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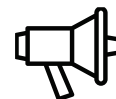


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EMPIRICAL VALIDATION OF DEVELOPMENT PATTERNS IN RAILWAY MANUFACTURING ENTERPRISES: DERIVED DEMAND, LEARNING EFFECTS IN SERIAL PRODUCTION, AND CUSTOMER DEPENDENCE

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Abstract. This article proposes a methodological framework for empirically testing the development patterns of enterprises engaged in railway rolling stock manufacturing and overhaul. Five hypotheses concerning the distinction between nominal growth and actual economic development, the existence of derived demand, the amplification of demand fluctuations through the ordering system, learning effects in serial production, and customer dependence are formulated as testable propositions with explicitly defined decision criteria. The proposed framework incorporates an order volatility amplification coefficient, a two-factor unit cost model that distinguishes learning effects from the allocation of fixed costs, and a threshold panel regression specification. The framework is illustrated using simulated time series for three hypothetical enterprises operating under different ordering regimes. The simulation results indicate that differences in ordering arrangements, rather than final demand alone, can influence order volatility, the realization of learning effects, and the responsiveness of profitability to changes in operating conditions.

Keywords: railway engineering, rolling stock overhaul, derived demand, bullwhip effect, volatility amplification coefficient, learning curve, cost elasticity, customer dependence, threshold effect.

Аннотация. В статье предложена методологическая основа эмпирической проверки закономерностей развития предприятий, осуществляющих производство и капитальный ремонт железнодорожного подвижного состава. Сформулированы пять проверяемых гипотез, касающихся разграничения номинального роста и фактического экономического развития, существования производного спроса, усиления колебаний спроса через систему заказов, эффекта обучения в серийном производстве и зависимости от заказчика. Для каждой гипотезы определены соответствующие критерии проверки. Предлагаемая методология включает коэффициент усиления колебаний объема заказов, двухфакторную модель удельных затрат, позволяющую разграничить эффект обучения и влияние распределения постоянных затрат, а также пороговую спецификацию панельной регрессии. Применение предложенного подхода проиллюстрировано на основе имитационных временных рядов трёх условных предприятий, функционирующих при различных режимах формирования заказов. Результаты моделирования показывают, что различия в организации заказов, а не только конечный спрос, могут влиять на волатильность заказов, реализацию эффекта обучения и чувствительность рентабельности к изменениям условий деятельности.

Ключевые слова: железнодорожное машиностроение, капитальный ремонт подвижного состава, производный спрос, эффект хлыста, коэффициент усиления колебаний, кривая обучения, эластичность затрат, зависимость от заказчика, пороговый эффект.

INTRODUCTION

Theories of enterprise development provide a range of propositions concerning enterprises engaged in the manufacturing, overhaul, and reconstruction of railway rolling stock. According to these propositions, demand for their products and services is derived from railway traffic volumes and the age structure of the rolling stock fleet; their production assets are characterized by specificity to railway gauge requirements and individual customers; their unit production costs are influenced by the continuity of production series rather than solely

by production volume; and their profitability is shaped by the pricing mechanisms established by dominant customers. Although these propositions have a theoretical foundation, a methodology for assessing enterprise development must establish whether they are supported by empirical evidence. Without such verification, an assessment index may assign excessive weight to less relevant factors while insufficiently capturing the determinants that materially influence enterprise development.

Empirical verification in this industry involves several methodological challenges. The relatively small number of enterprises and the limited length of available time series constrain the scope of statistical analysis. Rapid price increases can affect the interpretation of value-based indicators, while differences in product complexity complicate comparisons across production categories. Furthermore, enterprise orders are often influenced by the investment programmes of a principal railway operator rather than exclusively by decentralized market demand. These characteristics require the adaptation of conventional econometric approaches to the specific structure of the available data. Accordingly, each development pattern should be examined using an appropriate statistical test that accounts for the characteristics of the dataset and produces clearly interpretable results.

The purpose of this article is to develop a methodological framework for the empirical verification of these development patterns, introduce the analytical instruments required for their assessment—an order volatility amplification coefficient, a two-factor unit cost model, and a threshold panel regression specification—and demonstrate the application of the proposed framework using simulated time series for hypothetical enterprises operating under different ordering regimes.

