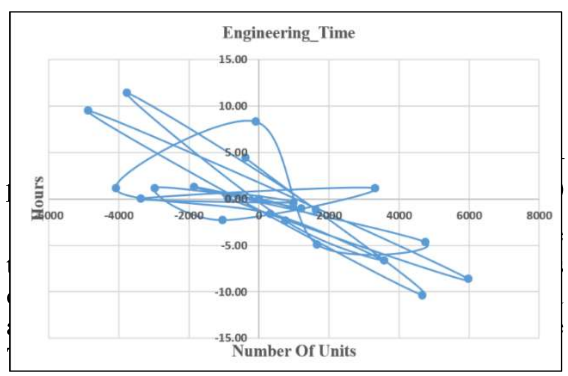


Figure 6: Production Yield vs. Repair Time performance in phase space





Change in DVT = current shift DVT – previous shift DVT (2)

The quadrant at the upper right section would be the most optimized situation for the factory as it emphasizes a condition where the ATE's performance increases in terms of both IVT and DVT from the earlier production shift. The situation is beneficial to the factory only if the increasing IVT is the 'positive' IVT, which is PT.

Points captured in the quadrant at the lower right section designate ATE has increased IVT but decreased DVT from the previous production shift. This is considered an undesirable situation for the factory where the ATE is involved in unproductive activities rather than producing output.

The quadrant at the upper left section represents conditions with decreased IVT but increased DVT from the previous production shift. Such state is also in the best factory's interests where it theoretically due to the results of factory improvement plans to augment the ATE's performance.

The lower left quadrant depicts both decreased IVT and DVT from the preceding production shift. Points located in this quadrant most likely indicate the ATE is in the state of powered down.

4. RESULTS AND DISCUSSION

For critical analysis, in the phase-space diagram, the movement of the disparity between the current shift and the prior shift for PY vs. PT, IT, RT, and ET are described in Fig. 4 through Fig. 7, correspondingly.

PY vs. PT exhibits an roughly positive linear path (Fig. 4). PY vs. ET illustrates an approximately negative linear path (Fig. 7). In these regard, a period two attractor (the phase-space diagram terminology) materializes which reveals comparatively normal two-phase fluctuations starting from the upper right quadrant to the lower left section (Fig. 4), and from the upper left to the lower right quadrants (Fig. 7), in that order. These modes of movements imply that the successive delta between the current and the prior timelines are shifting in a repeated and anticipated pattern.

Fig. 5 and Fig. 6 trajectory routes navigated all four quadrants that are impractical to predict any trends. These figures relate to the characteristics of a strange attractor, instead of a point or period two attractor. Consequently, these structures expose chaotic performance.

Some interpretations can be derived from the analysis (Table 2 listed out the summary of phase-space visual analysis):

Table 2: Summary of phase-space visual analysis

No	Variable Relationship	Phase-Space Characteristics	Key Behavior	Currently Scheduled Item In The Equipment Time?
1	PY vs. PT	Period two attractor	Non-chaotic	Yes
2	PY vs. IT	Strange attractor	Highly chaotic	No
3	PY vs. RT	Strange attractor	Highly chaotic	Yes
4	PY vs. ET	Period two attractor	Non-chaotic	Yes

• PY vs. PT, exhibiting positive linear, and PY vs. ET, showing negative linear, mimic period two attractor with non-chaotic characteristics. To be specific, PT and ET are anticipated and can be simply put into the equipment time schedule for maximum output. The shop floor can plan for the fluctuations to go deeper into Quadrant 1 and concurrently avoid Quadrant 3 for higher output

• IT reveals extremely volatile behavior to ATE performance. IT can emerge at any point during ATE schedules as evidenced by scattered trails in all four quadrants. With IT as an unanticipated unproductive activity in a real production scheduling, conceivable situations include production material getting delayed causing unproductive waiting time in Quadrant 1, or unproductive waiting time for appropriate equipment fixtures in Quadrant 2, or awaiting equipment shut down in Quadrant 3, or misplaced parts search in Quadrant 4

• IT can be one of the major factors contributing to process variability. As IT increases, process variability increases as a result, chipping away the precious production time required for building customers' orders. IT may need to be meticulously estimated to enable it to be forecasted in ATE scheduling time before it becomes out of control

• IT as a contributing factor to process variability are caused by any of these, random factors or assignable causes [5]. A number of tools are available for assignable causes, such as 7-step problem solving, Statistical Process Control (SPC), and Pareto, among others, can be utilized to solve the problem. Nevertheless, it is more challenging to diminish or to eradicate random factors. A way out would be to visualize them such that specific trends or patterns might transpire

