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A Comprehensive Survey on Machine Repair Problems with Standby Systems

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ABSTRACT

The Machine Repair Problem (MRP), *also referred to as the Machine Interference Problem, is a fundamental queueing framework used to analyze manufacturing and service environments where machines or service units are prone to random failures. Such failures may lead to considerable loss of productivity, revenue, and operational efficiency, particularly in large-scale automated systems. To mitigate these disruptions, modern industries incorporate standby units, cold, warm, or hot, to enhance reliability, maintainability, and system availability. This survey provides a comprehensive chronological and thematic review of standby-supported* $MRPs$, *covering classical queueing foundations, reliability-oriented formulations, and modern optimisation and AI-driven repair strategies. A taxonomy of* MRP *models is proposed to categorise existing literature, followed by an annotated summary table covering the years* 2021–2025. *This survey also outlines major research gaps and future directions to guide scholars and practitioners interested in the modelling and analysis of repairable standby systems. The authors believe that this paper serves as a valuable reference for researchers entering the domain of machine repair systems, reliability analysis, and queueing theory applications.*

Keywords: Machine Repair Problem; Standbys; Machine Interference Problem; Queueing Models; Reliability Engineering.

1 Queueing Theory: Basic Idea, Origin, and Applications

Queueing theory is a fundamental mathematical framework used to analyse systems in which customers, jobs, or units compete for limited-service resources. Developed initially to study telephone traffic congestion in the early 20th century, queueing theory has evolved a rich discipline with wide-ranging industrial, computational, and engineering applications. Classical contributions from **Erlang (1909), Kendall (1953), Cooper (1972), Takacs (1972), Kleinrock (1975), Gross and Harris (1998; 2008), and Bhat (2015)** laid the foundation for modelling arrival processes, service mechanisms, waiting-time distributions, and performance measures of service systems.

A queueing system is generally characterised by three major components: the arrival process of customers or jobs, the service mechanism (number of servers and service-time distribution), and the queue discipline. These systems are commonly described using Kendall's notation $A/S/c$, where A denotes the inter-arrival time distribution, S denotes the service-time distribution, and c represents the number of parallel servers. Depending on the structure and constraints, queueing models may include features such as balking, reneging, priorities, vacations, or server breakdowns.

Over the decade's, queueing theory has found extensive applications in manufacturing systems, communication networks, transportation systems, inventory management, digital services, healthcare operations, and computer/ telecommunication infrastructures. In manufacturing and maintenance environments, machines often undergo random failures, forming a queue of failed units awaiting repair. This scenario leads naturally to the **Machine Repair Problem** (MRP), a classical closed queuing system where the population is finite, the arrival process depends on the number of operating units, and repair activities play the role of service mechanisms. Early works such as **Govil and Fu (1999)** discuss the vital role of queueing theory in manufacturing and highlight the significance of repairable systems in production planning and system reliability.

In this context, queueing theory provides a powerful analytical foundation for modelling the operational behaviour of repairable and standby-supported systems. It enables performance evaluations such as system availability, expected queue length, downtime probability, and cost-benefit analysis. These characteristics are central to designing and optimising machine repair systems, especially when standby units (cold, warm, or hot) are included to enhance system resilience and operational continuity. Fig. 1 Basic structure of a queueing system illustrating the flow from arrivals to service through the waiting line.

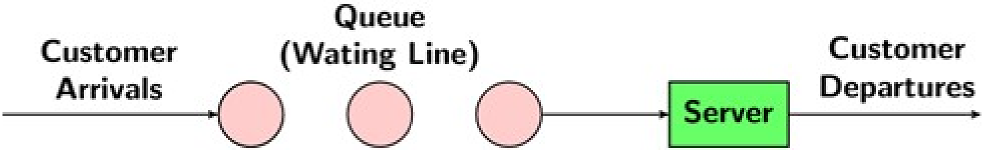

Fig. 1: Basic queueing system illustrating arrival, queue, and service components [$Raina$ & $Jain$ 2010].