LITERATURE REVIEW

The concept of derived demand can be traced to the work of Alfred Marshall, who explained that demand for factors of production is derived from demand for the goods and services they contribute to producing [8]. The amplification of demand fluctuations along supply chains was subsequently demonstrated by Jay Forrester through industrial dynamics models [4]. This phenomenon was further systematized by Lee, Padmanabhan, and Whang under the concept of the *bullwhip effect*, which they associated with demand signal processing, order batching, price fluctuations, and rationing mechanisms [7].

Learning effects in serial production were empirically documented by Wright [15] and subsequently provided with a theoretical foundation by Arrow through the concept of *learning by doing* [2]. Argote and Eppler demonstrated that accumulated organizational knowledge may depreciate during interruptions in production [1]. Their findings highlight the importance of production continuity in maintaining accumulated experience and sustaining learning-related efficiency improvements.

The distinction between economic growth and development is rooted in Schumpeter's theoretical contributions [10]. From a quantitative perspective, the separation of nominal growth into price and volume components can be achieved through index number methods [3]. This distinction is particularly relevant to railway manufacturing enterprises, where changes in reported production value may reflect both variations in physical output and changes in prices.

Customer dependence is examined within transaction cost economics through the concepts of asset specificity and the associated *hold-up problem* [13]. From an empirical perspective, the relationship between the proportion of sales attributable to a dominant customer and enterprise profitability can be investigated using panel data methods [14] and threshold regression techniques [5]. These approaches provide analytical tools for assessing whether customer concentration is associated with changes in financial performance and whether such relationships differ across specified concentration thresholds.

For empirical models involving relatively small samples and potentially autocorrelated residuals, heteroskedasticity- and autocorrelation-consistent (HAC) standard errors provide an approach to obtaining inference that accounts for these error characteristics [9]. Their application nevertheless requires consideration of sample size, model specification, and the assumptions underlying the selected estimation procedure.

Within railway economics, the theoretical and methodological foundations of industry cost formation and tariff regulation have been developed in the works associated with Teryoshina's research school [12]. The macroeconomic role of railway transport has also been examined by Lapidus and Macheret [6]. Research on Uzbekistan's railway sector has addressed the operational performance of the national railway operator and investment programmes aimed at rolling stock renewal. However, to the best of the authors' knowledge, a comprehensive methodological framework specifically designed to empirically verify the development patterns of railway rolling stock manufacturing and repair enterprises has not yet been systematically established.

The present study seeks to address this methodological gap by integrating the aforementioned theoretical concepts and analytical instruments into a unified empirical verification framework. The proposed approach

provides a structured basis for examining derived demand, order volatility amplification, learning effects in serial production, and customer dependence, while distinguishing nominal changes in enterprise performance from underlying economic development.

RESEARCH METHODOLOGY

Five research hypotheses are formulated to empirically examine the development patterns of railway rolling stock manufacturing and repair enterprises.

H0: The nominal growth of enterprise output is predominantly attributable to price increases rather than changes in physical production volume, indicating that real output does not increase.

H1a: Derived demand for the products and services of railway manufacturing and repair enterprises exists, and its underlying structural determinants—railway traffic volumes, rolling stock retirement, and the depreciation and wear of fixed assets—exhibit an expanding trend.

H1b: Derived demand is transmitted to manufacturing and repair enterprises through the ordering system, which amplifies fluctuations in the volume of orders received by these enterprises.

H2: Under conditions of volatile orders, unit production costs are primarily determined by current production volume rather than accumulated production experience, indicating the absence of a statistically identifiable learning effect.

H3: Enterprises with a high proportion of orders originating within the railway system exhibit persistently low profitability, reflecting limited responsiveness of profitability to changes in operating conditions.

For each hypothesis, an appropriate empirical test, the corresponding data requirements, and clearly defined decision criteria are specified in Table 1.

