Lean production in ETO situations: a multiple case study research

Violetta Giada Cannas*, Jonathan Gosling, Margherita Pero***, Rossella Pozzi***

School of Engineering, LIUC – Carlo Cattaneo University, 21053, Castellanza, Italy (vcannas@liuc.it, rpozzi@liuc.it); ** Department of Logistics and Operations Management , Cardiff Business School, CF10 3EU, Cardiff, UK (GoslingJ@cardiff.ac.uk); * Department of Management, Economics and Industrial Engineering, Politecnico di Milano, 20156, Milano, Italy (margherita.pero@polimi.it)*

Abstract: Lean Production (LP) has been widely and successfully employed in mass production situations, showing high capabilities in reducing non-added-value activities, providing process stability, high qualitative production outputs and competitive production lead times. In engineer-to-order (ETO) situations, instead, the high customisation and variability of the context bring complexity and make it very difficult to fully employ the potential of LP. Over the years several studies focused on this issue, studying the application of LP practices to ETO situations. However, recent literature reviews underlined that there is a lack of research addressing the issue of whether to adopt, adapt or reject LP practices in ETO situations, and there is still an ongoing debate on this field. To fill the gaps identified in the existing literature, this study aims to study what LP practices are implemented in ETO situations, as well as how, using multiple case study research. An original data set was constructed using a purposely defined research protocol using structured interviews. The findings of this study show what LP practices are implemented successfully in ETO situations and what, on the other hand, are not easily implemented. Also, the study analyses how LP practices are implemented and what adaptations they must undergo to be effective within the ETO situations.

Keywords: Lean Production, Engineer-to-order, machinery industry, case study research

1. Introduction

Lean Production (LP) is defined as a set of management principles and techniques aiming at eliminating waste in the manufacturing process and increasing the flow of activities that, from the customers' perspective, add value to the product (Womack & Jones, 1996). Initial implementations of LP started in the automotive industry, i.e., repetitive production systems (White & Prybutok, 2001). More recently, the application of LP to Engineer-to-Order (ETO) situations has been discussed in the literature. ETO situations relate to all the companies that are involved in the design and production of customised products such as construction projects, shipbuilding, and machine tools (Violetta Giada Cannas & Gosling, 2021). This makes ETO situations affected by high requests for customisation and large product variety, complex engineering work and novel production activities.

ETO situations implement LP practices less likely than repetitive production systems (White & Prybutok, 2001). Multiple barriers exist when implementing LP practices in ETO situations, especially related to the lack of process reliability, the low level of readiness, and the need for adaptation from repetitive and stable environments like mass production. Nevertheless, recent studies show that LP practices can be successfully applied to ETO situations and demonstrate numerous benefits that can be achieved through them (Fernanda S Bataglin et al., 2020; Braglia et al., 2020, 2024; Jünge et al., 2023).

However, literature also recognises a certain level of immaturity in literature and practice regarding this field (Violetta Giada Cannas & Gosling, 2021; Tomašević et al., 2020). Further research is needed to analyse the practical application of LP practices to reduce the effects of customisation and large product variety and the adaptation of these practices to ETO situations (Fernanda Saidelles Bataglin et al., 2022; Schulze & Dallasega, 2023). To fill this gap, this paper aims to empirically analyse the application of different LP practices in ETO situations through multiple case study research conducted in the Italian machinery industry. The purpose is to answer the following research question (RQ): *How do ETO companies operating in the machinery industry adopt, or adapt, LP practices?*

2. Literature review

LP was largely based on the Toyota Production System and was popularised in the West by '*The Machine that Changed the World*' (Womack et al., 1990) as a response to the flaws in mass production. Following this, the primary focus in research on LP has been on waste reduction and the five principles of lean: value, the value stream, flow, pull and perfection. The origins can be found in a merger of approaches from Just in Time (JIT), Total Quality Management (TQM), and findings from the International Motor Vehicle Program (Holweg, 2007; Papadopoulou & Özbayrak, 2005). According to LP theory, internal production flows can be stabilised by Kanban systems, and continuous improvement initiatives incrementally drive out forms of waste. To add value to the customer, the lean approach seeks to find ways to manage variability by flattening or controlling demand (Hines et al., 2004; Naylor et al., 1999).