2 Nomenclature:

Symbol	Description
N	Total number of machines in the system (finite population)
i	Number of failed machines in state i
R	Number of repairmen/servers available
S	Number of standby units (cold, warm, or hot)
S_c	Number of cold standby units
S_w	Number of warm standby units
S_h	Number of hot standby units
λ	Failure rate of an operating machine
λ_i	State-dependent failure rate when i machines are operating
λ_s	Failure rate of a warm standby unit
μ	Repair rate of a repairman/server
μ_i	State dependent repair rate when i machines are in the repair queue
θ	Switching failure probability (for standby activation)
p	Probability of successful switching or activation
q	Breakdown probability during standby switching
α	The rate of vacation initiation for a repairman
β	Rate of vacation termination
γ	Reneging rate of failed machines (leaving the queue)
δ	Working breakdown rate during repair
η	Deterioration or degradation rate of standby units
P_i	Steady-state probability of the system being in state i
L	Expected number of failed machines in the system
A	System availability
D	Expected system downtime
C	Cost function representing the total system cost
T_s	Expected system throughput
MAP	Markovian Arrival Process
MRP	Machine Repair Problem
BD	Birth–Death process
RL	Reinforcement Learning (for advanced maintenance)

3 Machine Repair Model:

The Machine Repair Model (MRM) is one of the classical models in queueing theory and reliability analysis. It is used to study systems where a finite number of machines are subject to random failures and require repair or maintenance by a limited number of servers (repairmen). The model has its origins in the study of manufacturing and industrial systems, where machine breakdowns and repair activities significantly affect productivity and reliability.

3.1 Basic Structure

In a machine repair model, a population of N identical machines operate simultaneously. Each machine functions for a random period before failing and joining a repair facility. The repair facility usually consists of R repairmen (servers) who attend to the failed machines. If more than R machines fail at the same time, the excess machines must wait in a queue until a repairman becomes available. Once repaired, a machine immediately returns to the operating group and resumes its work. This process continues indefinitely, creating a closed-loop system where machines cycle between the operating state and the repair state. In the Machine Repair Problem (MRP), the system inherently consists of a **finite population of machines**, typically denoted by N.

Unlike classical queueing models, where arrivals may originate from an infinite source, failures in MRP can occur **only from this limited set of operating units.** This structural characteristic makes the arrival rate state-dependent: as more machines fail and join the repair queue, fewer remain in operation, causing the effective failure "arrival" rate to decrease. Thus, the finite population assumption captures the realistic dependence between operational load and breakdown dynamics, ensuring accurate modelling of manufacturing and repair environments. Because failures in the Machine Repair Problem arise only from a fixed and finite set of operating machines, the MRP fundamentally differs from infinite-source queueing models. The number of units that can generate failures decreases as machines break down, making the failure arrival rate inherently state-dependent. This finite-population characteristic accurately reflects real industrial environments where breakdown intensity is directly linked to the number of machines currently in operation. A typical schematic of the process is shown in Fig. 2.

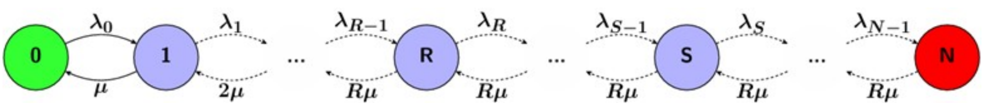

Fig. 2: Machine Repair Model $[Shekhar\ et\ al.,\ 2017]$.

The Machine Repair Model naturally aligns with a **birth–death** (BD) **process** because machine failures and repairs occur one at a time and correspond to simple state transitions. A "birth" represents a failure (moving the system to a higher state of broken machines), while a "death" represents a completed repair (reducing the number of failed machines). The evolution of the system is Markovian, with transitions only between neighbouring states and exponentially distributed failure/repair times—precisely the structure governed by a BD process. This allows the MRP to be analysed using well-established Markov chains, enabling closed-form solutions for steady-state probabilities, reliability measures, and performance indices.

