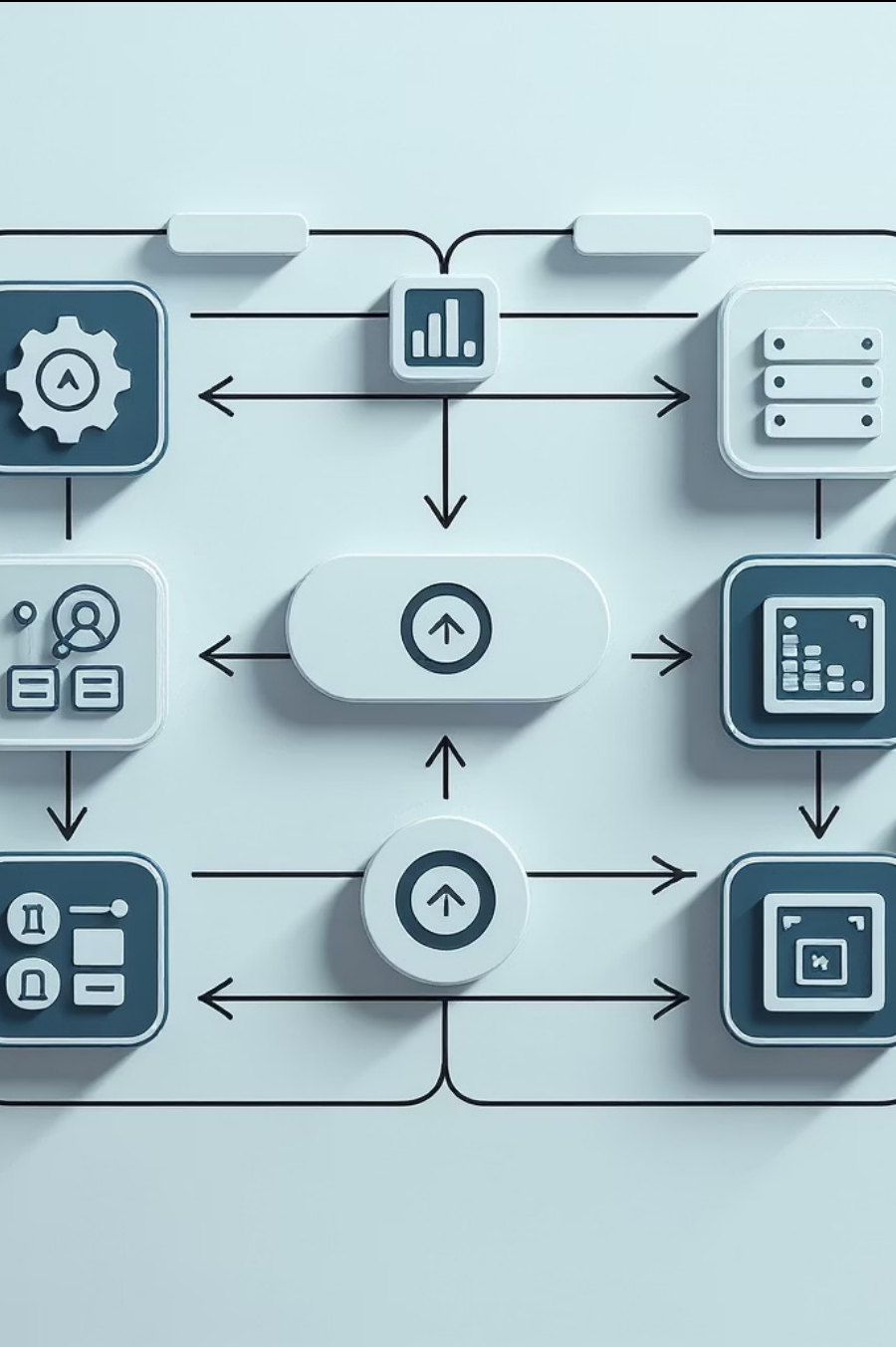


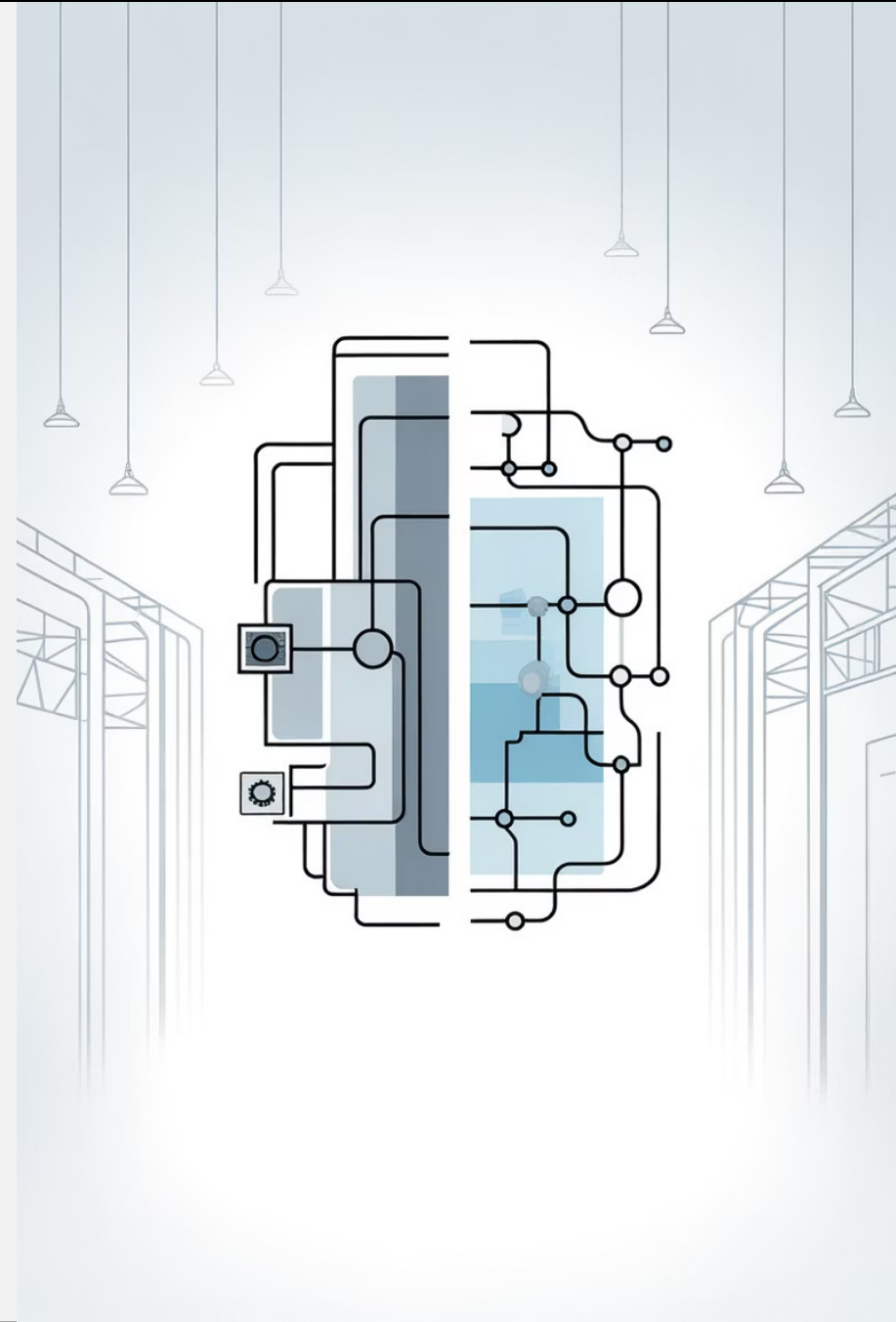


## 8.3.3 Maintenance Strategy Modeling:

### System-Level Maintenance Models

Throughout this presentation, we will examine the factors that influence maintenance decisions at the system level, including dependencies, economic considerations, and operational constraints. By considering these complex interactions, maintenance optimization at system level can develop more effective strategies that optimize overall system performance rather than individual components.

# From Component-Level to System-Level Strategies



# The Fundamental Disconnect in Maintenance Optimization

When transitioning from component-level to system-level maintenance strategies, engineers encounter a fundamental principle that shapes all subsequent decision-making:

## **System Optimum $\neq$ Sum of Component Optima**

This inequality represents a paradigm shift in maintenance thinking. While component-level strategies focus on optimizing the performance of individual parts based on their specific failure characteristics, system-level approaches must consider the complex interrelationships between components and their collective impact on overall system performance.