LP has been organised for research and practice by considering LP practices associated with specific LP 'bundles' to package them into meaningful constructs (Shah & Ward, 2003). In particular, Bai et al. (2019), building on a long lineage of work and previous frameworks, develops an aggregated classification of LP practices into 5 bundles: (i) supplier; (ii) production planning and control; (iii) process technology; (iv) workforce; (v) customer.

The supplier bundle is related to the following LP practices: (i) regular feedback to suppliers on quality and delivery performance; (ii) JIT delivery by suppliers, usually through the use of the Kanban technique; (iii) supplier involvement in product design and development; (iv) lean supplier development through training and improvement programs.

The planning and control bundle is related to the following LP practices: (i) production according to pull production supported by kanban calculations; (ii) setup time reduction activities; (iii) levelled stream of orders and production workload (Heijunka); (iv) Total Productive Maintenance (TPM); (v) visual management of production control; (vi) regular feedback to production on performance such as the overall equipment effectiveness (OEE); (vii) TQM; (viii) statistical process control for analysing production performance; (ix) root cause analysis for problem-solving implying the use of tools such as 5 why and fishbone diagram.

The process technology bundle is related to the following LP practices: (i) visual management of quality control; (ii) autonomation (Jidoka); (iii) one-piece flow; (iv) cellular manufacturing layout; (v) concurrent engineering; (vi) modular design and design for manufacturability; (vii) visibility and information exchange; (viii) Process improvement through Kaizen (continuous improvement); (ix) value identification through the use of techniques such as value stream mapping (VSM).

The workforce bundle is related to the following LP practices: (i) teamwork and leadership in kaizen activities; (ii) multi-functionality and cross-training to increase flexibility; (iii) workforce recognition and reward; (iv) continuous improvement by training workers in problem-solving methods; (v) workplace housekeeping through '5s'; (vi) standardised work.

The customer bundle is related to customer involvement concerning quality programs and/or product design.

These LP bundles and practices represented a rigorous base for recent studies on LP (e.g., Pozzi et al., 2021, 2024). For this reason, this classification is explored by this study in the context of ETO situations, where their potential applicability is unclear.

3. Methodology

This article presents multiple case study research that addresses companies operating in the machinery industry in Northern Italy. Multiple case study research allows the authors to collect data from multiple cases, increasing the validity of the results (Yin, 2018), while the focus on only one sector and one geographical area limits the research domain, increasing the control of variations within the population (Voss et al., 2016). Also, previous studies on the Italian machinery industry demonstrated that this sector is well representative of ETO situations and can provide significant insights into ETO issues (Cannas et al., 2019, 2020, 2022).

The unit of analysis of the study is the company and cases were selected from a list of companies operating in the machinery industry extracted from "AIDA" (https://aida.bvdinfo.com/). The selection criteria applied were based on replication logic, as suggested by Miles and Huberman (1994), based on the expectation that the companies are all performing engineering and production activities after the customer order and using LP practices, i.e., literal replication, while, at the same time, exploiting different LP practices, but for predictable reasons, i.e., theoretical replication. In total, seven cases were selected, which are presented in Table 1.

Table 1: Case study overview

Case study	Revenues [M€]	Employees	Products
A	5	40	Articulated robots and complete painting systems
B	65	148	Chipboard panel manufacturing plants
C	75	224	Foundations machines
D	85	364	Components, modules, and systems for the elevator industry
E	14	51	Machine tools
F	97	400	Industrial automation systems for storage, conveying and processing of plastic and food
G	18	160	Cutting-edge industry automation solutions

This case study research was based on multiple data collection, so to gather multiple sources of evidence (Stuart et al., 2002). First, semi-structured interviews were conducted by proposing a questionnaire to production managers, experts in LP and those responsible for the implementation of LP within the company analysed. They were required to answer open questions regarding what LP practices were implemented by the company, the way how they implemented them and the main reasons behind the implementation. To guide the interview and support it with a rigorous theoretical base, the authors founded their questions on the classification presented in the previous section 2. Then, secondary data were considered from the companies' websites, internal documentation provided during the interviews and direct observations during the companies' visits.

Finally, the interviews were recorded and transcribed, and the authors conducted a content analysis on the transcriptions, aiming at answering the RQ presented in section 1, looking at similarities and differences between the cases and triangulating data collected with the literature.