3.2 Classification of Machine Repair Models

Several variations of the MRP have been developed to address practical situations. Broadly, they can be classified as:

1. Single Repairman vs. Multiple Repairmen Models

• In the **single repairman** case, failed machines are repaired one at a time, leading to longer waiting times when the failure frequency is high.

• In the **multiple repairmen model**, parallel repair facilities exist, thus reducing congestion and improving system availability.

2. With and Without Standbys

• **Without standbys:** The number of operating machines decreases as failures occur, possibly leading to system downtime when too many machines fail.

• **With standbys (spares):** Failed machines are instantly replaced by identical standby units, ensuring continuity of service. The repair facility works to restore failed machines, which later replenish the standby pool.

3. Homogeneous vs. Heterogeneous Machines

• **Homogeneous machines** have identical failure and repair characteristics.

• **Heterogeneous machines** differ in operating behaviour, reflecting more realistic environments.

4. Markovian vs. Non-Markovian Models

• **Markovian assumptions** (exponential failure and repair times) simplify analysis but may not capture all real-world dynamics.

• **Non-Markovian models** with general distributions for failure and repair times offer more realistic approximations, though at the cost of analytical tractability.

3.3 Kendall's Notation

The machine repair problem is often modelled using Kendall's notation. For instance:

- $M/M/1/N$: A system with a finite population N, exponential time-to-failure (M), exponential repair times (M), a single repairman (1), and population size N.

- $M/M/r/N$: A system with r parallel repairmen and population N.

Unlike classical open queueing models, the machine repair model is a closed queueing system, since the number of customers (machines) is fixed and no external arrivals occur.

3.4 State Representation

The state of the system at any time can be described by the number of failed machines in the system, denoted as $X(t)$. Since there are at most N machines, the process is a finite Markov chain with states $0, 1, 2, ..., N$.

- **Arrival rate** (failure rate) when k machines are failed:

$$\lambda_k = (N-k)\lambda, k = 0, 1, 2, ..., N-1$$

because only $(N-k)$ machines are operational.

- **Service rate** (repair rate) when k machines are failed:

$$\mu_k = min(k, R)\mu, k = 0, 1, 2, ..., N$$

since at most R repairmen can work simultaneously. This structure leads to a **birth–death process** with finite states.

3.5 Performance Measures

Several important performance measures are derived from the steady-state probabilities $P_k = Pr(X = k)$, where K represents the number of failed machines in the long run. Some key measures include:

- **Mean number of failed machines:**

$$E[F] = \sum_{k=0}^{N} kP_k$$

- **Mean number of operating machines:**

$$E[O] = N - E[F]$$

• **Machine availability (fraction of time a machine is operational):**

$$A = \frac{E[O]}{N}$$

• **System throughput, especially in manufacturing, is proportional to $E[O]$.**

4 Machine Repair Problem with Standbys:

In many real-life systems, uninterrupted operation is essential, and downtime due to machine breakdowns must be minimised. To achieve this, **standby or spare units** are often incorporated into the system. The inclusion of standbys transforms the classical Machine Repair Problem (MRP) into a more robust model, where a failed machine is immediately replaced by a spare unit, thereby ensuring continuous system operation. This arrangement is commonly referred to as the **Machine Repair Problem with Standbys.**

4.1 Classification of Standbys

Machine repair models with standbys can be classified along several dimensions:

(a) **Standby Type**

• **Cold standby:** failure rate $= 0$.

• **Warm standby:** failure rate less than operating machines.

• **Hot standby:** failure rate equal to operating machines.

• **Mixed standby:** a combination of different standby types.

• **Multiple standby:** several spare units.

(b) **System Assumptions**

• Finite vs. infinite machine population.

