American Journal of Industrial and Business Management, 2025, 15(10), 1352-1363
https://www.scirp.org/journal/ajibm
ISSN Online: 2164-5175
ISSN Print: 2164-5167

The Role of Toyota Production System Methodology in Improving the Efficiency of Metallurgical Enterprises

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How to cite this paper: Sergei, S. (2025). The Role of Toyota Production System Methodology in Improving the Efficiency of Metallurgical Enterprises. *American Journal of Industrial and Business Management, 15,* 1352-1363.
https://doi.org/10.4236/ajibm.2025.1510069

Received: September 18, 2025
Accepted: October 11, 2025
Published: October 14, 2025

Abstract

The article is devoted to analyzing the potential of the Toyota Production System (TPS) methodology for enhancing the operational performance of metallurgical enterprises. The relevance of the study is driven by the need to increase the industry's competitiveness amid high volatility in commodity markets and the tightening of environmental regulatory requirements. The scientific novelty lies in proposing an integrated framework that combines the basic principles of TPS, the extended 6S concept, and project management tools, which enables the adaptation of Lean practices to the specifics of large-tonnage, continuous production. The paper systematically describes the key tools of the Lean approach: Kaizen, 5S/6S, Just-in-Time, and value stream mapping (VSM), and examines examples of their application at enterprises of heavy industry. Particular attention is paid to the barriers and critical success factors of transforming production culture. The aim of the study is to examine the Toyota Production System methodology in improving the efficiency of metallurgical enterprises and to propose a conceptual industry-specific TPS model for the metallurgical sector. To achieve this aim, methods of systems analysis, content analysis of scholarly literature, and comparative analysis were employed. The empirical and theoretical base comprises publications indexed in Scopus and Web of Science, materials from Springer proceedings, as well as industry-specific analytical reports. In the conclusion, findings are formulated on the synergistic effect of comprehensive TPS implementation and practice-oriented recommendations are offered. The results are addressed to managers of production units, quality and operational excellence engineers, as well as researchers specializing in the optimization of production systems.

Keywords

Toyota Production System, TPS, Lean Production, Metallurgy, Operational

Efficiency, 6S, Project Management, Kaizen, VSM, Productivity Improvement

1. Introduction

The metallurgical industry, serving as a backbone for numerous segments of the economy, operates under the pressures of a stringent competitive environment, accelerated growth in prices for raw materials and energy carriers, as well as tightening environmental regulation. Under these conditions, improving operational efficiency ceases to be a source of competitive differentiation and becomes a prerequisite for market viability. The Toyota Production System methodology, or lean manufacturing, has demonstrated its effectiveness as a coherent managerial paradigm focused on the systematic identification and elimination of waste. At the same time, the direct transfer of TPS tools from a discrete, assembly context (automotive manufacturing) to the realities of continuous and large-tonnage metallurgical production is associated with significant technological and organizational barriers and requires scientifically grounded adaptation.

The aim of the study is to examine the Toyota Production System methodology in enhancing the efficiency of metallurgical enterprises, as well as to propose a conceptual model of an industry-specific TPS for the metallurgical sector.

To achieve this aim, the following objectives are defined:

- Analyze contemporary scholarly literature to identify the key TPS tools applied in metallurgy, as well as the barriers to and success factors of their implementation.
- Systematize practical results of TPS implementation at metallurgical enterprises to highlight the most effective practices.
- Propose an original integrated model for TPS implementation that accounts for industry specifics and integrates the production system, workplace organization (6S), and a change management methodology (project management).
- **The scientific novelty** of the work lies in presenting a holistic model that is not limited to a list of TPS tools but arranges them into a single controllable system implemented through a project approach and grounded in the expanded 6S workplace organization concept (including safety, security, and employee satisfaction) as the basis of cultural transformation.
- **The author's hypothesis** is that the synergistic effect from implementing TPS in metallurgy is achieved not by the point application of individual tools but through systemic transformation: project management acts as the engine of change, and the 6S principles as the fuel forming a safe and engaged production environment necessary for sustainable improvement.

2. Materials and Methods

A systematic analysis of the scientific literature was conducted to prepare the article. The search and selection strategy was designed to ensure completeness and relevance of the data.