4. Results

4.1 Supplier Bundle

As far as the supplier bundle is concerned, companies operating in the machinery industry, including the ones in this study, involve many suppliers in their supply chain and strongly depend on their performance. They outsource most of the production activities to contractors and perform internally the engineering and assembly activities. Indeed, the machines' bill of material is composed of very diverse components, and each of them requires a high level of quality knowledge, specialised skills, and specific know-how. For this reason, in this sector, the application of LP practices related to the supplier bundle is considered important by the companies interviewed, because they can reduce the variability of the process and ensure better control of the supply chain and its efficiency. However, not all the LP practices are adopted by all the companies, since, in some cases, the ETO situation can represent an obstacle to the implementation.

In particular, JIT delivery has been implemented in 4 cases, but it is often limited to some components. Case F is the one that applies this practice most completely. They have a kanban system with the suppliers, to whom the production of the components sold in high volumes is outsourced. When a certain component is needed, an automatic notification is sent to the suppliers. Every day a company-owned truck is performing a "milk run" with a set of suppliers, to collect components. Whereas Case C and Case E adopt JIT delivery only for the small parts (e.g. screws, fittings). In case B this practice is limited to a set of suppliers that are long-term partners of the company and, similarly to cases C and E, to small parts that are managed with kanban systems. The complexity in the implementation of this practice can be identified in the reasoning provided by Case A, which underlined that JIT delivery by suppliers is hard for ETO companies due to the high variability of the demand and the complexity to achieve a reliable demand forecasting.

Also, Cases A and B considered supplier involvement in design a challenge for ETO situations, due to the highly innovative content of the engineering activities, which makes the company worried about sharing the design phase with external parties. Case F involves suppliers in product design to assure the technical feasibility of the product and the production process, to meet specific customer requests.

The other practices, i.e., feedback to suppliers and Lean supplier development, instead, are rarely applied. They do not depend on ETO characteristics and face challenges in the implementation mostly because of the characteristics of the suppliers operating in the Italian machinery industry, which are often small-medium enterprises not typically open to LP practices and Lean culture. However, if the company correctly approaches its suppliers and works on the diffusion of the Lean culture, the implementation of these practices can be compared to the one in mass production situations. Case B, for example, implemented the feedback to suppliers reporting no specific issues and sent regular reports to the suppliers as feedback on their performance.

4.2 Production planning and control bundle

As far as production planning and control concerns, Case A, as well as Case D and Case F, stated that they suffer the variability of the demand, typical of ETO situations, when trying to set the pace of production, which has an impact on the adoption of the pull production / takt time calculation. As well, company C recently suffered from higher variability but still calculates takt time. They adopt pull production / takt time calculation accepting that in case the completion times of the machines substantially differ, the assembly line will progress at a time that may not always equal the takt time. According to case B, the pull production is supported by the project managers who plan the installation site activities and timing. Case G applies pull production to machines sold starting from a catalogue, they assemble machines based on sold items and they keep no intermediate stock. To assure a pull and stable production they defined a set of assembly stations, but given the size and weight of the products, "the compromise we have made is that we assemble batches of 20 pieces". Case F applies an internal kanban system between the production departments for the more standardized items. For the design of the production lines for the highly standardized products, they use takt time. Finally, Case D affirmed that they computed takt times based on groups of products, trying to approximate an average takt time based on the product family, because it is impossible for the company to compute a precise takt time for each product, due to the high level of customisation.

Case A adopts Heijunka through the adaptation of the technique to the specific characteristics of ETO situations, in which the future customer demand is uncertain in terms of frequency and volumes. Case A affirmed that: "To date, with an American customer, we are trying to level the production peaks. This customer requested 20 machines within the year. And therefore, when the production system is undersaturated, we produce these machines, so to level the production. By doing this, we guarantee a minimum of continuity and avoid moments in which the operators are totally discharged or saturated". Company C adapts the Heijunka to the high variability in assembly time of different products typical of ETO situations accepting that sometimes the line is not well balanced. Case D highlighted that: "We have on some lines the Heijunka boxes to level production, we use sheets in which the standard time is defined for that type of operation and the expected daily output. On this sheet the operators update the actual production "hour by hour", also noting the characteristics of the various orders. In some cases, a delay can be created due to an order that requires different cycle times and, despite the Heijunka box, it is not possible to obtain the desired levelling. The driver remains the business: if orders of multiple types arrive, they must still be fulfilled".