• R repairmen.

• Switching failures or imperfect coverage.

- Server vacations.

- Retrial queues.

(c) **Methodologies**

- Markov chains.

- Matrix-analytic or matrix-augmentation methods.

- Renewal theory.

- Simulation approaches.

- Optimisation and cost models.

4.2 State Transition Representation

Fig. 3 depicts the state transition diagram of a machining system with standbys, consisting of N operating machines, and S standby machines. Whenever an operating machine fails, it is immediately replaced by a standby machine (if available). The failure rate can be extended as follows:

$$\lambda_n = (N-n)\lambda + n\theta \qquad (*)$$

where λ is the mean failure rate of operating machines, and θ is the mean failure rate of warm standbys which follow an $i.i.d.$ exponential distribution.

- For **cold standby** systems: set $\theta = 0$.

- For **hot standby** systems: set $\theta = \lambda$.

For a **mixed-type standby machining system** comprising S_c, S_w, S_h standbys of cold, warm, and hot type, respectively, the state-dependent failure rate in equation $(*)$ is modified as:

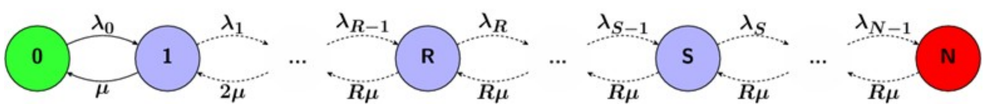

Fig. 3: State transition diagram of the machine repair problem with a standby.

5 Related Literature:

The MRP, also known as the Machine Interference Problem, has evolved substantially from classical queueing formulations to modern reliability-aware, optimisation-driven, and $AI-$enabled repairable system models. The foundational queueing texts by **Saaty (1961), Cooper (1972), Takács (1972), Newell (1971), Kleinrock (1975), Wolff (1989), and Gross and Harris (1998; 2008)** established the mathematical framework for modelling repair processes, service mechanisms, and stochastic breakdown behaviour. Early $MRP-$related analytical studies include the work of **Stecke and Aronson (1985)**, who reviewed operator/machine interference, and **Sivazlian and Wang (1989)**, who introduced economic analysis for warm-standby repairable models. The classical warm/cold/hot standby concepts were further shaped by studies such as **Sztrik and Bunday (1993) and Aissani (1994)**, who analysed interference queues with unreliable and redundant servers.

Throughout the $2000s$ and early $2010s$, modelling sophistication increased with emphasis on reliability, redundancy, and complex vacation policies. Comprehensive surveys such as **Haque and Armstrong (2007)** and **Jain, Sharma and Pundhir (2010)** summarised the major MRP formulations. Extensions involving warm standbys, imperfect switching, multiple vacations, and reneging behaviours appeared in works by **Maheshwari et al. (2010), Jain and Gupta (2011), Jain and Preeti (2014a; 2014b), Jain and Rani (2014), and Kumar and Jain (2013; 2014)**. Several authors contributed significantly to transient-state and reliability-based modelling, including **Jain, Shekhar and Shukla (2014; 2016) and Shree et al. (2015).** Queueing models integrating working vacations and MAP arrivals were studied by **Chandrasekaran et al. (2016) and Liu et al. (2015), while Gao and Wang (2015) and Jamshidi and Esfahani (2015)** introduced decision-theoretic and multi-level maintenance perspectives.