The search was carried out in leading scientometric databases: Scopus, Web of Science, and Google Scholar. To ensure the currency of the study, the publication window was set to 2021-2024. Search queries were formulated in English using the following keywords and their combinations: Toyota Production System AND metallurgy, Lean manufacturing AND steel industry, 6S OR 5S AND heavy industry, operational efficiency AND steelmaking, VSM AND metallurgy.

Inclusion criteria for sources:

- Publications in peer-reviewed scientific journals and conference proceedings.
- Articles containing empirical data, case studies, or models for implementing TPS in the metallurgical industry or related sectors of heavy industry.
- Works analyzing barriers, outcomes, and success factors in the application of Lean tools.

Exclusion criteria:

- Sources that were not peer-reviewed.
- Works focused exclusively on the automotive industry without adaptation to continuous process industries.
- Publications with purely theoretical descriptions of TPS tools without sector-specific grounding.

All sources were grouped into several thematic areas to conduct a comprehensive literature review.

Palhau M., Sá, J. C., Ávila P., Dinis-Carvalho J., Rodrigues C., & Santos, G. (Palhau, Sá, Ávila, Dinis-Carvalho, Rodrigues, & Santos, 2024) formulate Toyota Way as the basis of TPS and demonstrate that sustainable growth is ensured by the combination of hoshin kanri, PDCA/kaizen, the discipline of standardized work, and leadership on the line.

Minh N. D. (Minh, 2023) proposes a managerial loop for efficiency improvement based on TPS: loss diagnosis → tool selection (JIT, Jidoka, SMED/TPM) → improvement cycle → verification of metrics (OEE, FPY, WIP, lead time), emphasizing the risks of local optima and the importance of a proper architecture of indicators.

Lara A. C., Menegon E. M. P., Sehnem S., & Kuzma E. (Lara, Menegon, Sehnem, & Kuzma, 2022) conduct a meta-analysis and statistically confirm a positive association between JIT/Lean practices and quality, costs, and lead times. They identify heterogeneity of effects across industries, which is important when transferring TPS to high-capital-intensity thermal processes in metallurgy.

Małysa T., & Furman J. (Małysa & Furman, 2021) using evidence from steelmaking shops show that 5S, visual standards, and standardized work simultaneously reduce muda (motion, waiting) and improve safety by increasing the predictability of operations and eliminating sources of hazards.

Manzanares-Cañizares C., Sánchez-Lite A., Rosales-Prieto V. F., Fuentes-Bargues J. L., & González-Gaya C. (Manzanares-Cañizares, Sánchez-Lite, Rosales-

Prieto, Fuentes-Bargues, & González-Gaya, 2022) develop a green 5S strategy for welding processes: they extend 5S checklists with sustainability metrics (waste, energy), linking workplace order to environmental and quality objectives.

Florescu A., & Barabas S. (Florescu & Barabas, 2022) substantiate trajectories of convergence between Lean and Industry 4.0: IIoT sensors, cyber-physical systems, and analytics close the kaizen loop, shorten detection time for deviations, and strengthen pull through more sensitive management of demand and variability.

Price C. R., Nimbalkar S. U., Thirumaran K., & Cresko J. (Price, Nimbalkar, Thirumaran, & Cresko, 2023) show how smart pathways for decarbonization and intensification of thermal processes (heat recovery, heat-transfer intensification, closed loops) integrate with TPS flow thinking, reducing specific energy intensity/CO_2 while increasing the stability of production takt.

Maware C., & Parsley D. M., II. (Maware & Parsley, 2022) systematize barriers to lean transformations: the gap between tools and culture, a deficit of middle leadership, project orientation instead of systemness, weak integration with supply chains. They point to the typical rebound of metrics after pilots in the absence of an established operational routine.

Abu-Salim T. Y., Agarwal P., Abu Elrub E., Haoum L., & Almashgari M. H. (Abu-Salim, Agarwal, Abu Elrub, Haoum, & Almashgari, 2023) using a hybrid ISM–Fuzzy MICMAC hierarchize the causes of Lean Six Sigma failures: leadership, training, and measurability/data are primary; the logic is transferable to metallurgy, where reliable data-collection loops for downtime, quality, and energy are required.

Fridkin S., Winokur M., & Gamliel A. (Fridkin, Winokur, & Gamliel, 2024) introduce a quality degradation index as an early indicator of process drift; the approach is useful for continuous lines (rolling, heat treatment), where predictive warning of deterioration is required before parameters exceed control limits.