Table 1

Verification programme: hypotheses, tests and decision criteria

Hypothesis	Test	Key measure	Decision criterion
H0 growth vs development	three-factor index decomposition with alternative deflators	$IQ = IP \cdot IN \cdot IU$	$IQ/IP < 1$ for all deflators
H1a derived demand	derived-demand balance	required fleet $Kt^* = Wt/q_0$; retirement Rt	$Rt > 0$; wear rising
H1b amplified transmission	amplification coefficient; correlation of growth rates	$Kk = \sigma(\Delta \ln N) / \sigma(\Delta \ln W)$	$Kk > 1$; correlation insignificant
H2 serial learning	two-factor unit-cost model	$\ln c = a + \beta \ln N + \gamma \ln S$	γ insignificant; $\beta < 0$
H3 customer dependence	pooled and fixed-effects panel; threshold test	$m = \alpha + \delta \cdot s$	$\delta < 0$ or corridor above threshold

Source: compiled by the author.

The order volatility amplification coefficient Kk compares the standard deviation of the annual logarithmic growth rate of an enterprise's physical output with the corresponding standard deviation of final demand, measured by freight turnover. A coefficient of $Kk = 1$ indicates that enterprise output and final demand exhibit equal relative volatility, whereas $Kk > 1$ indicates that fluctuations in enterprise output exceed those observed in final demand, suggesting amplification through the ordering system.

The two-factor unit cost model extends Wright's learning curve by incorporating a current production volume term. The coefficient β measures the elasticity of unit production cost with respect to current output and captures the effect of production volume on the allocation of fixed costs. The coefficient γ represents the learning effect associated with accumulated production experience, while the corresponding learning-curve ratio is expressed as $LR = 2^\gamma$. Estimating both effects within a single equation makes it possible to distinguish cost reductions associated with the allocation of fixed costs across higher production volumes from those attributable to accumulated production experience.

The threshold panel regression specification compares pooled and fixed-effects estimates of the coefficient δ and examines whether enterprise profitability differs between observations above and below a specified threshold for the proportion of orders originating within the railway system. This approach provides a basis for assessing the relationship between customer concentration and profitability under different levels of dependence on railway-sector orders.

The proposed methodological framework is demonstrated using simulated ten-year time series for three

hypothetical enterprises that differ exclusively in their ordering arrangements: Enterprise A operates under annual batch orders, Enterprise B under a medium-term planning arrangement, and Enterprise C under a multi-year contractual arrangement. The simulated datasets were generated by the author using parameters intended to reflect typical industry conditions. They are employed solely for methodological illustration and do not represent the actual operations or financial performance of any existing enterprise.

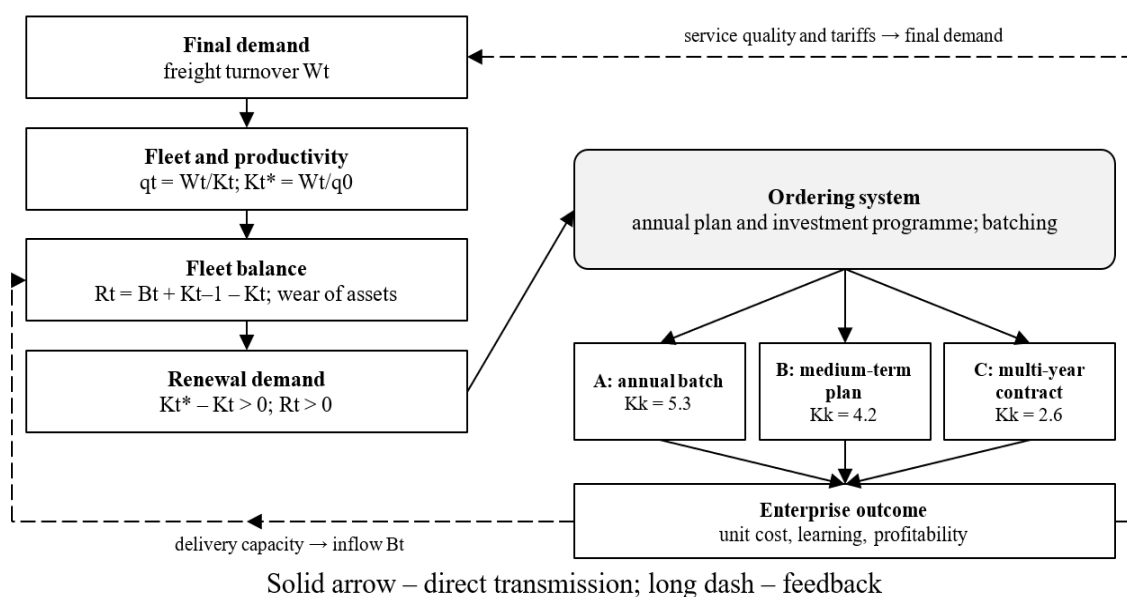
Approximately 10% of the manuscript preparation process involved the use of artificial intelligence tools exclusively for language refinement, grammatical correction, and technical editing. Artificial intelligence was not used to generate research data, conduct statistical analyses, or formulate the scientific findings and conclusions. The author assumes full responsibility for the accuracy, originality, and scientific integrity of the research.