A thematic progression toward optimisation and policy-driven machining systems emerged around 2015–20. Important contributions include the analysis of reliability and sensitivity for controllable repair systems **(Yen et al., 2016)**, cold/warm standby configurations **(Huang et al., 2015; Liu et al., 2015)**, and retrial systems with mixed standbys **(Kuo et al., 2014)**. Broader theoretical surveys during this period include the review on interruptions by **Krishnamoorthy et al. (2014)** and the progression summaries on retrial queues **(Shekhar et al., 2016)** and machining systems **(Shekhar et al., 2017a–d; 2018)**. Analytical advances continued in 2021–23, with studies focusing on matrix-exponential distributions for standby repair systems **(Kus and Eryilmaz, 2021)**, optimisation of cold-standby units with multiple vacations **(Ruiz-Castro, 2021)**, and comparative performance analysis for N-policy machining systems **(Meena et al., 2022)**. Reliability analysis for manufacturing systems with degradation and imperfections was extended by **Shekhar, Devanda and Kaswan (2023)**.

Recent work from $2024-25$ demonstrates a paradigm shift toward stochastic optimisation, predictive maintenance, and $AI-$ enabled reliability forecasting. Notable contributions include N-policy models with multiple spares and switching failure **(Gupta and Ashwathy, 2024)**, generally distributed repair-time formulations using matrix augmentation **(Wu et al., 2024)**, reliability and residual life estimation of cold standby systems **(Liu et al., 2024)**, and condition-based switching and age-dependent maintenance **(Xian et al., 2025)**. Research has expanded toward cyber-physical and computationally driven systems, as reflected in applications of Grey Wolf Optimisation for cloud-based repairable environments **(Parmeet et al., 2024)**. Storage failure effects on standby parts were analysed by **Jianfei et al. (2024)**, while new derivations for service-time distributions were provided by **Chaudhry et al. (2025)**. Cutting-edge multi-objective optimisation frameworks for retrial warm-standby systems appeared in **Wu and Wang (2025)**, and cost optimisation under imperfect coverage was introduced by **Yen et al. (2025)**. Recent discrete-time retrial repairable models with unreliable repair facilities were presented by **Ma et al. (2025)**.

The present survey aligns its scope with these historical developments while incorporating the most recent literature, including the 2025 survey by **Raina and Shaheen (2025)** and the reliability monograph by Raina and Jain (2021). Together, these works demonstrate the continuous expansion of MRP research toward more realistic, reliability-centred, and policy-optimised machining and service environments.

The evolution of research on the Machine Repair Problem (MRP) reflects a clear thematic progression in modelling complexity and analytical depth. Early studies concentrated on MRP basics, focusing on classical finite-source queues and Markovian birth–death formulations to capture machine failures and repair dynamics. As industrial needs grew, researchers advanced toward standby modelling evolution, introducing cold, warm, hot, mixed, and multi-level standby components to enhance system reliability. Subsequently, the field entered an optimisation era, integrating vacation policies, $N-$policies, $F-$policies, switching failures, and retrial mechanisms to minimise cost and maximise system availability. This was followed by a dominant reliability era, characterised by detailed reliability, maintainability, and degradation modelling using complex stochastic processes and state-dependent parameters. Most recently, the literature has shifted toward the AI/ML era, where metaheuristic algorithms, predictive models, and intelligent optimisation frameworks are employed to design cost-efficient, highly reliable machine repair systems suited for modern smart manufacturing environments.

The pioneer works for modelling of machining systems with different types of standby units are summarised in Table 1.

Literature on the machine repair problem with different types of standbys. To provide a comprehensive overview of contemporary research trends in the domain of machine repair problems with standby units, it is essential to systematically document and categorise recent scholarly contributions.

Table 1: Literature on the machine repair problem with different types of standbys.