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• RT apparently illustrates anarchic patterns parallel to IT. In this perspective, RT departs from being in the same league with IT is that RT is a standard production activity that can be inserted into ATE scheduling time. Anyway RT is only a 'supporting' activity to allow ATE to be functional to enable PT to be planned for actual productive output

• In certain occasions, additional unforecasted RT is necessary to allow the ATE to be in operation for productive output due to ATE complications. Unforeseeable ATE hard down might dictate additional RT which can be provisional and can become visible in the ATE scheduling time in a erratic trends.

• The application of phase-space diagrams helps detect patterns and furnish a nonlinear framework to comprehend a supposedly volatile ATE environment, parallel to [4] work in corporate environment. [23] elucidated the fact that phase-space diagrams is established on mathematically-sound chaos theory principles also corroborated this perspective. Chaos in itself is not a random or disordered state. In actuality, chaos synergize to some unknown or undisclosed patterns.

Plotted as a time-series plot in a chronological fashion, the diagrams' objective is to further understand, within the data collection timeframe, the cumulative ATE time performance. One example cited is that PY vs. RT diagram indicates that a sample of coordinates fluctuating between two opposite quadrants is comparable to PY vs. ET diagram. On the other hand, RT can be improved to prevent zero output through the shift.

A comparative analysis was performed to critique the results with existing work from the literature. The analysis includes authors, sample data, analysis methods and findings or outcomes related to process variability.

Authors	Sample Data	Analysis Method	Findings Or Outcomes Related To Variability
Primary: Ali, S. A., and Seifoddini, H. (2006) Others: Zadeh (1965) Aggarwal (1993) Cuevas et al. (2013), Ali, S. A., and Seifoddini, H. (2006), Butler (2012) Wang et al. (2004)	Consecutive 10 replications of 16 hours (double shift), 80 hours (weekly, double shift) and 500 hours (yearly, double shift)	Fuzzy Logic	Hard-coded configuration does not provide the flexibility of any other additional unexpected variations. For systems dealing with continuous values, a discrete classification scheme would simply fall apart
Holland, J. H. (1975), Sastry et al. (2014), May & Spanos (2006), Rojas (1996), Tabassum & Mathew (2014)	DNA individual data	Genetic Algorithm	May not able to locate global maximum; time is taken for convergence; Acceptable solutions obtained after trial & error. Need good fitness function design
Feigenbaum, (1981), Cooper (1989), Clifford et al. (1983), Nordlander, (2001) Nurminen (2003) Smith (1985) Speel et al. (2001)	Medical data	Expert Systems	Problematic knowledge acquisition phase due to experts' availability. High maintenance cost, 'IF-THEN'

Kendal & Creen, (2007), Boehm & Basili (2001) Todd (1992)			rules not appropriate to handle variability
Shintani et al. (2014)	Path delay from s38584 90-nm CMOS test chip compare with selected test pattern during a path delay test	Variability-Aware Adaptive test flow	If all the parametric faults due the variability in fabrication processes have not been fully characterized, this method might failed due to uncharacterized parametric faults
Eberts et al. (2012)	Empirical data from Functional Test 1	Virtual Time-Based Flow Principle (VTBFP)	Main detractors for time delay need to be identified and resolved on ongoing basis since variability rootcauses can change from time to time
Liu et al. (2011)	Two sets of hypothetical demand data	Multi-Objective Optimization (MOO)	Simultaneous consideration of only 2 objectives, total cost mean and variance using MOO method already requires high computational time, impractical for higher number of objectives
Covi et al. (2014)	One timing parameter per pulse measured for td & tf. Calibration equation number of unknowns n for td (tf) is determined	On-wafer statistical I-V characterization on emerging Resistive Switching Memories	Unanticipated process variability on the on-chip pulse generator area within the wafer scribe lanes can severely impact calibration accuracy

In summary, an examination of the existing research’s findings or outcomes related to process variability demonstrates that it is extremely challenging due to inflexibility, high computational time and error-prone, which makes them impractical for real-time applications on process variability characterization.

5. CONCLUSION

In review, the phase space diagrams, which is part of chaos theory, in addition to other methods,

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can provide some clarity in predictable equipment performance for support maintenance prioritization and task management, and for future research directions on prediction capability for equipment capacity improvement.

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