A Review of Automatic Lubrication Systems for Industrial Roller Chain Conveyors: Advances, Tribological Implications, and SME-Focused Design Considerations

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ABSTRACT

Roller chain conveyors are fundamental to materials handling and power transmission across modern industrial and manufacturing logistics. However, pin-bushing bearing wear and frictional degradation in chain joints remain primary drivers of unexpected downtime, premature chain elongation, and excessive energy consumption. Over the past six years, tribological research and engineering developments have increasingly focused on replacing inconsistent manual lubrication with cost-effective, automated alternatives. This review synthesizes recent literature and patented technologies on automatic lubrication systems (ALS) applied to industrial conveyor setups. It examines the mechanical and tribological mechanisms of chain joint failure, evaluates commercial and patented ALS solutions across pneumatic, mechanical, digital, and time-relay architectures, and highlights the trade-offs between system complexity and practical accessibility for small and medium-sized enterprises (SMEs). Special focus is given to dual-sided, time-relay drop/shot configurations as a low-cost, open-loop strategy for balanced lubricant application.

Keywords— Automatic Lubrication, Roller Chain Conveyor, Tribological Implications

INTRODUCTION

Roller chain conveyors are extensively employed in manufacturing, material handling, food processing, packaging, automotive assembly, and logistics applications because of their ability to simultaneously transport materials and transmit mechanical power under continuous operating conditions. Their robust construction, high load-carrying capability, and operational reliability make them a preferred solution for industrial production and material-handling systems. However, the continuous operation of roller chain conveyors subjects their mechanical components to repeated contact and relative motion, particularly at the pin–bushing, bushing–roller, and chain–sprocket interfaces. These interactions generate friction and progressively induce mechanical wear, which can adversely affect chain performance, energy efficiency, and service life. Among the various factors contributing to premature chain degradation, inadequate or inconsistent lubrication remains one of the critical causes of excessive friction, accelerated wear, chain elongation, increased energy consumption, and unplanned production downtime.

Lubrication is therefore a fundamental maintenance requirement for ensuring the reliability and operational efficiency of roller chain conveyor systems, as adequate lubrication is a core component of effective chain maintenance programmes (Wright, 1992) and directly mitigates the wear that leads to unexpected failure and costly downtime (Kerremans et al., 2011). An appropriate lubricant reduces direct metal-to-metal contact between interacting surfaces, minimizes frictional resistance, dissipates heat, inhibits corrosion, and mitigates progressive surface degradation. In addition, maintaining an adequate lubricant film at the chain joints can improve mechanical transmission efficiency and extend the fatigue life of critical components. From a tribological perspective, the effectiveness of lubrication is strongly influenced not only by lubricant properties but also by the frequency, quantity, and consistency of lubricant application. Inadequate lubricant delivery may result in boundary lubrication and increased surface interaction, whereas excessive application can lead to lubricant wastage, contamination, and unnecessary maintenance expenditure. Consequently, the ability to deliver the appropriate quantity of lubricant consistently at the required intervals is an important consideration in maintaining the long-term performance of industrial roller chain conveyors.

Despite the importance of controlled lubrication, manual lubrication remains common, particularly among small and medium-sized enterprises (SMEs). Conventional practices typically involve the application of lubricant using brushes, oil cans, or handheld spray devices. Although these approaches require relatively low initial investment, their effectiveness is highly dependent on operator experience and adherence to maintenance schedules. Variations in lubricant quantity, application frequency, and distribution can therefore occur between maintenance cycles and operators. Under-lubrication may accelerate adhesive and abrasive wear, increase frictional losses, and promote chain elongation, whereas over-lubrication can result in excessive lubricant consumption, contamination of adjacent equipment, slippery working surfaces, and increased maintenance costs. Furthermore, manual lubrication may require machine access or temporary production interruption, thereby increasing maintenance-related downtime and reducing overall equipment availability.

Automatic Lubrication Systems (ALS) have emerged as an alternative approach to address the limitations associated with manual lubrication. An ALS is designed to deliver a controlled quantity of lubricant to predetermined lubrication points automatically, either at defined time intervals or in response to machine operating conditions. By reducing dependence on manual intervention, such systems can improve lubrication consistency, reduce maintenance labour, minimize lubricant wastage, and contribute to improved equipment reliability. Commercial ALS solutions developed by established manufacturers, including DropsA, SKF Lincoln, Tsubaki, and OPCO, incorporate various levels of automation and lubrication control, including programmable controllers, pneumatic injection systems, progressive metering devices, centralized pumping arrangements, and sensor-assisted monitoring. These technologies demonstrate the potential of automated lubrication to provide precise and repeatable lubricant delivery in demanding industrial environments.

Nevertheless, the technical sophistication of existing commercial ALS solutions can present significant challenges for SMEs. Many industrial-grade systems are developed primarily for large-scale manufacturing facilities and may require programmable logic controllers (PLCs), compressed-air infrastructure, centralized pumping units, multiple metering components, or sophisticated electronic control systems. While such architectures offer high levels of precision and monitoring capability, they simultaneously increase system acquisition cost, installation requirements, maintenance complexity, and technical skill requirements. These factors may limit their economic feasibility for SMEs, particularly where maintenance budgets, supporting infrastructure, and specialized technical expertise are constrained. In addition, certain commercial lubrication arrangements are configured to deliver lubricant predominantly to a single side or specific lubrication points of the chain, potentially resulting in non-uniform lubricant distribution across the chain assembly. Such non-uniformity may contribute to inconsistent lubrication conditions and localized wear during prolonged conveyor operation.

Recent developments in low-cost industrial automation have created opportunities for developing simpler and more application-specific lubrication solutions. Research into timer-controlled actuators, microcontroller-based systems, compact pumping mechanisms, and low-cost electronic control architectures has demonstrated that automated lubricant delivery can potentially be achieved without the extensive infrastructure associated with conventional industrial ALS. These approaches offer an opportunity to improve lubrication consistency while reducing system complexity and implementation cost. However, the existing body of research has predominantly emphasized centralized lubrication architectures, intelligent condition-monitoring systems, predictive maintenance, or highly integrated industrial automation solutions. Comparatively limited attention has been given to the development of compact, low-cost, dual-side automatic lubrication systems specifically designed for roller chain conveyors operating within SME environments.