For example, replacing a bearing in a gearbox based solely on its individual condition might seem optimal when viewed in isolation. However, if this replacement requires disassembling the entire gearbox, it may be more efficient to simultaneously replace other components that are approaching the end of their useful life, even if they could theoretically operate longer.

This fundamental disconnect necessitates a global optimization approach that considers not just the technical aspects of component degradation, but also the economic, logistical, and operational implications of maintenance actions across the entire system.

# Quantifying the Component vs. System Perspective

## Component-Level Optimization:

Traditional component-level maintenance optimization typically focuses on finding the optimal replacement interval ( $\tau$ ) that minimizes the long-term cost rate  $C(\tau)$  for each component individually:

$$C(\tau) = \frac{C_p F(\tau) + C_u (1 - F(\tau))}{\tau}$$

Where:

- $C_p$  = Cost of preventive replacement
- $C_u$  = Cost of unplanned (failure) replacement
- $F(\tau)$  = Probability of failure by time  $\tau$

This approach implicitly assumes components are maintained independently of each other.

The mathematical contrast between these approaches illustrates why maintenance strategies that are optimal at the component level often lead to suboptimal system performance. Engineers must therefore adopt more sophisticated modeling techniques that capture the complex interplay between components in a system context.

## System-Level Complexity:

At the system level, the objective function becomes significantly more complex, incorporating interactions between components:

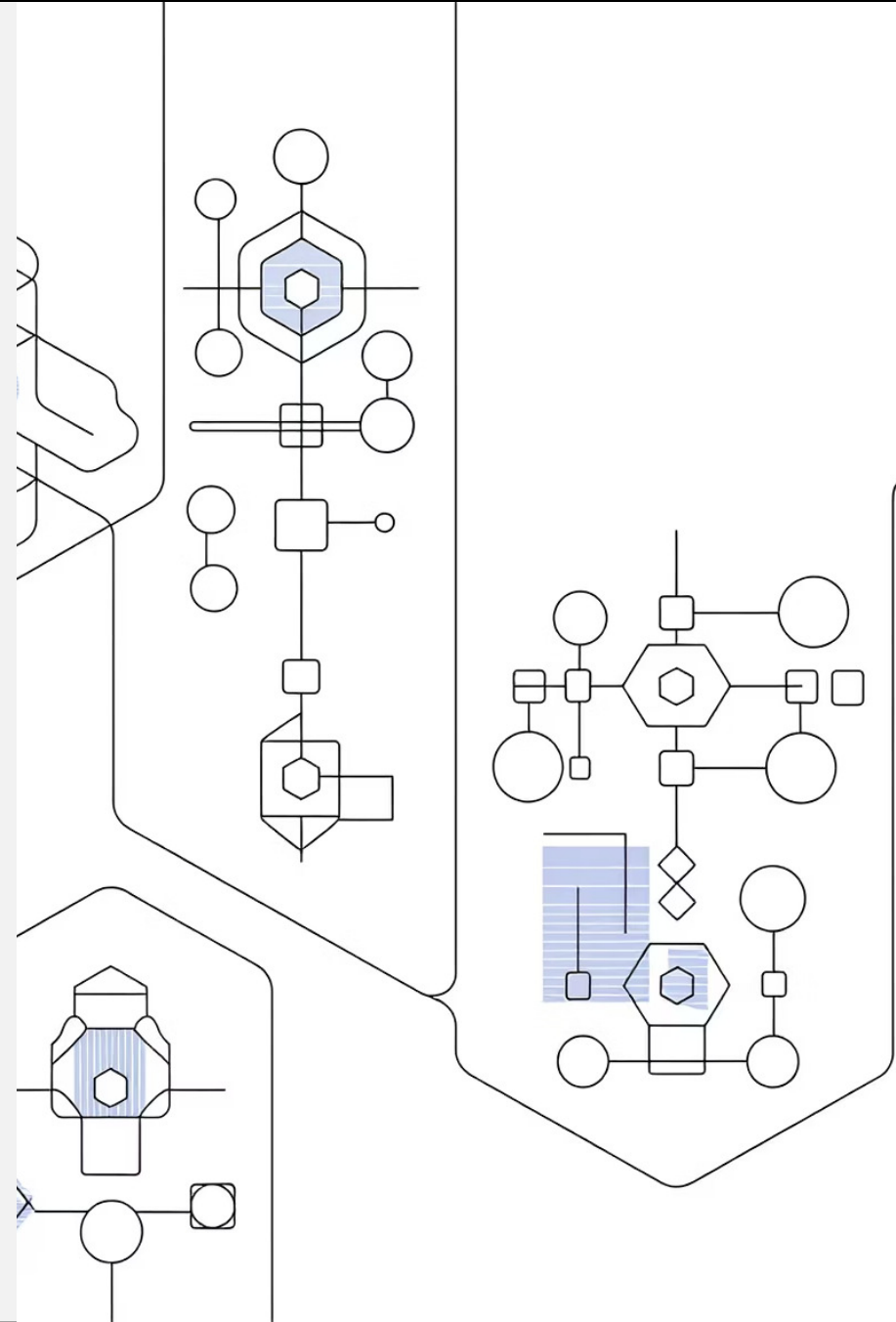
$$C_{sys}(\tau_1, \tau_2, \dots, \tau_n) = f(C_1, C_2, \dots, C_n, D, S)$$