Setup reduction and total productive maintenance are adopted by only one company, and this is related to the fact that setups and maintenance are often not needed in the assembly activities of machines, according to case A. Case C has implemented some autonomous maintenance activities, such as daily and periodical inspections, limited to the painting system.

Feedback on performance metrics is adopted by company A limited to quality. Case B supports the feedback on performance with a manufacturing execution system (MES) that records the production progress and compares the planned and the actual times that are then used as a reference for future activities. Case C shows department efficiency and effectiveness charts updated daily. Whereas Case D measures the Overall Equipment Effectiveness (OEE), as a support to production, to maintain performance and continuously improve it.

Total Quality Management is applied by Case A, which is currently performing data gathering on defects in materials and their classification to statistically analyse them. Case C shows pictures of detected defects on screens, while case F collects information and pictures of wastes (Muda) to activate kaizen activities. To reduce human errors, poka yoke solutions could be applied, however, due to the costs connected to producing new, e.g. holders, it is difficult to apply (Case F). Statistical process control is limited in its application by the interviewed companies. Case F collects quantitative data through a Manufacturing Execution System (MES). However, this is an isolated case, since according to both Case C and Case E, the same activity is rarely performed many times, and the amount of data that can be gathered is too limited.

Visual management of production control is adopted by Case A and Case D without any adaptation, they have developed a digital Andon system linked to Power BI, which is updated in real-time by the operators with information on the progress of the productions. The same situation is for feedback on performance metrics, which has been introduced through a documentation system on machine downtimes. Also, Case D adopted visual management. They have several tools implemented, such as the "totems", which are then also used for factory visits, for example, by top management or customers. The totems show the current state of the plant in terms of flows, volumes produced, and Lean techniques adopted, with also images depicting the before and after. Then other totems inside the workshop show the improvement projects and therefore the direction you want to take. Additionally, they have billboards showing the different teams which are mainly used to make operators feel part of the company. At the process management level, they have Quick Response Quality Control (QRQC) boards, that is the tables in front of which QRQC is done and on which the performances of the individual departments are shown. They are accessible to all, and the performances are in terms of quality, on-time delivery, productivity, and waste. Finally, they have the Andon Boards for real-time monitoring of the performance of the individual lines.

Finally, regarding root cause analysis for problem-solving, Case D affirmed that they apply root cause analysis through the QRQC method: "It is precisely the structure of the QRQC that leads you to carry out an analysis of the causes and to define treatment actions for the problem and containment actions. Then, at a later stage, changes are made to the process to prevent the problem in the future", while Case F collects the customer complaints, and then analyses the causes of the defects in depth involving engineering and production departments.

4.3 Process technology bundle

As far as process technology is concerned, concurrent engineering, parts standardization/modularisation, visibility and information exchange, kaizen, and value identification are implemented by the cases. Continuous flow (one-piece-flow), visual management of quality control, Jidoka and cellular manufacturing are not applied in the cases analysed. Concurrent engineering represents a way of managing the design tasks and information that is mostly appreciated and applied, especially in ETO situations that involve the design of complex machines by several departments that rely on each other work. Case A affirmed that this is very important, and they always design new products leveraging on synergies between engineering and production, to anticipate problems right from the start and avoid a proliferation of customization. Also, in Case B, the engineering activities are organized into three departments that work parallelly on different aspects of the design, i.e. plant, electrical and mechanical, integrating data from the commercial department.

Regarding parts standardization/modularisation, for Case C the choice of adopting is restricted by the fear of investing in activities that will have a limited application in time, due to the high variability in the offered product. Whereas Case A affirmed that they have a standard for wiring that allows them to customize them after the order by combining the modules. Also, Case D asserted that they have Research & Development policies to standardize some components across different product lines and identify modules, but this is not always easy because "as part of the design comes from customers, you can't always standardise right away when you launch your new product. And so, this is the reason why after a few years we find ourselves having so many variations of the same component and why this type of research is in progress".

Visibility and information exchange are crucial to ensure timely delivery to the customers. Case B, as well as Case A, exploit the MES and the enterprise resource planning system to provide timely information to the planning department. Also, Case A supports communication through the reading of a QR code on the product that connects to all the design, commercial and production up-to-date information.