This limitation highlights an important research opportunity to develop an ALS architecture that achieves an appropriate balance between lubrication effectiveness, dosing consistency, system simplicity, reliability, and affordability. In particular, a simplified dual-side lubrication mechanism could provide more uniform lubricant distribution across the chain while eliminating the need for costly industrial infrastructure such as PLC-based control, compressed-air systems, or centralized pumping stations. Such an approach is particularly relevant to SMEs seeking practical automation solutions that can be implemented using readily available and maintainable components.

The remainder of this paper is organized as follows. Section 2 describes the systematic methodology adopted for conducting the literature review, including the search strategy, selection criteria, and article screening process. Section 3 presents the results of the literature review, highlighting the key findings and research trends related to automatic lubrication systems for roller chain conveyors. Section 4 discusses the reviewed findings critically, with emphasis on existing technologies, limitations, and identified research gaps. Finally, Section 5 concludes the paper by summarizing the main findings and highlighting the implications and potential directions for future research.

METHODOLOGY

A structured and systematic literature review methodology was adopted to ensure that the literature investigation was comprehensive, transparent, reproducible, and closely aligned with the research objectives concerning Automatic Lubrication Systems (ALS) for industrial roller chain conveyors. The review was designed to identify, evaluate, and synthesize relevant academic studies addressing the mechanical, tribological, control, and economic aspects associated with automated lubrication of roller chain conveyor systems.

The literature search was conducted using three established multidisciplinary and engineering-focused academic databases, namely IEEE Xplore, Scopus, and Web of Science (WoS). These databases were selected based on their extensive coverage of peer-reviewed publications in mechanical engineering, tribology, mechatronics, industrial automation, manufacturing systems, and related engineering disciplines. The combined use of these databases was intended to minimize database-specific publication bias and provide a broader representation of relevant research.

A comprehensive search strategy was developed through the identification of primary keywords, technical synonyms, and domain-specific terminology associated with automatic lubrication, roller chain mechanisms, tribology, wear, and automated lubrication control. Representative search terms included “automatic lubrication system,” “roller chain conveyor,” “chain drive wear,” “pin-bushing tribology,” “chain lubrication,” “automated lubrication,” “micro-dose lubrication,” and “solenoid timer lubrication.”. These keywords were systematically combined using Boolean operators such as AND, OR, and NOT to construct targeted search strings and improve the precision and relevance of the retrieved literature.

To maintain consistency and academic relevance, predefined inclusion and exclusion criteria were applied during the literature screening process. The review primarily considered publications from 2020 to 2026, thereby emphasizing recent technological developments and contemporary research trends while retaining sufficient coverage of established engineering principles. Only publications written in English and classified as peer-reviewed journal articles or conference proceedings were considered for detailed evaluation.

The database searches were further refined according to their respective research strengths. Publications retrieved from IEEE Xplore were primarily examined for research involving electromechanical control systems, sensor integration, automation architectures, programmable controllers, relay/timer-based actuation, and digital control strategies. Meanwhile, Scopus and Web of Science were extensively utilized to identify studies related to tribological behavior, roller chain wear mechanisms, pin-bushing interaction, frictional losses, chain-drive efficiency, lubrication effectiveness, and dynamic or condition-based lubrication approaches.

Studies that were unrelated to roller chain lubrication, focused exclusively on unrelated lubrication applications, lacked sufficient technical information, or did not directly contribute to the research objectives were excluded from the final analysis.

The retrieved publications were subjected to a staged screening process consisting of title and keyword screening, abstract evaluation, and full-text assessment. Duplicate records and publications that did not satisfy the predefined eligibility criteria were removed prior to detailed analysis. Particular attention was given to studies that provided measurable or technically relevant information regarding lubrication mechanisms, lubricant delivery strategies, wear reduction, frictional behavior, control architectures, system complexity, and implementation cost.

Following the screening process, approximately 45 high-relevance publications, representing approximately 15 selected studies from each database, were retained for comprehensive full-text analysis. Rather than relying solely on publication counts, the final selection emphasized the technical relevance, methodological quality, and contribution of each study to the development of an accessible ALS solution for industrial roller chain conveyors.

A structured data-extraction framework was subsequently employed to systematically organize information obtained from the selected literature. Key parameters extracted from each publication included lubrication delivery method, lubrication frequency and dosing strategy, actuation mechanism, control architecture, sensor utilization, tribological performance, wear characteristics, frictional behavior, energy efficiency, system complexity, and implementation cost.

The extracted findings were then synthesized into several major thematic areas:

- Mechanisms of Roller Chain Pin-Bushing Wear and Boundary Friction - Investigation of contact mechanics, lubrication regimes, adhesive and abrasive wear, frictional losses, and degradation mechanisms occurring at roller chain joints.
- Comparative Evaluation of Automatic Lubrication Architectures - Assessment of commercially available pneumatic, mechanical, micro-dosing, and electronically controlled lubrication systems in terms of lubrication effectiveness, complexity, reliability, and operational requirements.
- Automation and Triggering Mechanisms - Examination of mechanical triggering mechanisms, solenoid-based actuation, timer-controlled systems, sensor-assisted lubrication, and emerging Industry 4.0-enabled digital control strategies.
- Design Requirements for SME-Oriented ALS Solutions - Identification of practical design considerations for developing a low-cost, reliable, maintainable, and easily deployable lubrication system suitable for small and medium-sized manufacturing enterprises (SMEs).

The final stage of the review involved a critical synthesis of the identified literature to establish existing research gaps and define the technological requirements for the proposed ALS development. Particular emphasis was placed on the trade-off between lubrication performance and system complexity, as well as the accessibility, affordability, and maintainability of existing commercial solutions.

The review indicates that although considerable research has been conducted on roller chain tribology, wear mechanisms, and sophisticated automatic lubrication technologies, comparatively limited attention has been given to the development of low-cost, open-loop, dual-side lubrication architectures specifically designed for industrial roller chain conveyors operating in SME environments. This gap provides the basis for investigating a simplified ALS architecture incorporating controlled lubricant dosing and automated actuation while minimizing system complexity and implementation cost.

