

From Mean Performance to Variance Sensitivity: A Reliability-Centred Theory of Human Performance in Manufacturing Systems

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Abstract: *Performance variability among first-line manufacturing engineers is persistent, consequential, and under-theorized. This paper develops a variance-regulation framework integrating four pillars: employee aptitude as performance capacity, stability-oriented dispositions as behavioural consistency regulators, organizational enablers as structural variance compressors, and manufacturing system characteristics as amplifiers of individual-level variability. Drawing on Factory Physics, trait activation theory, behavioural operations management, High Reliability Organization theory, and multi-level emergence logic, the framework advances three core arguments. First, manufacturing systems are variance-sensitive: the distribution of human performance, not merely its central tendency, determines operational outcomes. Second, human behavioural variance is mathematically analogous to machine processing time variance and propagates nonlinearly through tightly coupled systems. Third, collective reliability emerges compilation from the configuration of individual performance distributions, not their average. The framework contributes to performance theory by identifying human behaviour variability as the primary unmanaged source of processing time variance, and offers actionable implications for selection, reinforcement, and system design.*

Keywords: performance variability, manufacturing reliability, variance regulation, behavioural operations, trait activation, compilation emergence, human performance, organizational enablers

1. Introduction

Performance variability among first-line engineers remains a persistent and under-theorized challenge within manufacturing organizations. Even in facilities where production systems are standardized, technologies are comparable, and role expectations are clearly defined, observable differences in output quality, safety adherence, error rates, downtime resolution, and process stability continue to emerge across individuals occupying similar positions (Fletcher et al., 2008; Folgado et al., 2015). This variability is not trivial. In tightly coupled production systems, minor deviations in individual execution can cascade into larger operational disruptions, affecting throughput, cost structures, and safety outcomes.

Manufacturing environments differ in meaningful ways from loosely structured service or knowledge-based industries. Production processes are often interdependent, time-sensitive, and safety critical. Deviations are rarely isolated events; rather, they propagate across units and shifts. The Variability Law established in Factory Physics demonstrates that increasing variability always degrades the performance of a production system, with cycle time increasing nonlinearly as variability rises under high utilization (Hopp & Spearman, 2011). Consequently, performance in such settings cannot be adequately evaluated solely in terms of productivity or efficiency. Reliability, variance reduction, and disciplined execution assume equal, if not greater, importance (Bendoly, 2016). These characteristics raise an important theoretical question: Why do individuals operating within the same structured systems exhibit markedly different performance stability?

Extant research offers partial answers. Human capital theory emphasizes cognitive ability (Becker, 1964; Ployhart et al., 2014). Occupational psychology highlights dispositional traits (Barrick & Mount, 1991; Judge & Zapata, 2015). Organizational behaviour emphasizes contextual factors (Kurtessis et al., 2017; Schneider et al., 2017). Behavioural operations documents how human factors introduce systematic variance (Gino & Pisano, 2008; Croson & Donohue, 2006; Bendoly et al., 2006). These streams proceed independently. No integrative framework addresses how they interact to regulate performance variance in manufacturing.

Much of the literature focuses on average performance. In manufacturing, stability may matter more: the worker performing a task can be the most significant source of processing time variability, and worker differences cause blocking and starving in coupled lines (Dalal et al., 2014; Folgado et al., 2015; Doerr et al., 2004; Buzacott, 2002). Variance control is a theoretical and operational concern. This observation exposes a structural limitation in performance theory as currently constructed. The dominant paradigm is mean-based: it conceptualizes performance as a level to be predicted and maximized, treats individual variance as noise to be controlled statistically, not managed operationally, and assumes that variance across individuals aggregates linearly into unit-level outcomes.

Three axioms distinguish the variance-based paradigm advanced in this paper from this conventional approach. First, mean-based theory assumes independent variance: one worker's inconsistency does not systematically affect another's output. Variance-based theory assumes nonlinear aggregation: in tightly coupled systems, individual variabilities interact multiplicatively, not additively, producing system-level volatility disproportionate to any

Volume 15 Issue 10, October 2026

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single contributor. Second, mean-based theory optimizes central tendency. The goal is to shift the workforce mean upward through training, selection, or motivation. Variance-based theory optimizes distributional compression. The goal is to narrow the performance distribution across individuals and across time, even at the cost of marginal reductions in peak output. Third, mean-based theory treats context as a moderator of mean levels. Variance-based theory treats context as an amplifier of variance consequences. Identical individual variability produces categorically different system outcomes depending on coupling tightness, as established by the Variability Law from Factory Physics (Hopp & Spearman, 2011).