ANALYSIS AND RESULTS

The derived-demand balance presented in Figure 1 establishes the relationship between final demand for railway transportation and the orders received by railway manufacturing and repair enterprises through three interconnected equations: wagon productivity, expressed as $q = W/K$; the fleet required at base-year productivity, expressed as $K^* = W/q_0$; and the fleet balance, expressed as $R = B + K_{t-1} - K_t$, where B denotes the inflow of new wagons and R represents the number of wagons retired from service.

This balance provides an analytical basis for determining whether increases in freight traffic are accommodated through fleet expansion or through more intensive utilization of the existing rolling stock fleet. It also allows the contribution of fleet retirement and asset wear to replacement demand to be assessed.

The ordering system subsequently translates the resulting demand for rolling stock manufacturing and repair services into enterprise-level orders. The specific ordering arrangement influences the extent to which fluctuations in the underlying demand signal are transmitted, amplified, or moderated before reaching manufacturing and repair enterprises (Figure 1).



Solid arrow – direct transmission; long dash – feedback

Figure 1. Derived-demand balance and the transmission of demand to the enterprises through the ordering system

The simulated time series illustrate the transmission of fluctuations in final demand through different enterprise ordering arrangements. Final demand increases steadily by 21.8% over the ten-year period, with a standard deviation of annual logarithmic growth rates of 0.014. Although the orders received by the three enterprises follow the same general growth trend, their volatility differs substantially. The order volatility amplification coefficient K_k reaches 5.3 under annual batch ordering, 4.2 under a medium-term planning arrangement, and 2.6 under a multi-year contractual arrangement.

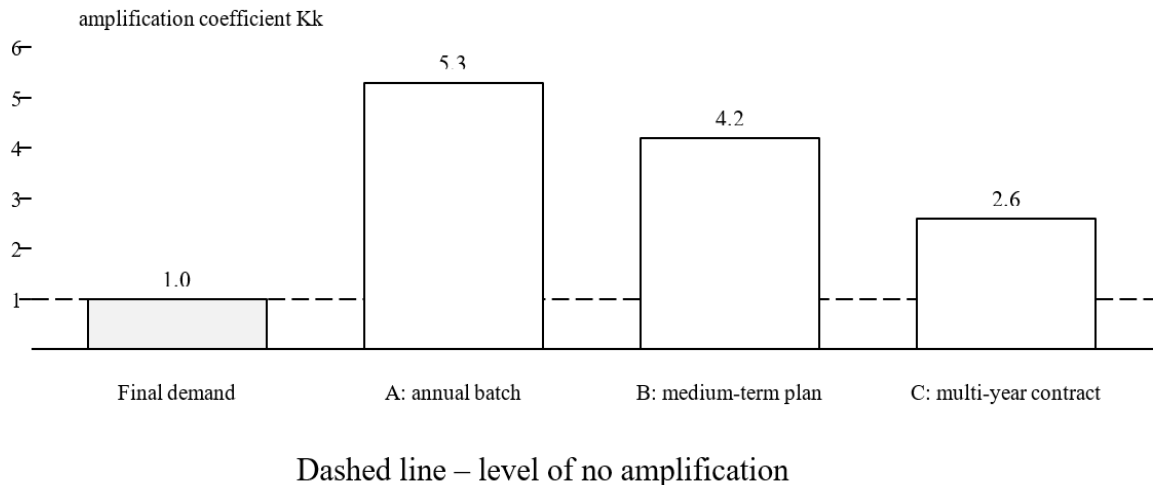
In all three cases, $K_k > 1$, indicating that fluctuations in enterprise orders exceed those observed in final demand. Accordingly, the simulation results support hypothesis H1b within the specified model conditions.