Overall, the systematic methodology provided a structured basis for integrating findings from tribology, mechanical engineering, and industrial automation literature. By combining database-driven searching, predefined eligibility criteria, systematic screening, structured data extraction, thematic synthesis, and critical research-gap analysis, the review establishes a robust foundation for the subsequent design and development of the proposed Automatic Lubrication System for industrial roller chain conveyor applications.

REVIEW RESULTS

Nowadays, roller-chain conveyors are widely used in manufacturing and logistics as they can transport loads well across varying conditions. However, one of the most common causes of mechanical failure in these systems is inadequate lubrication [1]. Manual lubrication practices are often inconsistent, labour-intensive and the human error will lead to excessive wear, corrosion and reduced operational efficiency [2]. So, a proper lubrication of the pin, bushing and roller interfaces is critical because based on the industry guidance indicates that about 60% of chain damage is attributed to lubrication faults [3].

Research strongly supports these observations. Studies on tribological performance show that poor lubrication significantly increases frictional losses and surface damage in roller chain joints [4]. Likewise, investigations into lubrication supply methods demonstrate that inconsistent or single-point lubrication causes uneven wear patterns and reduced chain efficiency [5]. Beyond mechanical wear, lubrication degradation has been shown to directly reduce system reliability, increasing maintenance costs and downtime [6].

To solve these issues, Automatic Lubrication Systems (ALS) deliver a precise quantity of lubricant at programmed intervals or when triggered by specific events to ensure uniform lubrication without stopping the conveyor operation. A commercial example is the RotaLube® system, which delivered substantial savings in lubricant consumption and extended chain life when implemented in a large-scale conveyor application [1]. ALS typically include a reservoir, pump, metering device, tubing and nozzles under a 6-control module. By automating lubrication, maintenance downtime is reduced, waste is minimised and equipment lifespan is improved. Recent advances also highlight the importance of intelligent, condition-based lubrication, which enhances consistency and reduces operational risks [7][8].

In recent years the drive to adopt ALS has extended from large industrial plants to small and medium enterprises (SMEs), but they often face problems such as limited maintenance resources, inconsistent lubrication schedules and higher relative downtime costs. Thus, developing a cost-effective ALS tailored for roller-chain conveyors represents is very important for operational efficiency and equipment sustainability.

A. History and Development of ALS

The development of ALS is actually closely related to the evolution of industrial machinery and the need to reduce friction, wear, and maintenance downtime in continuously operating mechanical systems. The earliest concept of automatic lubrication can be traced back to the late 19th century during the Second Industrial Revolution, a period marked by widespread adoption of steam engines and mechanized power transmission. An invention in this era was the automatic lubricator patented by Elijah McCoy in 1872 with a patent number US129843A, which introduced the principle of delivering lubrication continuously to moving engine parts without requiring machinery shutdown [9]. Elijah McCoy's invention reduced frictional damage and overheating in steam-driven locomotives and industrial equipment, forming the conceptual basis for what would later become the modern automatic lubrication systems. This design demonstrated that maintaining lubrication during operation could extend machine life and reduce maintenance frequency, and become a foundational concept retained in ALS technology today.

The primary function of lubrication is to establish a protective oil film between contacting surfaces, thereby reducing friction, minimizing adhesive and abrasive wear, dissipating heat, preventing corrosion, and improving energy transmission efficiency. In roller chain systems, the lubricant must penetrate the internal pin-bushing interfaces where relative sliding motion occurs. External lubrication of the chain plates alone provides minimal protection because most wear originates inside the chain joints. Consequently, effective lubrication depends not only on lubricant quality but also on accurate delivery to the critical wear interfaces.

Numerous tribological investigations have demonstrated the direct relationship between lubrication quality and chain service life. Studies have reported that inadequate lubrication increases friction coefficients, accelerates pin and bushing wear, promotes chain elongation, and reduces transmission efficiency. Progressive wear eventually alters chain pitch, causing poor sprocket engagement, increased vibration, elevated noise levels, and premature mechanical failure. Conversely, excessive lubrication introduces additional operational problems, including lubricant wastage, contamination of conveyed products, accumulation of dust and debris, and increased housekeeping requirements. Therefore, optimum lubrication requires both accurate timing and controlled lubricant quantity rather than simply increasing lubricant volume.

Industrial maintenance guidelines estimate that a significant proportion of roller chain failures originate from improper lubrication practices rather than material defects or manufacturing inaccuracies. Consequently, lubrication management has become a key element of preventive and predictive maintenance programmes. Modern maintenance strategies increasingly recognise lubrication as an engineering control rather than a routine maintenance activity, emphasising consistency, precision, and repeatability throughout the equipment lifecycle.

B. DropsA S.p.A – VIP4Chain Automatic Lubrication System

The DropsA VIP4Chain is an advanced micro-lubrication system designed to be used for industrial roller chain and conveyor. It integrates a modular pump and electronic control system that precisely meters and delivers oil or air/oil mixtures to selected lubrication points. According to the manufacturer, the VIP4Chain can operate in both air/oil and drop/shot modes, depending on system configuration and application type.

The system consists of three main components which are a microprocessor-based controller, micropump distribution modules, and air/oil injectors or drop nozzles. Each micropump is individually and adjustable, which capable of dispensing precise volumes ranging from 0 to 30 mm^3 per stroke. The controller allows lubrication cycles to be triggered either by time interval or chain link counting, using sensor feedback to synchronize lubrication with the chain motion. The system can be expanded with additional distribution modules, which can up to 6 injection modules from a single control unit.

The VIP4Chain is highly complex and make sure the precise control of the amount of lubricant used. It is suitable for high-value conveyor lines where need a precision lubricant, clean operation, and minimal contamination are priorities, such as in food, packaging, or automotive assembly industries. Its electronic control unit provide an advanced programmability, alarms for system failure and compatibility with remote monitoring systems. The system’s air/oil injection design make sure fine atomization and distribution of oil, which can reduce overspray and improves lubrication uniformity on moving chains.