Manufacturing systems are, in this formulation, variance-sensitive systems: environments where the distribution of

human performance, not merely its central tendency, determines operational outcomes.

This paper proposes that employee aptitude defines performance capacity; stability-oriented dispositions regulate the consistency of that capacity's expression; organizational enablers compress or expand behavioural variance; and manufacturing system characteristics amplify the consequences of individual-level variability for organizational outcomes. By integrating human capital, trait activation, contextual reinforcement, and systems perspectives, the framework seeks to explain not only differences in performance levels but also differences in performance reliability. It introduces collective reliability as a novel compilation emergent construct and articulates nine formal propositions linking the framework's components.

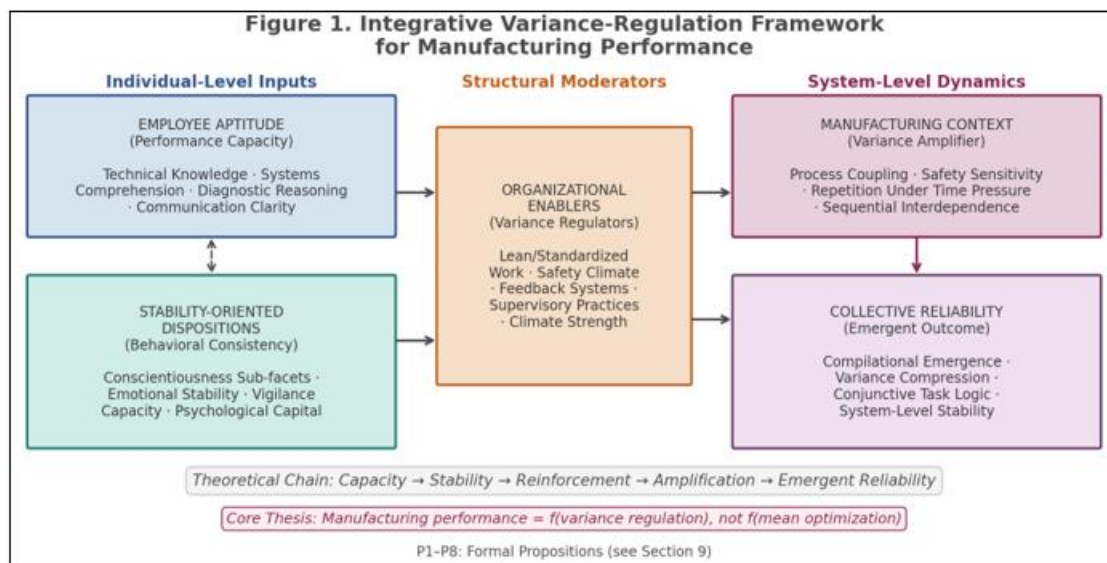


Figure 1: Integrative Variance-Regulation Framework for Manufacturing Performance

2. Theoretical Foundations

2.1 Aptitude, Human Capital, and Performance Capacity

Human capital theory posits that investments in education, training, and skill development enhance individual productivity (Becker, 1964). Within manufacturing environments, aptitude encompasses not only formal technical knowledge but also systems comprehension, diagnostic reasoning, procedural memory, and communication clarity across functional units.

From a theoretical standpoint, aptitude represents performance capacity, defined as the upper boundary of what an individual is capable of achieving under optimal conditions. Engineers with strong technical grounding and analytical ability can identify root causes of production anomalies, anticipate downstream process implications, and implement corrective actions with precision. Recent meta-analytic work, however, has refined earlier estimates of cognitive ability's predictive power, finding that conscientiousness and structured interviews may rival general mental ability as performance predictors when methodological corrections for range restriction are applied (Sackett et al., 2022). This suggests that aptitude, while necessary, may have been overweighted relative to

dispositional and contextual factors in traditional models and may not be sufficient to ensure performance stability.