Standbys	Authors
Cold Standby	Goel (1985), Azaron et al. (2009), Jamshidi and Esfahani (2015), Liu et al. (2015), Wu and Wu (2011). Kus & Eryilmaz (2021), Ruiz-Castro (2021), Kus & Eryilmaz (2021) Liu et al. (2024), Ruiz-Castro, J. E. (2021). He et al. (2024).
Warm Standby	Arullnozhi (2002), Wang & Chiu (2006), Yen et al. (2016), Yen et al. (2022), Yen et al. (2025), Huang et al. (2015), Jain and Rani (2014), Jain et al. (2014), Wells (2014), Kumar and Jain (2013), Meena et al. (2022), Maheshwari et al. (2010), Wu & Wang (2025), Gupta & Aravind (2024).
Hot Standby	Rykov & Ivanova (2024), Shree et al. (2015).
Mixed Standby	Gupta & Aravind (2024), Jain et al. (2016), Kuo et al. (2014), Jain & Saxena (2006), Wang (1993), Wang & Kuo (2000), Maheshwari & Ali (2013), Kuo et al. (2014), Jain et al. (2015) Jain & Upadhyaya (2009).
Multiple Standby	Kumar and Jain (2014), Jain and Preeti (2014).

While significant theoretical models have been proposed historically, the period from 2021 to 2025 has witnessed a noticeable shift towards multi-standby configurations, optimisation-based policies, and hybrid analytical-simulation approaches. Researchers have increasingly focused on warm and mixed standby systems, age-dependent switching, matrix-analytic formulations, and performance optimisation under realistic industrial constraints.

To highlight these developments clearly and assist future scholars in identifying relevant methodological directions, we present below an annotated literature table (Table 2), summarising key works published between 2021 and 2025. The table classifies the studies based on standby type, modelling approach, analytical tools employed, and major findings, thereby serving as a valuable reference framework for advanced research in this area.

Table 2: Annotated Literature Table (2021–2025).

Year	Authors	Standby Type	Assumptions	Method	Key Findings
2021	Kus & Eryilmaz	Cold standby	Two-unit system	Matrix-exponential	Reliability via phase-type analysis
2021	Ruiz -Castro	Cold standby	Multi-state, vacations	Matrix -analytic	Optimisation with preventive care
2023	Shekhar et al.	Standby provisioning	Multi-unit system	Reliability engineering	Standby provisioning impacts downtime
2024	Gupta & Ashwathy	Multiple spares	Switching failure	Successive-over-relaxation technique	Cost/reliability balance
2024	Wu	Standby + limited capacity	R repairmen	Matrix-augmentation	Efficient solution for large systems
2024	Liu et al	Cold standby	Equivalent systems	Reliability modeling	Equivalent cold standby depiction
2024	Rykov & Ivanova	Hot standby	Double system	Marked Markov processes	Hot standby dynamics analyzed
2024	Qi et al.	Warm & Cold standby	Multi-state standby	Semi-regeneration process	System care & switching strategy
2025	Yen et al.	Warm standby	Retrials, imperfect coverage	Stochastic optimization	Cost-based policies for warm standbys
2025	Zhao et al.	Standby (general)	Condition -based	Profit optimization	Age-based care improves reliability

6 Applications of $MRPs$ with Standbys:

Machine Repair Problems $(MRPs)$ with standby provisions have extensive applications across modern engineering and industrial systems. In manufacturing environments, machining centres, automated production lines, and flexible manufacturing systems frequently experience random failures that disrupt operational flow. Incorporating standby machine units ensures uninterrupted production and improves overall equipment effectiveness (OEE). Industries dealing with high-speed assembly lines or semiconductor fabrication rely on standby-supported repair models to reduce downtime and maintain quality standards.

MRP frameworks are equally critical in **computer and communication systems**, where servers, routers, and data-processing units may fail due to overload or hardware degradation. Cloud computing infrastructures, in particular, utilise standby servers and dynamic switching policies to guarantee service continuity and minimise cost. Recent optimisation-based systems, such as those presented by **Parmeet et al. (2024)**, demonstrate the relevance of modern metaheuristics in managing cloud-based repairable systems with $N-$ policy and feedback mechanisms.