However, this precision and flexibility lead to another problem, which is high cost. The VIP4Chain requires both an electrical power supply (24 V DC) and compressed air source, which increases installation complexity. Calibration and configuration also need skilled technicians, and periodic inspection of injector 10 performance is important. The overall system is suitable for large industrial setups rather than small-scale or budget-sensitive applications. If compared with the proposed dual-side, time-relay drop/shot ALS, this project perform lubrication through simple electrical timing control rather than complex microprocessor logic. It does not need to compress air, so it can reduce system cost significantly. Moreover, it lubricates both sides of the roller chain simultaneously better than the typically single-sided VIP4Chain configuration. While the VIP4Chain excels in accuracy, feedback, and scalability, the proposed system focuses on cost efficiency, simplified operation, and sufficient lubrication performance for small to medium conveyor systems.

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Fig. 1 VIP4Chain Automatic Lubrication System [10][11]

From a tribological standpoint, the VIP4Chain's (as shown in Fig. 1) individually adjustable micropumps (0–30 mm^3 per stroke) and microprocessor-triggered, chain-link-synchronized dosing represent the most tribologically rigorous architecture reviewed, since the ability to fine-tune both dose volume and timing per lubrication point directly targets boundary-lubrication risk at the pin–bushing interface rather than relying on a fixed-volume assumption. The air/oil injection mechanism further improves tribological outcomes by producing fine atomization, which promotes more even oil-film coverage on moving chain surfaces and reduces the localized dry-contact events that drive adhesive and abrasive wear. However, this tribological precision comes at a clear design-efficiency cost: the system's dependence on a 24 V DC power supply and compressed-air source, combined with its default single-sided configuration, means that unless custom dual-side hardware is added, one side of the chain remains under-serviced relative to the other — creating an asymmetric wear profile that partially undermines the very precision the system is engineered to deliver. In efficiency terms, therefore, the VIP4Chain optimizes for dosing accuracy and monitoring at the expense of installation simplicity, energy/infrastructure overhead, and — without modification — lubrication symmetry.

C. Tsubaki – TCL Conveyor Chain Automatic Lubricator

The Tsubaki Conveyor Chain Automatic Lubricator (TCL Type) is a mechanically driven lubrication device designed to apply lubricant to conveyor chains without the required of electric or external power. Its unique feature is that it is self-actuated by the motion of the chain. When the roller of the chain passes over the lubricator's checker arm, it will press the pump's internal piston and releasing a precise, fixed quantity of oil through the attached nozzles. The system thus provides accurate, consistent lubrication directly synchronized with chain movement.

The TCL model range includes TCL-2 (two-port) and TCL-4 (four-port) configurations. Each discharge port delivers a fixed amount of oil which is 0.05 cc per shot to allow a stable and predictable lubrication. The unit includes a 5 L oil reservoir equipped with a 50-mesh filter, and all necessary copper and rubber piping for connection to the nozzles. The entire unit weighs approximately 5.3 kg and is compact, making installation straightforward on conveyor structures. Lubrication occurs only during conveyor motion to avoid any waste when the conveyor stops.

The operating temperature range is between −10 °C and 120 °C, and oils with viscosity grades ISO VG 32–100 can be used. Due to the system is purely mechanical, it can operate in environments where electrical or pneumatic power is unavailable. The checker arm includes a spring-loaded safety mechanism to prevents damage if the chain reverses or backlashes.

The Tsubaki TCL system was an elegantly simple design. Its mechanical reliability leads to low maintenance requirements and power independence makes it ideal for remote or hazardous environments. The lubrication action is inherently synchronized with chain motion. This provides an excellent proportional lubrication relative to operating speed. However, this same characteristic is also its main limitation: lubrication frequency is related directly to conveyor speed and cannot be adjusted independently. The lubricant volume per stroke is fixed and non-adjustable without mechanical modification. Standard configurations typically lubricate only for one side of the chain.

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Compared to the proposed dual-side, time-relay ALS, the TCL provide an unmatched simplicity but limited control. This project's system allows adjustable timing intervals, enabling precise control over lubrication cycles regardless of conveyor speed. The dual-side design also makes sure symmetrical oil coverage on both side of chain, reducing uneven wear. In contrast, the Tsubaki TCL relies entirely on mechanical actuation and generally lubricates only one side. Thus, while the TCL is maintenance free and reliable, the proposed system offers greater operational flexibility and optimized lubrication distribution.

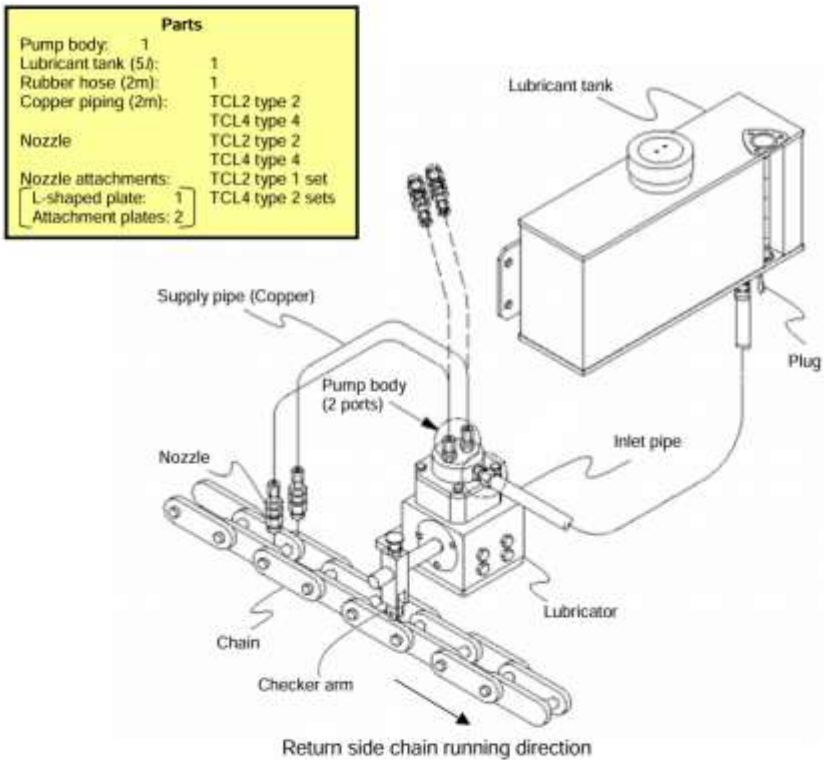

Fig. 2 TCL-4 (four-port) [12][13]