The analysis demonstrated that, despite the large number of studies confirming the effectiveness of TPS, certain contradictions and gaps persist. Most works are case studies at individual enterprises and do not offer a universal, systemic implementation model for the entire metallurgical industry. There is a contradiction between the need for rapid adaptation and the high inertia of metallurgical production systems. Issues of the long-term sustainability of implemented changes and methods for integrating soft aspects (motivation, safety culture) with hard production tools within a single system are poorly covered. It is precisely these problems that this study is aimed at addressing.

As research methods used in writing the article, the following were applied: the comparative analysis method to compare various approaches to TPS implementation; content analysis of scholarly publications to systematize knowledge; the systems analysis method to identify interrelationships among elements of the production system; and the modeling method to develop the author's conceptual model.

3. Results

The implementation of the Toyota Production System methodology, adapted to the specifics of the metallurgical industry, demonstrates significant improvements in key performance indicators (KPI). An analysis of successful cases and practices described in the scientific literature makes it possible to systematize the achieved results. The foundation for transformation is a comprehensive approach that begins with the introduction of basic principles of workplace organization and personnel engagement, such as 5S/6S, followed by the deployment of more complex tools, such as Kaizen, value stream mapping (VSM), and the Single-Minute Exchange of Die (SMED) system (Małysa & Furman, 2021; Fridkin, Winokur, & Gamliel, 2024).

The practical results of implementation can be grouped into several areas.

1) Increased productivity and efficiency of equipment utilization. A central element here is the fight against equipment downtime. Through the introduction of the Single-Minute Exchange of Die (SMED) it is possible to achieve a reduction in changeover time for rolling mills, converters, and casting machines, which directly increases the useful operating time of the equipment. The implementation of autonomous maintenance principles (Jishu Hozen) within the Total Productive Maintenance (TPM) system makes it possible to reduce the number of emergency shutdowns and increase overall equipment effectiveness (OEE).

2) Reduction of defect rates and improvement of product quality. Systematic work to identify the root causes of problems (the 5 Whys method) and the embedding of quality into the process (Jidoka) yield tangible results. At enterprises that have implemented statistical process control (SPC) and quality circles, a reduction in defect rates is observed for such parameters as nonconformity of chemical composition, geometric deviations, and surface defects (Abu-Salim, Agarwal, Abu Elrub, Haoum, & Almashgari, 2023; Maware & Parsley, 2022).

3) Optimization of logistics and production flows. The VSM tool makes it possible to visualize and analyze the entire value stream, from ordering raw materials to shipping finished products. The use of VSM to analyze the production cycle of rolled metal makes it possible to identify bottlenecks and reduce total order lead time, primarily by decreasing interoperation inventories and waiting time.

4) Improvement of safety and employee engagement. The extended 6S concept, in which particular attention is paid to safety and security, forms the basis for changing production culture. Companies that systematically implement 6S report a decrease in Lost Time Injury Frequency Rate (LTIFR) and a simultaneous increase in the employee engagement index, measured through anonymous surveys (Małysa & Furman, 2021; Minh, 2023).

These results demonstrate that the TPS methodology is not merely a set of tools but a holistic production philosophy capable of fundamentally transforming a metallurgical enterprise.

It is important to note that achieving the described results is associated with overcoming a number of systemic barriers. The analysis conducted has demonstrated that the principal obstacles are:

- Resistance to change and cultural inertia: deeply entrenched habits and skepticism among personnel and line management.
- Focus on tools rather than the system: attempts to implement isolated tools (e.g., 5S) detached from the overarching philosophy and without managerial support.
- Insufficient leadership involvement: declared support at the top level without genuine participation in processes on the shop floor (gemba).

Overcoming these barriers is directly linked to critical success factors. Successful cases demonstrate that a key role is played by:

- Visible and consistent support from top management: leaders must sponsor change not only verbally but through action.
- Involvement of personnel at all levels: formation of small improvement teams, a system for collecting and implementing kaizen proposals, training, and delegation of authority.
- Establishment of a transparent measurement system: introduction of intelligible KPIs that directly reflect operational improvements and enable teams to see the results of their work.