The Big Five framework identifies conscientiousness as the strongest personality predictor of job performance (Barrick & Mount, 1991). Manufacturing's strong situational cues of procedural repetition, safety criticality, and error propagation risk may selectively activate orderliness and dependability more than achievement striving. In addition to conscientiousness sub-facets, two further dispositional domains a) Emotional stability which moderates the expression of technical capability under time pressure, fatigue, and interpersonal friction, all conditions endemic to manufacturing shifts.

b) Vigilance capacity represents an underexplored but theoretically critical dimension i.e Boredom proneness predicts reduced satisfaction and performance in manufacturing populations (Kass et al., 2001). Vigilance capacity as used here refers to stable individual differences in sustained attention, a trait-level construct (Warm et al., 2008), not a momentary state.

This configuration regulates behavioural consistency, defined as the stability of performance execution across production cycles, instead of predicting mean performance levels.

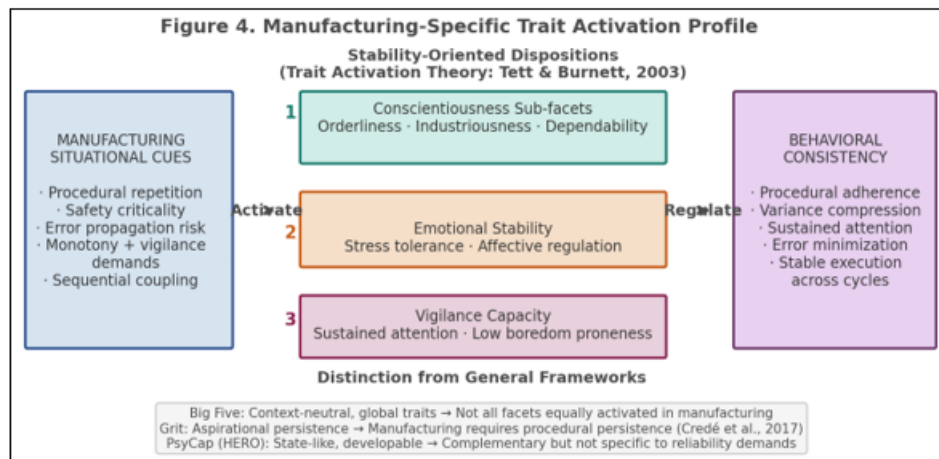


Figure 2: Manufacturing-Specific Trait Activation Profile.

2.3 Organizational Enablers as Variance Regulators

The present framework reconceptualizes organizational enablers not as generic performance enhancers but as structural variance regulators: mechanisms whose primary function in manufacturing is to compress the distribution of behavioural variability across individuals and across time.

This reconceptualization draws on five evidence bases. First, lean management and standardized work, originating in the Toyota Production System, explicitly target Mura (variation) alongside Muda (waste) and Muri (overburden). Second, safety climate research, originating in manufacturing with Zohar's (1980) seminal study, demonstrates that strong safety climates reduce behavioural variability by establishing clear norms. Zohar and Luria (2005) showed that consistent supervisory action patterns predicted climate strength at the group level, functioning as a direct variance regulation mechanism. Third, organizational climate strength itself (low within-unit variance in climate perceptions) reduces the range of behaviours individuals display regardless of personality differences, consistent with Mischel's (1968, 1973) situational strength thesis: strong situations override individual differences. Fourth, feedback systems operationalize control theory (Carver & Scheier, 1990), detecting deviations from standards and triggering corrective action. However, Kluger and DeNisi's (1996) meta-analysis cautions that poorly designed feedback can increase variability instead of decreasing it. Fifth, perceived organizational support (Eisenberger et al., 1986; Kurtessis et al., 2017) enhances commitment and discretionary effort, indirectly supporting variance reduction through increased behavioural alignment. When reinforcement systems are strong and consistent, they strengthen the situational context, compressing behavioural variance even among individuals with varied dispositional profiles.