The Tsubaki TCL-4's (refer to Fig. 2) tribological behavior is defined by its self-actuated, motion-synchronized triggering: because the checker arm only releases oil when the chain physically passes over it, lubricant delivery is inherently proportional to operating speed, which prevents the over-lubrication and dry-running conditions that can occur with poorly tuned timer-based systems. This synchronization is a genuine tribological strength, as it ensures lubricant is applied only during relative sliding motion at the joint, when film replenishment is actually needed. However, the fixed 0.05 cc-per-shot dose per port is a significant design-efficiency limitation, because it cannot be recalibrated for varying load, speed, or environmental conditions without mechanical modification — meaning the dosing that is tribologically "correct" at one operating speed may become insufficient or excessive at another. Combined with the standard four-port configuration servicing only one side of the chain, the TCL-4 trades adjustability and lubrication symmetry for mechanical simplicity, zero power dependency, and near-zero maintenance — an efficient design in terms of reliability and cost, but a tribologically conservative one that cannot adapt its dosing strategy to actual wear conditions the way a sensor- or microprocessor-driven system could.

D. SKF / Lincoln – Centro-Matic Single-Line Automatic Lubrication System

The SKF Lincoln Centro-Matic system is one of the most well-known centralized lubrication technologies for heavy industrial applications. It is a single-line (progressive) system that delivers oil or grease through a central pump to multiple injectors via a central pump. As line pressure increases, each injector precisely measures the amount of lubricant used; when pressure is released, the injector automatically resets.

A typical Centro-Matic system includes a central pump station, a main supply line, and SL-series injectors. The injectors are adjustable and can deliver between 0.01 and 1.5 cm^3 per stroke. Each injector serves a single lubrication point, ensuring equal distribution across multiple chain or bearing sites. The system is suitable for both oil and fluid grease applications and can be expanded to cover hundreds of lubrication points from a single pump. Control can be manual, timer-based, or integrated with a PLC for fully automated operation.

SKF's Centro-Matic system excels in large-scale or complex lubrication networks. It provides accurate control of lubricant volume, easy expansion, and reliability under demanding operating conditions. The system can be equipped with pressure switches, monitoring sensors, and feedback indicators for fault detection. These features make it ideal for heavy-duty conveyors or manufacturing lines where consistent lubrication across long distances is necessary.

However, the installation is relatively complex and requires high-pressure tubing, fittings, and regular injector maintenance. The initial cost is substantial, making it less practical for small-scale or single-chain conveyors. Moreover, while the system ensures precise dosing, it generally applies lubrication to multiple discrete points rather than focused dual-side chain coverage.

The dual-sided timed relay-based ALS is designed to achieve localized, flexible lubrication at a significantly lower cost. It utilizes low-pressure solenoid valves and short piping, making its design more compact. While the SKF Lincoln system offers superior scalability, monitoring, and integration capabilities, this system provides sufficient lubrication control without requiring complex infrastructure, making it ideal for small conveyor systems.

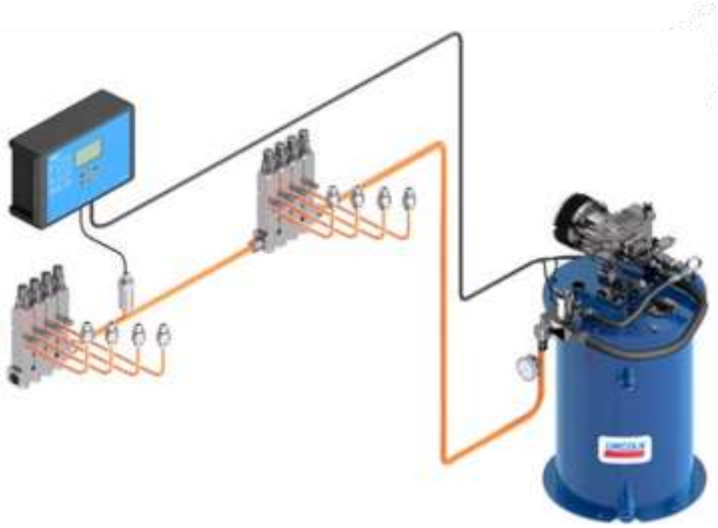

Fig. 3 SKF's Centro-Matic system [14][15]

E. OPCO / Graco – OP-139 General Purpose Air-Operated Conveyor Lubricator

The OP-139 General Purpose Air-Operated Conveyor Lubricator, developed by OPCO Lubrication Systems Inc., a division of Graco Inc., is a pneumatic automatic lubrication system designed to deliver precise, consistent lubrication to conveyor chains, roller systems, and similar continuous-motion equipment. This system is widely used in industrial and automotive conveyor applications where timed or cycle-based lubrication is important to maintaining optimal wear performance and reducing manual maintenance.

The OP-139 lubricator operates using compressed air as the actuation medium. When the timer or control signal activates the system, air pressure enters the pump chamber, forcing a measured amount of lubricant through delivery lines to precision mounted spray or drip nozzles. Each discharge delivers a controlled shot volume—typically between 0.01 and 0.1 cm^3 per cycle—onto the roller-chain pins and bushings.

The system includes a lubricant reservoir, pneumatic control valve, adjustable timing device, and distribution manifold, all mounted in a compact housing. Air pressure and lubricant flow rate can be fine-tuned independently, allowing operators to adjust lubrication frequency and quantity based on conveyor speed or environmental conditions. A built-in check valve prevents backflow, while a pressure regulator ensures consistent atomization of the lubricant during each cycle. The system's components are constructed from corrosion-resistant materials, making it suitable for humid, dusty, or temperature-variable environments such as automotive assembly or material-handling lines.

The OP-139 can be configured for either spray or drop lubrication modes. In spray mode, atomized oil particles provide coverage across chain link surfaces, while drop mode delivers discrete oil droplets directly onto roller interfaces. This flexibility makes the OP-139 adaptable for a range of conveyor chain geometries and lubrication needs. Additionally, the pneumatic system eliminates the need for electrical pumps, reducing electrical hazard risk and simplifying maintenance in flammable or high temperature zones.