Thus, the outcomes of TPS implementation—are not solely the consequence of applying technical tools, but the result of profound organizational transformation.

4. Discussion

The literature review and synthesis of the results of TPS implementation in metallurgy indicate that the success of transformation depends not so much on the choice of specific tools as on the systematic and comprehensive nature of the approach. Many enterprises make the mistake of implementing isolated Lean elements (for example, only 5S or only TPM) detached from the overall strategy, which leads to short-term improvements but does not change the system as a whole. The main problem lies in the absence of a connecting link between the company's strategic objectives, operational improvements at the shop-floor level, and corporate culture.

To address this problem, we propose the authors' integrated model PM-6S-TPS for metallurgical enterprises. This model (see **Figure 1**) is a three-level system in which each element performs its unique function.

As can be seen from **Figure 1**, the first level is project management (based on DMAIC). This is the strategic level that sets the direction and governs change. Any initiative to implement TPS should be considered as a project with clear objectives, timelines, budget, and team. The DMAIC cycle (Define, Measure, Analyze, Improve, Control) is an ideal framework for managing such projects, ensuring their structured nature and the measurability of results.

The second level, the 6S culture and environment, constitutes the foundation of the entire system. Without a clean, organized, and—critically important for metallurgy—safe workspace, it is impossible to expect employees to engage in

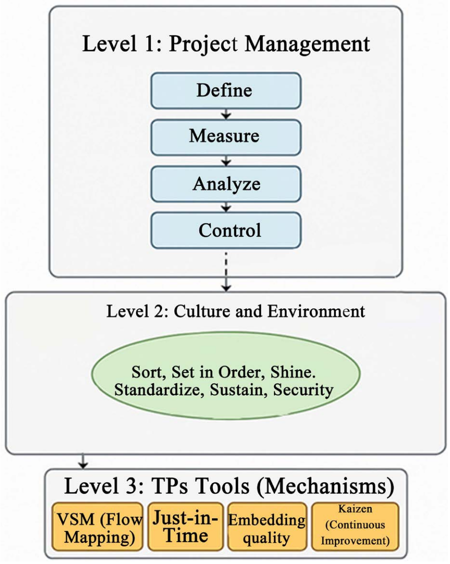

Figure 1. Integrated model PM-6S-TPS (Małysa & Furman, 2021; Abu-Salim, Agarwal, Abu Elrub, Haoum, & Almashgari, 2023; Florescu & Barabas, 2022).

improvement processes. In our model, the classical 5S concept (Sort, Set in Order, Shine, Standardize, Sustain) is deliberately expanded to 6S to reflect the specifics of heavy industry. The new elements are defined as follows:

- Safety: Unlike traditional 5S, where safety is merely an indirect outcome of order, here it is distinguished as an independent, proactive element. This is not simply the absence of injuries, but a risk management system: hazard identification, implementation of lockout/tagout (LOTO), ergonomic assessment of workplaces, and behavioral safety audits. If 5S removes a hose from a walkway to prevent tripping, then the Safety component requires analyzing why that hose was present in the first place and designing the process to eliminate its appearance in the future.
- Security: This element is aimed at protection against external threats, sabotage, and subversion, which is relevant for strategically important industrial facilities.
- Satisfaction: This component is directly linked to the human factor, which drives all improvements. Satisfaction is the creation of a production environment in which personnel are motivated, engaged, and feel valued. If 5S provides physical comfort, then Satisfaction shapes psychological comfort through recognition of achievements, a suggestion system (kaizen), fair feedback, and opportunities for professional development. This is the fuel for continuous improvement.

The third level comprises TPS tools. This is the tactical level, a set of specific methods for solving production problems. The choice of tools (VSM, SMED, TPM, etc.) is dictated by the results of Analyze at the project level.

The practical application of the model can be illustrated by a table linking typical metallurgical problems with the proposed solutions within the PM-6S-TPS model. See Table 1.

Table 1. Application matrix of the PM-6S-TPS model for solving problems in metallurgy (Małysa & Furman, 2021; Price, Nimbalkar, Thirumaran, & Cresko, 2023; Palhau, Sá, Ávila, Dinis-Carvalho, Rodrigues, & Santos, 2024).