Process improvement/kaizen is applied by Case D, which organises the "kaizen week". It involves a week, sometimes two, of workshops in which figures belonging to different company functions participate in process improvement. Industrial engineering and production are always present, but typically logistics, maintenance and quality are also involved. Kaizen Week focuses on a specific problem and tries to approach it looking at it from different perspectives, to leave the week with a solution already implemented. The people involved are almost dedicated to the workshop during the week. According to Case D, the kaizen week is organised as follows: "There is a first day of training where the basic concepts of Lean are presented, then the concept of waste, the concept of 5S, the concept of standardization, etc. This serves to bring "on board" all the people, including the operators, who are those who work, and who can therefore give more added value to this type of activity. Then from the second day, the real workshop begins which includes a day of observation/analysis, a day of implementation of the changes, a day of standardization, or rather new observation and standardization to verify that what was done the previous day is effective, and then the presentation to management and the celebrations take place on the last day". To reduce Muda and improve efficiency, Case F performs a value analysis of the production lines to identify value-added and non-value-added activities.

4.4 Workforce bundle

As far as the workforce bundle is concerned, companies operating in the machinery industry, including the ones in this study, strongly rely on the involvement of the workforce. In Case B and Case F operators and engineers work in teams to solve assembly problems while respecting product quality. Case E leverages teamwork to spread the lean culture and knowledge of lean techniques. Also, in Case A, as well as in Case B, within the manufacturing and assembly departments, the workforce is multi-functional and cross-trained. Case F uses job rotation, to ensure a multi-skilled workforce and cross-training. Company C declares that its multi-functionality training activities lack a plan and would benefit from more regularity.

Workforce recognition and reward are applied by Case A, Case D, Case E and Case F. Cases E and F reward operators that achieve plant goals, Case A also consider if they increase the innovativeness of the production process or the product by bringing new ideas. Whereas Case D affirmed that: "The team on the production line where the greatest increase in productivity was achieved during the year is awarded. But also, the team who managed to complete the analysis required by the QRQC within a single day is rewarded. And this is very difficult because it requires to analyse the problem and have already implemented the solution within a day".

Both Case A and Case D apply continuous improvement and train workers in problem-solving methods and involve them every time kaizen activities start, to increase their awareness of the Lean plant activities and increase their know-how to support them.

Workplace housekeeping is applied by Case A, which stated that they implement the 5S in the plant to arrange the layout of the assembly areas, isolate the dirty and noisy areas, ad-hoc warehouse area, reorganize small parts dispensers, but also standardize the operator stations. This, according to Case A, helps the operators in managing process variability in the ETO context, thanks to higher control of the workplace and the production tools. Operators in companies B and C have been trained to implement workplace housekeeping.

Finally, Case A apply the standard work instructions. Indeed, they created documents, together with the operators, in which they entered the standards for the assembly activities, supporting them with visual management, and updating them regularly, following product innovation.

4.5 Customer bundle

As far as the customer bundle is concerned, companies operating in the machinery industry usually go towards customer involvement in product design, with the definition of the specifications in collaboration. Case B, for example, states that many consultations with the customers are needed to define the data required to develop the new product.

5. Discussion

The results obtained from this exploratory study show that ETO companies widely apply LP practices. On the other hand, practices belonging to different bundles are not applied equally. As the customer focus is fundamental in ETO companies (Cannas et al., 2020), Customer involvement is applied by all interviewed companies. Also, as these companies are mainly labour-intensive and perform manual assembly activities, the practices involved in the Workforce bundle are mostly applied. Considering the Production Planning and Control bundle, its practices are not fully adopted, but they can help companies manage uncertainties and effectively deliver customers' orders (Cannas et al., 2018). On the contrary, the Process technology bundle is the one with the smallest coverage of implementation, as machines provide a lower contribution to the investigated production systems.

Some of these practices can be simply adopted, without any adaptations concerning the variability that characterises the engineering and production activities after the customer order. In this case, the traditional scope of the LP practice, i.e. reduction of waste and efficiency improvement, is kept as valid also for the ETO context, and no differences can be identified in the implementation of the practice for the mass production situations. For example, visual management practices can be applied in the same way to ETO and mass production shopfloors to reach the same scope of production and quality control. Accordingly, workplace housekeeping and kaizen events are aimed at reducing waste (Cannas et al., 2018b) and the 5 steps do not differ between ETO and mass production systems. Other practices, instead, need adaptation to the context as the ETO characteristics can influence the applicability of LP practices and some propositions for ETO companies, as summarised in Table 2.