The OP-139 represents a balance between pneumatic precision and mechanical simplicity. Its reliance on compressed air enables rapid, repeatable lubrication cycles with smooth piston motion and minimal mechanical wear. The air-actuated design also allows for quick response times and clean lubricant delivery without over-application. Compared with purely electric or mechanical lubricators, the OP-139 provides superior control over shot volume through independent adjustment of air pressure and timing.

However, this system's dependence on a clean, stable compressed-air source can be a limitation in smaller facilities lacking centralized air infrastructure. Air-line moisture or contamination can also affect valve performance, requiring proper filtration and periodic inspection. Furthermore, the system's lubrication pattern is primarily configured for single-side application unless modified with dual manifolds or custom nozzles. While reliable, it does not feature built-in feedback sensors or digital monitoring capabilities, which limits automation and diagnostic functions in advanced environments.

When compared to the proposed dual-side, time-relay drop/shot ALS, the OP 139 shares several operational similarities—both are time-based systems designed to deliver discrete lubricant shots at programmed intervals. However, the proposed ALS differs in using an electric timer relay instead of pneumatic actuation, thereby removing the need for compressed air and simplifying installation.

Functionally, the proposed ALS provides dual-side lubrication, ensuring symmetrical oil distribution across the chain plates and rollers. This feature directly addresses one of the OP-139's major shortcomings: its default single-side lubrication layout. While the OP-139 achieves higher atomization quality and smoother delivery through air assistance, it introduces additional system cost and complexity due to the need for air compressors, regulators, and maintenance of pneumatic seals.

Fig. 4 OP-139 General Purpose Air-Operated Conveyor Lubricator [16][17]

F. Comparative Evaluation of Commercial ALS Architectures

1) DropsA VIP4Chain: Strength - The DropsA VIP4Chain system achieves extremely precise lubricant metering through individually adjustable micropumps, each fine-tuned for different lubrication points. The

system employs a microprocessor-based controller that triggers lubrication based on time and chain link count, synchronizing with conveyor operation. Its modular design expands to up to six distribution modules, making it suitable for complex multi-point lubrication applications. Air/oil injection technology ensures fine atomization of the lubricant, achieving clean and efficient lubrication even on high-speed roller chains. Integrated alarm and fault detection functions enhance system reliability, making it suitable for harsh industrial environments. Weakness - Although it is precision and flexibility, the VIP4Chain requires both electrical power and compressed-air supply, increasing installation cost and complexity. The system's pneumatic and electronic components demand regular calibration and skilled maintenance personnel. It is generally configured for single side lubrication and adapting it for dual-side spraying requires custom hardware. The overall system cost is high, which limits its practicality for small or budget-sensitive conveyor systems.

2) Tsubaki TCL Automatic Lubricator: Strength – The Tsubaki TCL automatic lubricator operates entirely mechanically, eliminating the need for any electrical or pneumatic power supply. Its structure is simple, durable, and exceptionally reliable, requiring minimal maintenance throughout its lifetime. Lubrication is synchronized with chain movement—oil is only discharged when the chain passes the checker arm—ensuring lubricant is applied precisely during motion and not wasted when the conveyor stops. Its compact, integrated design allows easy installation, making it ideal for remote or power-restricted conveyor lines. Weakness - The main limitation of the TCL system is its fixed lubrication volume per actuation, which cannot be adjusted dynamically to match varying load or speed conditions. The lubrication frequency is strictly linked to the conveyor's motion and cannot be independently programmed. Moreover, the standard unit lubricates only one side of the chain, meaning uneven wear may occur on the untreated side. The absence of electronic feedback or monitoring capability also restricts control over lubrication performance.

3) SKF Lincoln Centro Matic: Strength – The SKF Lincoln Centro-Matic single-line lubrication system delivers high reliability and scalability for large industrial applications. Each injector provides a consistent, metered volume of lubricant that can be adjusted individually, ensuring balanced distribution across multiple lubrication points. The system supports integration with PLCs and monitoring sensors for automatic supervision and fault detection. Its robust pump and injector configuration allow operation with both oil and grease, maintaining efficiency under high-pressure and heavy-duty conditions. For large-scale conveyor networks, its precision and reliability make it a proven industrial standard. Weakness - The Centro-Matic system has a complex installation process that requires a dedicated pump station, extensive tubing, and multiple injectors, resulting in high initial cost and setup time. Regular inspection and injector maintenance must be performed by trained technicians. The system's large-scale nature makes it less efficient for small conveyors or localized lubrication zones. Additionally, while the system can serve multiple lubrication points, it is not optimized for dual-side roller-chain lubrication unless heavily modified.

4) OPCO / Graco OP 139 Air Operated Lubricator: Strength – The OP-139 system offers precise pneumatic control and flexibility between drop and spray lubrication modes. Its compressed-air actuation ensures consistent shot volume and clean application, minimizing excess oil usage. Adjustable timing and pressure settings allow the user to adapt the lubrication to different conveyor speeds and environments. The lack of electrical components enhances safety in high-temperature or hazardous areas. Weakness - The system's requirement for a clean compressed-air supply introduces maintenance and infrastructure costs, limiting use in small or low-budget operations. It is primarily designed for single-side lubrication unless customized. Without digital feedback or electronic monitoring, operational verification relies on manual inspection. Additionally, moisture or contaminants in the air line can impair system reliability.

I. DISCUSSION

The findings of this review demonstrate that the development of an effective Automatic Lubrication System (ALS) for roller chain conveyors involves a fundamental trade-off between lubrication precision, automation capability, system complexity, and economic feasibility. Although existing commercial systems provide highly controlled and reliable lubricant delivery, their technical sophistication is not necessarily aligned with the requirements of small and medium-sized enterprises (SMEs). Conversely, mechanically driven systems offer excellent simplicity and reliability but provide limited flexibility in controlling lubrication frequency and quantity. Therefore, the key issue is not whether automatic lubrication can improve chain maintenance, but rather how an appropriate level of automation can be achieved without introducing unnecessary system complexity and cost.