Typical metallurgy problem	Project Management level (DMAIC)	6S level (Foundation)	TPS level (Tools)	Key KPI for monitoring
Extended equipment changeover time	Project Reduction of changeover time of mill X	Standardization of operations, changeover safety	SMED, standardized work	Changeover time (min), OEE (%)
High level of industrial injuries	Project Zero injuries in shop Y	Safety, orderliness, cleanliness	Risk analysis, 5 Whys (for incidents)	LTIFR, number of micro-injuries
Low product quality (defects)	Project Reduction of defect rate by parameter Z	Standardization of control, operator satisfaction	Jidoka, Poka-Yoke, statistical process control (SPC)	Defect rate (%), cost of losses
Excess inventory and long waiting	Project Optimization of the value stream	Sorting of unnecessary items, orderliness	VSM, Kanban, Just-in-Time (JIT)	Production cycle time (Lead Time), inventory level

Table 2 will be presented below, in which the advantages, limitations, and future trends in the application of the Toyota Production System (TPS) methodology to improve the efficiency of metallurgical enterprises are systematized.

Table 2. Advantages, limitations, and future trends in applying the Toyota Production System (TPS) methodology to enhance the efficiency of metallurgical enterprises (Małysa & Furman, 2021; Manzanares-Cañizares, Sánchez-Lite, Rosales-Prieto, Fuentes-Bargues, & González-Gaya, 2022; Lara, Menegon, Sehnem, & Kuzma, 2022; Minh, 2023).

Focus/area	Advantages (effect)	Limitations/risks (why it can be difficult)	Future trends (where practice is moving)
OEE and equipment downtime	SMED for rolling mills/casting machines shortens changeovers; TPM/Jishu Hozen reduces emergency stops; increase in OEE and available productive time	Large-sized tooling, high thermal inertia of heat equipment; lack of data on actual losses, weak standard work discipline	IIoT/ML-based PdM; digital SMED maps; AR guidance for changeovers; cascading TPM from bottlenecks to the entire line
Quality/defect rate	Jidoka, 5 Whys, Poka-Yoke, SPC reduce defects by chemical composition, geometry, and surface defects	Variability of raw materials/charge; delays in laboratory control; late detection of defects	Online metallurgy: inline analyzers, computer vision for surface; automatic stops on anomalies; digital Q-Kanban

Continued

Logistics/Lead Time	VSM exposes bottlenecks; Kanban/JIT reduce interoperation inventories and cycle time	Risk of starving continuous units under strict JIT; long transport legs, unstable sales	Hybrid pull systems satellite buffers; dynamic Kanban; flow simulations digital twin for tuning WIP
Assortment flexibility	Standardized work plus fast changeover increase variability of profiles/steel grades	High cost of roll/mold changeovers; constraints by heat campaigns	Optimization-based campaign planning; modular tooling; end-to-end heat traceability for micro-batches
Safety and culture 6S	6S adds Safety, Security, Satisfaction: lower LTIFR, higher engagement and discipline of standards	Harsh conditions high T°, dust, CO, normalization of deviations; resistance to change	Behavior-based safety plus gamification of Kaizen; wearables and geofences; visual management with e-Andon
Energy and environment	Eliminating waste ↓ specific energy consumption per unit; flow without waiting ↓ idle reheats	Thermodynamic limits; energy KPIs often decoupled from flow; local optimization versus systemic	E-VSM Energy/Emissions VSM and carbon takt times; integration of Lean with decarbonization EAF/DRI-H2; CO_2-Kanban
Cash cycle/inventories	Reducing WIP and finished goods frees up working capital	Peak demand swings, contractual shipping schedules; risk of penalties for underdelivery	Forecast-driven buffers; S&OP linked to pull; end-to-end supply chain visibility
Reliability/maintenance	TPM/Autonomous Maintenance increase MTBF; visual standards simplify care of dirty zones	Heterogeneous fleet, unique units; shortage of operator competencies for autonomous maintenance	TPM + PdM coupling vibration, acoustics, thermography; mobile checklists; digital equipment passports
Process transparency	VSM/gemba create a shared vision; Andon accelerates escalation	Island APCS, data are hard to share; visualization overload	Real-time flow boards; unified data models ISA-95/OPC UA; data factories for Lean
Workplace organization	5S/6S reduce search/motion losses; facilitates training and shiftwork	Hard to sustain due to dust/sludge; backsliding without audits	e-5S with digital audits and photo standards; 3D labeling, AR tool contours