2.4 Manufacturing Systems and Variance Amplification

Manufacturing systems often operate as tightly coupled structures in which components are interdependent (Perrow,

1984). Normal Accident Theory identifies tight coupling as the mechanism by which individual variability propagates rapidly through systems. In loosely coupled systems, buffers absorb variability; in tightly coupled systems, perturbations cascade. Leveson (2004) further noted that accidents in truly complex systems often result from interactions among perfectly functioning components. The problem is variability resonance, not individual failure.

High Reliability Organization (HRO) theory highlights the necessity of disciplined routines and heightened sensitivity to failure in such environments (Weick & Sutcliffe, 2001). Operations management research, particularly the Variability Law and VUT equation from Factory Physics (Hopp & Spearman, 2011), provides mathematical proof that processing time variability increases cycle time nonlinearly, especially under high utilization. Folgado et al. (2015) empirically confirmed that the human worker performing a task can be the most significant source of variability, and that worker differences cause blocking and starving in tightly coupled lines.

The framework's core move is to decompose the coefficient of variation attributable to human performance, $cv(h)$, into three regulable components: dispositional variance, organizational compression, and coupling amplification. In Factory Physics, the VUT equation shows that processing time variability (cv) drives system degradation nonlinearly. The decomposition parallels SPC's treatment of machine process capability (C_p , C_{pk}): human performance variance becomes a manageable parameter with identifiable sources amenable to intervention.

This framework should be differentiated from Hollnagel's (2004, 2012) Functional Resonance Analysis Method (FRAM), which also treats performance variability as normal. FRAM analyses variability at the functional/system level; the present framework operates at the individual performance distribution level.

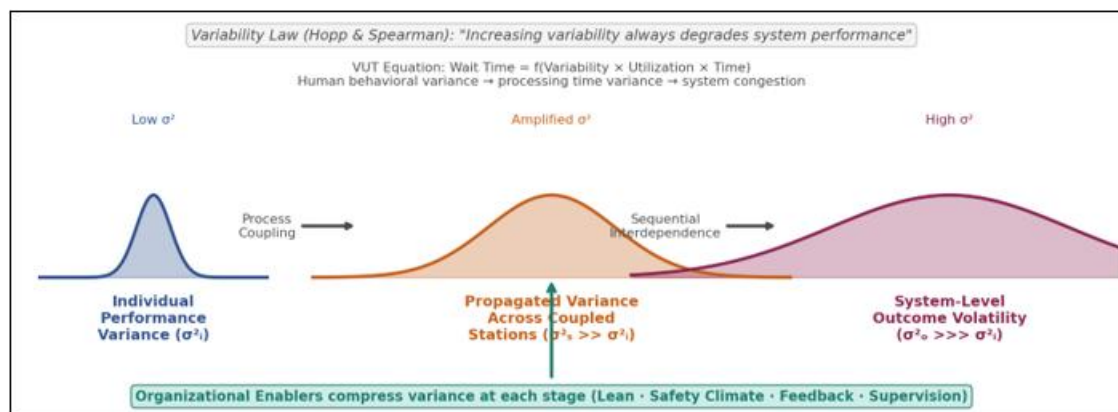


Figure 3: Variance Amplification Mechanism in Tightly Coupled Manufacturing Systems

3. Comparative Conceptual Positioning

To situate the proposed dispositional configuration within established frameworks, Table 1 provides a comparative conceptual positioning.

Table 1: Comparative Positioning of Dispositional Frameworks in Relation to Manufacturing Reliability