In reliability engineering, $MRP-$based formulations contribute significantly to the development of optimal maintenance and replacement strategies for repairable systems subject to degradation, imperfect switching, and multiple failure modes. Recent advancements explore the reliability behaviour of multi-state standby systems under realistic operational constraints. For instance, **Qi et al. (2024)** analyse an optimal maintenance policy for a multi-state warm standby configuration considering imperfect switching mechanisms. Their study demonstrates how reliability-oriented decision models can effectively balance maintenance cost, switching failure risk, and system availability, thereby emphasising the increasing integration of reliability optimisation within standby-supported repair systems.

MRP models with standbys also find applications in **transportation systems, energy systems, logistics hubs, and critical infrastructure**, where redundancy and rapid repair are essential for operational resilience. In robotic and cyber-physical systems, standby-based repair strategies support autonomous fault recovery and enhance system survivability.

Overall, the integration of standby-supported MRP models is increasingly aligned with **Industry 4.0** initiatives, where smart manufacturing, predictive analytics, digital twins, and intelligent maintenance systems demand robust, reliable, and cost-optimised repair frameworks.

7 Future Directions and Open Problems:

Future research on Machine Repair Problems $(MRPs)$ with standby systems can advance in several impactful directions. First, the integration of carbon-aware operations into standby optimisation offers a promising avenue. With increasing global emphasis on energy sustainability, analysing machine repair and standby activation under **carbon-emission constraints** can help industries design environmentally optimal maintenance schedules. Multi-objective models balancing cost, downtime, reliability, and carbon footprint can lead to greener and more resilient production systems.

Second, the rise of **additive manufacturing** (AM) presents new opportunities for MRP modelling. Unlike traditional manufacturing lines, AM systems operate with unique machine degradation patterns, dynamic toolpaths, and material-based failures. Developing MRP frameworks tailored for AM environments with provisions for standby printers, component swapping, and layer-wise repair can significantly enhance productivity and reduce scrap.

Another promising direction lies in the application of **reinforcement learning** (RL) for repair and replacement decision-making. $RL-$based agents can learn optimal repairman dispatching, standby switching, and failure-prevention strategies in real time, even under uncertain or nonstationary environments. This aligns well with the growing shift toward autonomous manufacturing and smart maintenance systems.

Furthermore, **digital twin modelling** represents a transformative opportunity for future MRP research. Digital twins can replicate machine behaviour, predict failures, and simulate standby activation policies using real-time sensor data. Integrating $MRPs$ with digital twin architectures would enable continuous monitoring, predictive diagnostics, and adaptive maintenance strategies, thereby improving reliability and operational efficiency.

Overall, these emerging directions of sustainability-aware repair policies, advanced manufacturing integration, $AI-$driven decision-making, and digital twin–enabled predictive maintenance highlight the expanding relevance of MRP research in the era of Industry 4.0 and beyond.

8 Conclusions:

This survey provides a comprehensive overview of Machine Repair Problems $(MRPs)$ with standby systems, covering foundational queueing-theoretic models, classical repair formulations, and advanced extensions involving cold, warm, hot, mixed, and multi-state standby units. Through a detailed, chronological, and thematic synthesis, the paper highlights the evolution of MRP research from basic Markovian formulations to modern, reliability-oriented, and optimisation-driven frameworks. A structured **taxonomy of MRP models** and an **annotated literature table** $(2021–25)$ are presented to assist researchers in systematically understanding current trends, methodological advancements, and application domains.

The survey underscores how $MRPs$ have expanded in scope with the incorporation of retrial mechanisms, vacation policies, switching failures, degradation modelling, and cost–reliability trade-offs. Recent years, particularly $2024–25$, have witnessed rapid developments driven by stochastic optimisation, predictive maintenance, metaheuristics, and AI-enabled decision-making, reflecting the growing importance of intelligent and resilient repairable systems in modern industry.

Overall, this survey aims to serve as a valuable resource for researchers, practitioners, and graduate scholars working in reliability engineering, queueing systems, and industrial maintenance. By consolidating existing knowledge and identifying emerging directions, the paper provides a strong foundation for future work in the modelling, analysis, and optimisation of repairable systems with standby provisions.

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