A. Relationship Between Lubrication and Roller Chain Performance

The reviewed literature consistently identifies lubrication as a critical factor governing roller chain reliability and service life. The interaction between the pin, bushing, roller, and sprocket generates repeated relative motion and friction, making the internal chain joints particularly susceptible to wear when lubricant delivery is inadequate or inconsistent. The review further indicates that lubrication effectiveness depends not only on the lubricant itself but also on the timing, quantity, and location of lubricant application.

An important implication of this finding is that increasing the quantity of lubricant alone does not necessarily improve chain performance. Excessive lubrication may result in lubricant wastage, contamination, and additional maintenance requirements, whereas insufficient lubricant delivery can accelerate friction and wear. Hence, the effectiveness of an ALS should be evaluated in terms of its ability to provide controlled and repeatable lubrication, rather than simply maximizing lubricant volume. This finding provides a strong engineering justification for automated dosing mechanisms in which lubrication frequency and quantity can be deliberately controlled.

The review also highlights the importance of delivering lubricant to the internal chain-joint interfaces. Since significant relative motion occurs within the pin–bushing interface, lubrication directed only toward the external chain surfaces may not provide sufficient protection to the critical wear regions. Consequently, the spatial distribution of lubricant should be considered an important design parameter alongside dosing accuracy.

B. Comparison of Existing ALS Architectures

The reviewed commercial systems demonstrate four distinct approaches to automatic lubrication: electronically controlled micro-lubrication, mechanically actuated lubrication, centralized metered lubrication, and pneumatic lubrication. Each architecture provides a different balance between precision, complexity, flexibility, and infrastructure requirements.

The DropsA VIP4Chain represents the highest level of automation among the reviewed systems. Its microprocessor-based control, individually adjustable micropumps, sensor-assisted triggering, and air/oil injection provide highly precise lubricant metering and synchronization with chain operation. Such characteristics make the system particularly appropriate for high-value production lines where lubrication precision, monitoring, and scalability are critical. However, this performance is achieved through a relatively complex architecture requiring electrical power, compressed air, calibration, and skilled maintenance.

In contrast, the Tsubaki TCL automatic lubricator adopts a fundamentally different design philosophy. Rather than relying on electronic or pneumatic control, lubrication is mechanically triggered by chain movement. This architecture provides a significant advantage in terms of simplicity, power independence, and maintenance requirements. The system also inherently synchronizes lubrication with conveyor movement, thereby avoiding lubricant discharge when the conveyor is stationary. However, the same mechanical simplicity limits its flexibility because lubrication frequency is directly dependent on conveyor speed and the lubricant volume per actuation is essentially fixed.

The SKF Lincoln Centro-Matic occupies another position in the technology spectrum. Its centralized pumping and metered injector architecture provide excellent scalability and accurate lubricant distribution across multiple lubrication points. This makes it highly suitable for large-scale industrial installations involving multiple chains, bearings, or other lubrication points. Nevertheless, the requirement for a dedicated pump station, extensive tubing, multiple injectors, and trained maintenance personnel increases installation and operating complexity. As a result, the architecture may be excessive for a relatively small conveyor requiring localized lubrication.

Meanwhile, the OPCO/Graco OP-139 provides an intermediate solution by combining pneumatic actuation with adjustable timing and lubricant delivery. Its ability to operate in both drop and spray modes provides greater flexibility than purely mechanical systems. Nevertheless, its dependence on a clean and stable compressed-air supply introduces additional infrastructure and maintenance requirements. The reviewed system is also primarily configured for single-side lubrication unless additional manifolds or customized nozzles are incorporated.

Overall, these findings indicate that no single existing architecture simultaneously maximizes precision, simplicity, flexibility, low cost, and dual-side coverage. High-end electronic and pneumatic systems provide superior controllability but require greater infrastructure, whereas mechanical systems minimize complexity but sacrifice controllability. This technological trade-off represents the central design challenge identified from the literature.

C. Precision Versus Simplicity: The Core Design Trade-Off

A significant finding from the comparative review is the inverse relationship between system sophistication and implementation simplicity. The VIP4Chain and Centro-Matic systems demonstrate that increased automation enables more accurate dosing, monitoring, scalability, and fault detection. However, these capabilities are accompanied by additional components, including controllers, pumps, sensors, pneumatic infrastructure, distribution modules, and extensive tubing.

For large-scale manufacturing facilities, such complexity may be justified because the consequences of lubrication failure can be substantial and the available infrastructure can support sophisticated maintenance systems. However, the same design philosophy may not be appropriate for SMEs operating relatively small conveyor systems.

The review therefore suggests that technological sophistication should not be treated as synonymous with technological suitability. A simpler system may provide greater practical value when its performance is sufficient to satisfy the actual lubrication requirements of the application.

This observation is particularly relevant to SME-oriented engineering design. Rather than reproducing the full functionality of advanced commercial ALS platforms, a targeted system can focus on the essential functions required for reliable lubrication: controlled dosing, repeatable timing, appropriate lubricant positioning, and reliable actuation. Eliminating non-essential functions such as complex feedback monitoring, centralized pumping, and compressed-air infrastructure can potentially reduce both capital and maintenance costs while retaining the fundamental benefits of automation.

D. Importance of Dual-Side Lubrication

Another important finding emerging from the review is the relatively limited emphasis on dual-side lubrication among the commercial systems examined. The reviewed VIP4Chain, Tsubaki TCL, and OP-139 configurations are predominantly described around specific lubrication points or single-side application arrangements, while the Centro-Matic system focuses primarily on multiple discrete lubrication points rather than dedicated symmetrical coverage of both sides of a roller chain.

This observation has important implications for chain lubrication design. If lubricant delivery is concentrated on only one side of the chain, lubricant distribution across the chain assembly may not be uniform. Over extended operating periods, non-uniform lubrication may potentially contribute to differences in wear behavior between lubricated and less-lubricated regions. The review therefore identifies lubricant distribution geometry as an important but comparatively underexplored design consideration.