Framework	Core Emphasis	Strengths	Limitations in Manufacturing	Variance-Regulation Relevance
Big Five (Barrick & Mount, 1991)	Broad personality dimensions	Strong meta-analytic validity; strongest in routinized jobs (Shaffer & Postlethwaite, 2013)	Global traits mask sub-facet differences; context-neutral design does not specify which facets are activated by manufacturing cues	Partially relevant via conscientiousness sub-facets and emotional stability; explains between-person variance but not within-person variance
Grit (Duckworth et al., 2007)	Long-term perseverance toward goals	Intuitive appeal for persistence-related outcomes	Correlates at $\rho = .84$ with conscientiousness; no incremental validity (Credé et al., 2017); no manufacturing-specific evidence; aspirational not procedural persistence	Weak: does not distinguish procedural discipline from aspirational persistence; empirically redundant with conscientiousness
PsyCap/HERO (Luthans et al., 2007)	Hope, Efficacy, Resilience, Optimism	Validated scale (PCQ-24); manufacturing-specific evidence exists; state-like and developable	Focuses on psychological resources, not behavioural consistency; does not address vigilance or procedural compliance	Complementary: explains adaptive capacity but not variance compression; useful adjunct rather than core framework
Present Framework: Trait Activation Profile	Conscientiousness sub-facets, Emotional Stability, Vigilance Capacity	Context-specific; grounded in trait activation theory; maps dispositions to manufacturing situational demands; addresses variance not just means	Requires empirical validation; configuration approach needs measurement development for vigilance capacity in manufacturing contexts	Directly aligned: each component addresses a specific source of behavioural variance in manufacturing execution

4. Formal Propositions

The integrative framework generates nine formal propositions organized across the four pillars. Each proposition is derived from the theoretical arguments developed in preceding sections.

Aptitude–Performance Relationships

P1: Employee aptitude (technical knowledge, systems comprehension, diagnostic reasoning, communication clarity) exerts a direct positive effect on individual task performance in manufacturing contexts.

P2: The relationship between aptitude and sustained performance is moderated by stability-oriented dispositions. Specifically, the effect of aptitude on performance consistency across production cycles is stronger among individuals exhibiting high conscientiousness sub-facet scores (orderliness, industriousness, dependability), high emotional stability, and high vigilance capacity. Aptitude without

dispositional stability produces episodic brilliance rather than sustained reliability.

Organizational Enabler Effects

P3: Organizational reinforcement systems (standardized work, feedback loops, supervisory alignment, safety climate) strengthen the relationship between aptitude and realized performance by increasing the probability that cognitive and technical capacity is consistently expressed across production cycles.

P4: Organizational reinforcement mechanisms reduce within-person performance variability over time. As corrective feedback becomes institutionalized, deviations narrow, contributing to variance compression at the individual level.

Amplification Effects

P5: In manufacturing systems characterized by tight coupling and sequential interdependence, individual-level performance variability exerts amplified effects on unit-level outcomes.

P6: Safety-sensitive environments intensify the moderating role of stability-oriented dispositions. Under high safety risk, emotional stability and procedural compliance orientation become more critical in stabilizing performance, consistent with trait activation theory's prediction that stronger situational cues increase trait-behaviour correspondence (Tett & Burnett, 2003).

Emergent Reliability

P7: The joint presence of high aptitude, high stability-oriented dispositions, and strong organizational enablers predicts emergent collective reliability beyond the additive effects of each factor alone.

P8: The absence of alignment among aptitude, stability-oriented dispositions, and organizational enablers produces disproportionate volatility in organizational outcomes, particularly in tightly coupled production systems.

P9: Under conditions of high process coupling, manufacturing units composed of individuals with lower mean aptitude but lower within-person performance variance will achieve superior operational outcomes (throughput stability, defect rate consistency, safety compliance) compared to units composed of individuals with higher mean aptitude but greater within-person performance variance. That is, variance dominates mean in determining collective reliability in tightly coupled systems.

Proposition 9 represents the framework's most provocative and directly testable prediction. It follows logically from the conjunction of the Variability Law (variance degrades system performance nonlinearly), compilation emergence (collective outcomes reflect variance configuration, not mean aggregation), and conjunctive task dynamics (the weakest performer constrains throughput). If confirmed empirically, it would challenge conventional talent management practices that prioritize maximizing average ability, suggesting instead that variance compression may be the more consequential lever for manufacturing reliability.

5. Conclusion

Performance in manufacturing emerges from the interaction of capacity, stability, reinforcement, and amplification. The framework's core thesis, that manufacturing performance is a function of variance regulation, extends the Variability Law to human behavioural variability as the last major unmanaged source of processing time variance.

Future research on longitudinal designs that capture within-person performance variance as a primary outcome may further clarify how manufacturing organizations can compress performance variance and enhance systemic reliability in increasingly complex production environments.