Table 2: Propositions for ETO companies in the adoption of LP practices

Lean Production Practice	Proposition
JIT delivery by suppliers	Limited to small parts and to standard parts
Supplier involvement in design	Need to protect the intellectual property of the design phase
Pull production / Takt time calculation	Accept line cycle time slightly different from takt time; Limited to standard products
Smoothed (levelled) production (Heijunka)	Apply to a long-term planning horizon; Accept slight daily variations from levelled production
Statistical process control	Limited to standard processes
Continuous flow (one-piece-flow)	Limited to the custom parts
Concurrent engineering	Involving customers
Parts standardization/ modularisation, design for manufacturability	Limited to non-custom parts
Teamwork and leadership	Involving people from engineering and operations
Customer involvement	Important in the product design phase

Indeed, there are LP practices that struggle to be applied in ETO situations, due to the nature of the markets, products and processes that characterise these contexts. For example, JIT delivery by suppliers is hard for ETO situations, due to the high variability of the demand and the complexity to achieve reliable demand forecasting. Hence, JIT deliveries can be applied to small and standard parts. Involving the supplier in the design phase would need the adoption of intellectual property protection or collaboration mechanisms. Pull production / takt time calculation and smoothed (levelled) production (Heijunka) suffer variability. To overcome this limitation, the cases analysed adapted the practices either applying them to a limited set of products or applying the levelled production planning to a long-term horizon or accepting variations from the calculated time and workload. Some quality practices, such as statistical process control, cannot be adopted to manage all processes in ETO systems, as many of them are performed to fulfil limited orders. Another example is the continuous flow, which is very complex to apply by machinery companies since they often perform some engineering and production activities before the customer orders, so to reduce the engineering and production lead times by leveraging on modularity and a standard base, and then wait for the customer order for refine the product design and customise the final production activities (Cannas et al., 2019). Thus, a production area with works in progress is a typical scenario in these companies and it is strictly related to the contingency factors characterising the ETO situations (Cannas et al., 2020). Concurrent engineering presents some differences from its typical application in mass production systems the integration of information is not limited to the company boundaries but involves customers. Regarding standardization, even if ETO companies benefit a lot from the application of this practice that helps to reduce variability, it is limited to parts that are not subject to customer customization. Among the workforce practices, teamwork often requires the collaboration of people from engineering and operations, who work together on the perfection of the production/assembly process whet it is ongoing, to ensure product quality. Last, the involvement of the customer is fundamental for ETO companies that need, in particular, much information from the customer in the product design phase.

6. Conclusion

This paper aims to analyse the practical application of LP practices to reduce the effects of customisation and large product variety and the adaptation of these practices to ETO situations. In particular, the results show that LP is widely applied in ETO contexts such as the machinery industry but is not always easily applied. Indeed, some practices suffer variability and customization, requiring specific adaptation to the ETO peculiarities. All the specific needs resulting from the cases were presented as propositions for the adoption of LP in ETO companies. This made it possible for this study to contribute in two ways. On the one hand, this paper aims to enrich empirical knowledge on LP applications in the ETO context, which has been little covered in the literature. On the other hand, practitioners can see this paper as a guideline for understanding possible challenges that ETO companies face when implementing LP practices.

Despite the interesting results obtained from this research, it represents only a first attempt to explore the implementation of the whole set of LP practices in ETO situations and limitations can be surely identified. The propositions developed in Table 2 are currently indicative and need further investigation and testing. The cases did not give insight into all practices across all of the bundles, and a more in-depth understanding of the relationship and sequencing of the bundles is needed. Also, this study is based on qualitative data gathered from seven case studies in one country in one sector. Further research is needed to validate the results obtained and generalise them. The authors suggest studying successful and unsuccessful cases in other countries and different ETO sectors, e.g., shipbuilding or construction. But also, survey research could be useful to quantitatively validate the results and analyse if companies’ features (e.g., size/ownership type) can affect LP adoption. Finally, it would be useful to involve Lean and ETO experts in the investigation, using methods such as the Delphi study, to explore new potential applications that are still not implemented in practice.

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