Moreover, the differences in amplification coefficients suggest that ordering arrangements play an important role in determining the magnitude of order volatility, since the underlying final-demand series is identical for all three enterprises. The multi-year contractual arrangement exhibits the lowest volatility amplification, whereas annual batch ordering is associated with the highest amplification.

Before examining the transmission of demand fluctuations, hypothesis H0 is assessed using a three-factor decomposition of nominal output growth. In the simulated series, the nominal output value of Enterprise A increases by a factor of 3.2 over the ten-year period, while the industry-specific price index increases by a factor of 3.0. Deflating nominal output by the industry-specific price index produces a real output index of approximately 1.07. By contrast, applying the general producer price index, which increases by a factor of 3.4, produces a real output index of approximately 0.94, indicating a reduction in inflation-adjusted output value under this alternative deflator.

The two deflators therefore yield different conclusions regarding the direction of real output growth. To address this discrepancy, the proposed decision rule requires the use of a physical-volume index as an additional verification measure. The Laspeyres physical output index, constructed by weighting newly manufactured wagons, overhauled wagons, and rebuilt locomotive sections using base-year unit values, increases by only 5% over the observation period. This result indicates that the majority of nominal output growth is attributable to price changes rather than an equivalent expansion in physical production.

Consequently, hypothesis H0 receives support in its weaker interpretation: nominal output growth is predominantly price-driven, while physical production exhibits only limited positive growth. The simulation illustrates the importance of reporting both deflator-adjusted output measures and a physical-volume index, as conclusions regarding real production growth may be sensitive to the choice of deflator (Figure 2).



Dashed line – level of no amplification

Figure 2. Order volatility amplification coefficient under three ordering regimes (simulated series)¹

The two-factor cost model separates the two mechanisms by which volume affects unit cost (Table 2).

Table 2

Estimates of the two-factor unit-cost model $\ln c = a + \beta \ln N + \gamma \ln S$ for two ordering regimes (simulated series, $n = 10$)

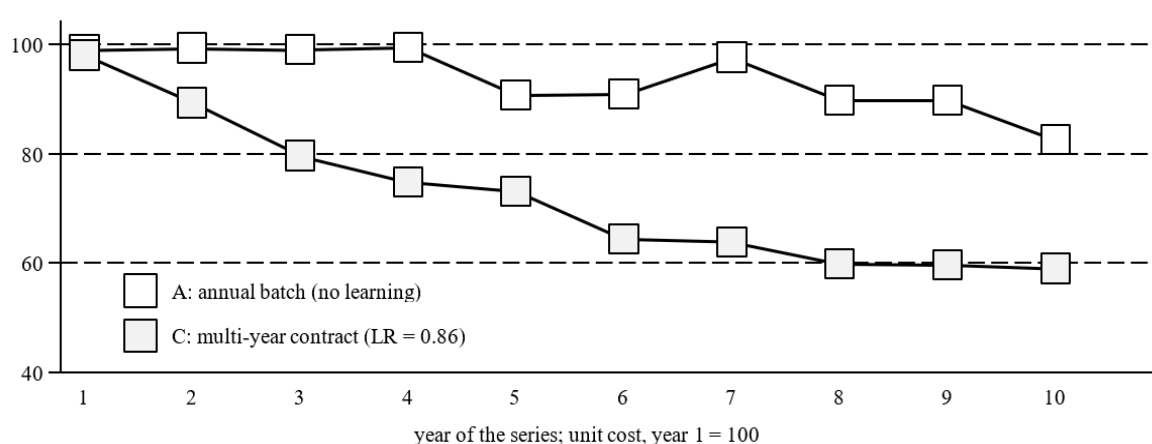
Enterprise and parameter	Estimate (s.e.)	p	Interpretation
A ($K_k = 5.3$): β , current volume	-0.658 (0.195)	0.012	fixed-cost spreading
A: γ , cumulative output	-0.015 (0.019)	0.48	no learning, $LR \approx 0.99$
A: R^2	0.83	–	–
C ($K_k = 2.6$): β , current volume	-0.171 (0.265)	0.54	insignificant
C: γ , cumulative output	-0.220 (0.025)	< 0.001	learning, $LR = 0.86$
C: R^2	0.97	–	–