Continued

Project management DMAIC	Improvement portfolio with clear goals/KPI; scalability of results	Project orientation without embedding into routine; initiative fatigue	Hoshin Kanri + DMAIC; OKR linked to flows; reverse reviews on sustaining the effect
People and competencies	Quality circles, Kaizen events grow problem-solving skills	Turnover, shift schedule; weak motivation to participate	Microlearning at the workplace; Lean career ladders; recognition and non-material incentives
Finance/capital expenditures	Lean delivers quick effects without CAPEX; focus on hidden losses	At some bottlenecks CAPEX is unavoidable; risk of financial myopia	Lean investments CAPEX only after VSM/SMED; value engineering jointly with suppliers
Integration with digitalization	Digital sensors reinforce Jidoka/TPM; e-Kanban accelerates flow	Automated chaos: digitalization without a standard; cybersecurity Security from 6S	Lean plus Industry 4.0 as a double helix; digital shadow flows; cyber-resilient pull systems
Supply chain	Reduction of variability, synchronization of deliveries of raw materials/ferroalloys	External shocks logistics, ore/coke; rigid contracts	Regionalization of chains; end-to-end VSM across the chain; joint Kanban with key suppliers

The proposed PM-6S-TPS model constitutes an original contribution to the development of the theory and practice of lean manufacturing in metallurgy. It closes the gap between strategy and tactics, places safety and production culture at the forefront as the foundation for improvements, and offers a structured approach to transformation management. This enables a shift from piecemeal improvements to building an integrated, efficient, and sustainable production system.

For empirical verification and confirmation of the effectiveness of the proposed PM-6S-TPS model, the following pilot testing plan is proposed:

Selection of the pilot area: Select one production area with clearly measurable indicators and known issues (e.g., a strip finishing line or a continuous casting section).

Stage 1: Baseline assessment (1 month). Collect baseline data on key performance indicators (KPI) at the selected area: OEE, defect rate (%), production cycle time, lost time injury frequency rate (LTIFR), and employee engagement index.

Stage 2: Implementation (4 - 6 months).

- Project Management level: Form a project team and launch a DMAIC project aimed at solving the area's key problem (e.g., reducing line downtime).
- 6S level: Provide personnel training and implement 6S standards, paying par-

ticular attention to risk mapping (Safety) and feedback collection (Satisfaction).

- TPS tools level: Apply targeted tools identified at the Analyze phase of the DMAIC project (e.g., VSM for flow analysis, 5 Whys for root-cause analysis of failures).

Stage 3: Results evaluation (2 months). After completion of implementation, remeasure the same KPI. Compare before and after data, perform statistical analysis to confirm the significance of the changes. Conduct anonymous surveys to assess shifts in production culture.

The expected timeframe for pilot project implementation is 7 - 9 months. Successful completion will confirm the operability of the model and enable the development of a roadmap for its full-scale deployment at the enterprise.

5. Conclusion

Within this study, the stated objective of developing a conceptual model for adapting the TPS methodology to the metallurgical industry was achieved. The analysis of the scientific literature confirmed the relevance and potential effectiveness of lean manufacturing for enhancing the competitiveness of metallurgical enterprises, yet revealed a shortage of systemic approaches that account for the specific characteristics of the industry.

In addressing the first task, the key TPS tools were systematized and the main barriers to their implementation were identified, such as resistance to change, the high inertia of technological processes, and insufficient management engagement. Addressing the second task made it possible to synthesize practical results and confirm that the greatest effect is achieved in improving equipment utilization efficiency, reducing defect rates, optimizing logistics, and improving safety indicators.

The key outcome of the work, addressing the third task, is the proposed original integrated model PM-6S-TPS. It unifies three crucial aspects of transformation: project management as a methodology for change management, 6S culture as the foundation for safe and organized work, and TPS tools as tactical means for eliminating waste. This model confirms the hypothesis that the maximum synergistic effect is achieved precisely through a comprehensive and systemic approach.

The implementation of the proposed model will enable metallurgical enterprises not merely to copy external experience but to build their own production system capable of adaptation and continuous improvement. This will ensure long-term operational efficiency and create a sustainable competitive advantage in the global market.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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