A dual-side arrangement provides a relatively straightforward means of addressing this issue by positioning lubrication delivery points on both sides of the chain. Importantly, this improvement does not necessarily require a sophisticated control architecture. A synchronized pair of low-cost actuators or nozzles can potentially achieve symmetrical lubricant application while retaining a simple open-loop control strategy. This represents one of the clearest opportunities for improving the practical suitability of ALS technology for SME applications.

E. Suitability of Time-Relay Control for SME Applications

The comparison also indicates that time-based control represents a potentially appropriate compromise between manual lubrication and highly sophisticated condition-based systems. The VIP4Chain demonstrates the benefits of advanced triggering based on time intervals and chain-link counting, while the Tsubaki TCL achieves synchronization through direct mechanical actuation. The OP-139 similarly employs time-based lubrication but introduces pneumatic actuation.

For SMEs, a timer-relay architecture can provide many of the fundamental benefits of automated lubrication without requiring PLCs, microprocessors, sensors, or compressed-air systems. The principal advantage is the ability to establish a repeatable lubrication interval using relatively simple electrical components. Furthermore, the timing interval can be adjusted according to conveyor operating conditions and maintenance requirements.

However, the open-loop nature of such a system should also be recognized as a limitation. Unlike sensor-assisted or condition-based systems, a timer-relay ALS does not directly measure lubricant condition, chain wear, temperature, load, or actual lubrication effectiveness. Therefore, its performance depends on the appropriate selection of lubrication interval and dosing quantity. This suggests that the proposed low-cost architecture should not be positioned as a replacement for advanced condition-based lubrication in high-value or highly critical applications. Instead, its value lies in providing a practical intermediate solution between manual lubrication and high-complexity intelligent ALS platforms.

F. Research Gap and Implications for ALS Development

The overall synthesis of the reviewed technologies reveals a distinct research gap. Existing studies and commercial solutions have achieved considerable advancement in tribological analysis, precision dosing, centralized lubrication, sensor-assisted monitoring, and intelligent lubrication control. However, relatively limited attention has been directed toward a compact, low-cost, open-loop, dual-side ALS specifically designed for SME-scale roller chain conveyor applications.

This gap should be interpreted not as a lack of automatic lubrication technologies, but as a mismatch between the capabilities of existing technologies and the practical requirements of a specific user group. Advanced systems address the need for precision and monitoring, whereas SMEs may prioritize affordability, ease of installation, ease of maintenance, and compatibility with existing conveyor infrastructure. Consequently, the research opportunity lies in developing an architecture that deliberately removes unnecessary complexity while preserving the core functional requirements of automated lubrication.

Based on the reviewed evidence, four design requirements can therefore be identified for an SME-oriented ALS: (i) controlled and repeatable lubricant dosing, (ii) adjustable lubrication intervals, (iii) balanced or dual-side lubricant distribution, and (iv) low system complexity and implementation cost. These requirements provide a logical design framework for the proposed system and directly address the limitations identified across the reviewed commercial architectures.

G. Overall Discussion

Taken collectively, the reviewed literature suggests that the future development of roller chain lubrication systems should not be driven solely by increasing automation sophistication. Instead, the appropriate level of automation should be determined by the operational context, maintenance requirements, infrastructure availability, and economic constraints of the target application. High-end systems such as VIP4Chain and Centro-Matic are highly advantageous where precision, scalability, monitoring, and integration are essential, while mechanically actuated systems such as Tsubaki TCL demonstrate the value of simplicity and power independence. Pneumatic systems such as OP-139 provide an intermediate level of control but remain dependent on compressed-air infrastructure.

Therefore, the reviewed evidence supports the development of a simplified, time-controlled, dual-side ALS as a potentially appropriate solution for SME-scale conveyor applications. Such a system occupies an important middle ground between manual lubrication and sophisticated industrial ALS: it retains the consistency and repeatability of automated dosing while avoiding the cost and infrastructure associated with PLCs, centralized pumping stations, compressed air, and advanced sensor networks. The proposed design philosophy is consequently not to compete with commercial ALS systems in terms of technological sophistication, but to optimize functional adequacy, affordability, maintainability, and lubrication coverage for the specific requirements of SME-operated roller chain conveyors.

Ultimately, the review establishes that the principal contribution of an SME-oriented ALS lies in achieving an appropriate balance between performance and practicality. The findings provide a clear basis for subsequent development and experimental evaluation of the proposed dual-side time-relay lubrication architecture, particularly in terms of dosing consistency, lubricant distribution, operational reliability, and potential reduction of maintenance-related intervention.

II. CONCLUSIONS

This review has systematically examined the development of Automatic Lubrication Systems (ALS) for industrial roller chain conveyors, with particular emphasis on tribological performance, lubrication architectures, automation strategies, and their suitability for small and medium-sized enterprises (SMEs). The reviewed literature demonstrates that lubrication consistency, dosing accuracy, and lubricant distribution are critical factors influencing chain wear, frictional losses, maintenance requirements, and overall conveyor reliability. Existing commercial systems, including electronically controlled, mechanically actuated, centralized, and pneumatic lubrication architectures, provide different levels of precision and automation; however, higher performance is generally accompanied by increased system complexity, infrastructure requirements, and implementation cost.

The review further identifies a clear opportunity for a low-cost, open-loop, dual-side automatic lubrication architecture targeted specifically at SME-scale roller chain conveyors. Compared with sophisticated commercial systems, a time-relay-based approach can provide controlled and repeatable lubricant delivery while minimizing dependence on PLCs, compressed-air systems, centralized pumping stations, and advanced monitoring hardware. The dual-side configuration also offers a practical approach to achieving more balanced lubricant distribution across the chain. Therefore, the findings suggest that an effective SME-oriented ALS should prioritize an appropriate balance between lubrication performance, dosing consistency, operational reliability, simplicity, maintainability, and affordability, rather than technological sophistication alone.

Future work should focus on experimental validation of the proposed architecture under different conveyor operating conditions, including variations in conveyor speed, lubrication interval, lubricant quantity, and operating duration. Further investigation of lubricant distribution, chain wear, frictional behavior, and long-term reliability would also provide stronger evidence regarding the effectiveness and practical viability of the proposed system. Such development could contribute toward a more accessible and economically sustainable approach to automated lubrication for SME manufacturing and material-handling applications.

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