Source: author's calculation on simulated data; ordinary least squares.

¹ Author's development.

For enterprise A the learning coefficient is insignificant ($\gamma = -0.015$, $p = 0.48$) while the elasticity with respect to current volume is significant and negative ($\beta = -0.658$, $p = 0.012$): a one per cent fall in orders raises unit cost by about 0.66 per cent, which implies that roughly two thirds of costs are fixed with respect to volume. The learning rate $LR = 2^{\gamma} \approx 0.99$ means that cumulative experience does not reduce cost. For enterprise C the picture is reversed: $\gamma = -0.220$ ($p < 0.001$), $LR = 0.86$, so that each doubling of cumulative output lowers unit cost by 14.2 per cent, while the current-volume term is insignificant. Figure 3 shows the two unit-cost paths: under the batch regime cost oscillates with orders and remains close to its initial level, under the contract regime it declines along a learning curve. Figure 3 illustrates the simulated trajectories of unit production costs under two alternative ordering regimes: annual batch ordering (Enterprise A) and a multi-year contractual arrangement (Enterprise C). Both series are expressed in real terms and normalized to a base-year value of 100, allowing changes in unit costs to be compared over the ten-year observation period.

Under the annual batch ordering regime, unit costs fluctuate around their initial level, with temporary reductions followed by subsequent increases. The simulated trajectory indicates that irregular production schedules and interruptions in order continuity limit the accumulation of sustained learning benefits. Consequently, although unit costs occasionally decline, these improvements are not consistently maintained over time, and the series does not demonstrate a persistent downward trend (Figure 3).



Dashed lines – grid; square markers – annual values

Dashed lines – grid; square markers – annual values

Figure 3. Unit-cost paths under the batch and the contract ordering regimes (simulated series, real terms)²

The customer-dependence hypothesis is examined on a simulated panel of three enterprises over ten years. The pooled estimate of δ is negative and significant (-5.56 , $p < 0.001$): an enterprise with a ten-point higher share of in-system orders has a net margin lower by about 0.56 points. The fixed-effects estimate, which uses only within-enterprise variation, is insignificant ($p = 0.50$). The two results are reconciled by the threshold test: in the 21 observations with an in-system share of 50 per cent or more the net margin averages 1.64 per cent with a standard deviation of 0.59, whereas in the 9 observations below the threshold it averages 4.29 per cent with a much wider dispersion. Dependence does not reduce profitability linearly; once the in-system share exceeds the threshold, the cost-plus pricing rule of the dominant customer locks the margin in a narrow corridor irrespective of the exact share. H3 is therefore supported in its threshold form (Table 3).

Table 3

Customer dependence: panel estimates and threshold comparison (simulated panel, 30 observations)

Specification	Estimate (s.e.)	p	Interpretation
Pooled OLS: δ	-5.557 (0.905)	< 0.001	negative between-enterprise relation
Fixed effects: δ	-1.629 (2.371)	0.50	no within-enterprise relation
Share ≥ 50 %: mean margin, % (n = 21)	1.64 ($\sigma = 0.59$)	–	locked corridor
Share < 50 %: mean margin, % (n = 9)	4.29 ($\sigma = 1.35$)	–	external-market zone
Difference of means	2.65	< 0.01	threshold effect

Source: author's calculation on simulated data.

Three methodological implications emerge from the analysis. First, value-based indicators should be deflated using an industry-specific price index, with the resulting estimates cross-checked against alternative deflators, since both the magnitude and direction of measured real growth may depend on the choice of price index. Second, the order volatility amplification coefficient should complement the production-series stability indicator within the enterprise development assessment framework. The former measures the extent to which fluctuations are amplified relative to final demand, whereas the latter characterizes the degree of stability in production over time. Together, these indicators provide a more comprehensive assessment of production dynamics and the influence of ordering arrangements.

Third, the elasticity of unit production cost with respect to current output should be incorporated into the financial component of the assessment framework as an indicator of an enterprise's capacity to adjust its cost structure in response to fluctuations in order volumes. The learning coefficient should be estimated jointly with this elasticity to distinguish cost reductions associated with current production volume from those attributable to accumulated production experience, thereby reducing the risk of incorrectly identifying volume-related cost reductions as learning effects.

CONCLUSION AND RECOMMENDATIONS

The development patterns of railway rolling stock manufacturing and repair enterprises can be examined empirically through a compact methodological framework comprising five hypotheses, each supported by a corresponding statistical test and an explicitly defined decision criterion. The simulation results demonstrate that ordering arrangements play a significant role in shaping order volatility, the realization of learning effects, and the responsiveness of profitability to changes in operating conditions, even when the underlying final-demand trajectory remains unchanged.

Under the simulated conditions, annual batch ordering amplifies demand fluctuations severalfold, limits the realization of cumulative learning benefits, and increases the sensitivity of unit production costs to current output volumes. In contrast, multi-year contractual arrangements are associated with lower volatility amplification and more favorable conditions for sustained cost reductions through accumulated production experience. The simulated threshold analysis further suggests that the relationship between customer dependence and profitability may vary across different levels of customer concentration rather than following a uniform linear pattern.

From a practical perspective, the proposed framework highlights the importance of introducing multi-year framework contracts aligned with railway fleet renewal programmes as a mechanism for improving production continuity and supporting the long-term development of manufacturing and repair enterprises. It also suggests considering a gradual transition from conventional cost-plus pricing arrangements toward contractual mechanisms that encourage efficiency improvements and allow the benefits of cost savings to be shared between enterprises and customers.

Furthermore, the order volatility amplification coefficient and the elasticity of unit production cost with respect to current output should be incorporated into regular enterprise performance monitoring. These indicators would provide additional analytical information for evaluating the stability of production programmes, the adaptability of cost structures, and the effectiveness of ordering arrangements.

Future research should apply the proposed methodological framework to the official financial and operational reporting data of railway manufacturing and repair enterprises in Uzbekistan. Particular attention should be given to estimating and validating the threshold values used in the decision criteria, assessing the robustness of the proposed indicators, and examining the applicability of the simulation-based findings to actual enterprise operating conditions.

Based on the findings of the study, the following practical recommendations are proposed:

Strengthen production planning through multi-year contractual arrangements. Railway manufacturing and repair enterprises should consider introducing multi-year framework contracts aligned with railway fleet renewal programmes. Such arrangements may reduce order volatility, improve production continuity, facilitate capacity utilization, and create favorable conditions for realizing learning effects in serial production.

Improve pricing mechanisms and cost management practices. Enterprises and their principal customers should consider gradually incorporating performance-based pricing and savings-sharing mechanisms into existing contractual arrangements. These mechanisms should encourage productivity improvements, support the efficient allocation of production costs, and provide incentives for both parties to achieve sustainable economic benefits.

Introduce an integrated system for monitoring enterprise development indicators. Railway manufacturing and repair enterprises should incorporate the order volatility amplification coefficient, unit cost elasticity, production-series stability, and customer concentration into their regular performance assessments. These

indicators should be evaluated using comparable, inflation-adjusted financial and production data to support evidence-based management decisions and identify opportunities for improving operational efficiency.

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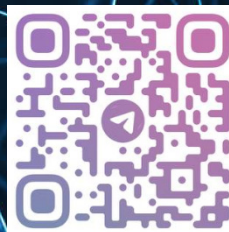
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