Where:

- $C_i$  = Cost function for component  $i$
- $D$  = Dependency matrix between components
- $S$  = System structure function
- $\tau_i$  = Maintenance interval for component  $i$

This formulation captures the reality that maintenance decisions for one component influence the optimal decisions for others through various dependencies.

# Key Factors in System-Level Maintenance



# System Structure and Its Impact on Maintenance Strategy

1

## Series Systems

In series configurations, the system functions only if all components function.

**Maintenance implications:** The weakest component dominates system reliability. Preventive maintenance should focus on components with highest failure rates or those with catastrophic failure modes.

2

## Parallel Systems

In parallel configurations, the system functions if at least one component functions.

**Maintenance implications:** Provides inherent redundancy, allowing for corrective maintenance strategies for some components while maintaining acceptable system reliability.

3

## k-out-of-n Systems

System requires at least k out of n components to function.

**Maintenance implications:** Provides a balance between redundancy and resource efficiency. Requires careful calculation of the optimal number of spare components.

- ❏ Understanding system structure is foundational for developing effective maintenance strategies. The configuration directly determines how component failures propagate to system failures, which in turn influences the prioritization and scheduling of maintenance activities. Engineers must analyze the reliability block diagram of their systems to identify critical components and potential single points of failure that require special attention in maintenance planning.

# Inter-Component Dependencies

Dependencies between components create complex interactions that significantly impact maintenance decision-making. These dependencies can be classified into three primary categories:

## Stochastic Dependencies

Occur when the state or failure of one component influences the degradation rate or failure probability of another component. For example, a failing bearing may increase vibration, accelerating wear on nearby components. Mathematically represented as conditional probabilities:

$$P(X_j \text{ fails} | X_i \text{ failed}) > P(X_j \text{ fails})$$

## Structural Dependencies

Arise from the physical arrangement of components, where maintenance on one component necessitates disassembly or deactivation of others. For instance, replacing an internal gear may require removing several other components first, creating "maintenance inclusion" relationships that must be considered in planning.

## Economic Dependencies

Reflect shared costs when maintaining multiple components together, including setup costs, downtime costs, and shared resources. The cost of maintaining component  $i$  and  $j$  together is often less than the sum of maintaining them separately:

$$C(i, j) < C(i) + C(j)$$

- ❏ These dependencies create both challenges and opportunities. While they complicate maintenance modeling, they also provide potential for efficiency gains through strategic grouping of maintenance activities. Advanced maintenance models must explicitly account for these dependencies to develop truly optimal system-level strategies.

# Support System Constraints in Maintenance Planning



## Resource Limitations

The finite number of maintenance technicians, engineers, and specialists creates scheduling constraints that must be addressed in system-level planning. These human resource limitations often become binding constraints, particularly during major maintenance campaigns or emergency situations. Advanced workforce scheduling algorithms must be integrated with maintenance optimization models to ensure feasible plans.



## Spare Parts Logistics

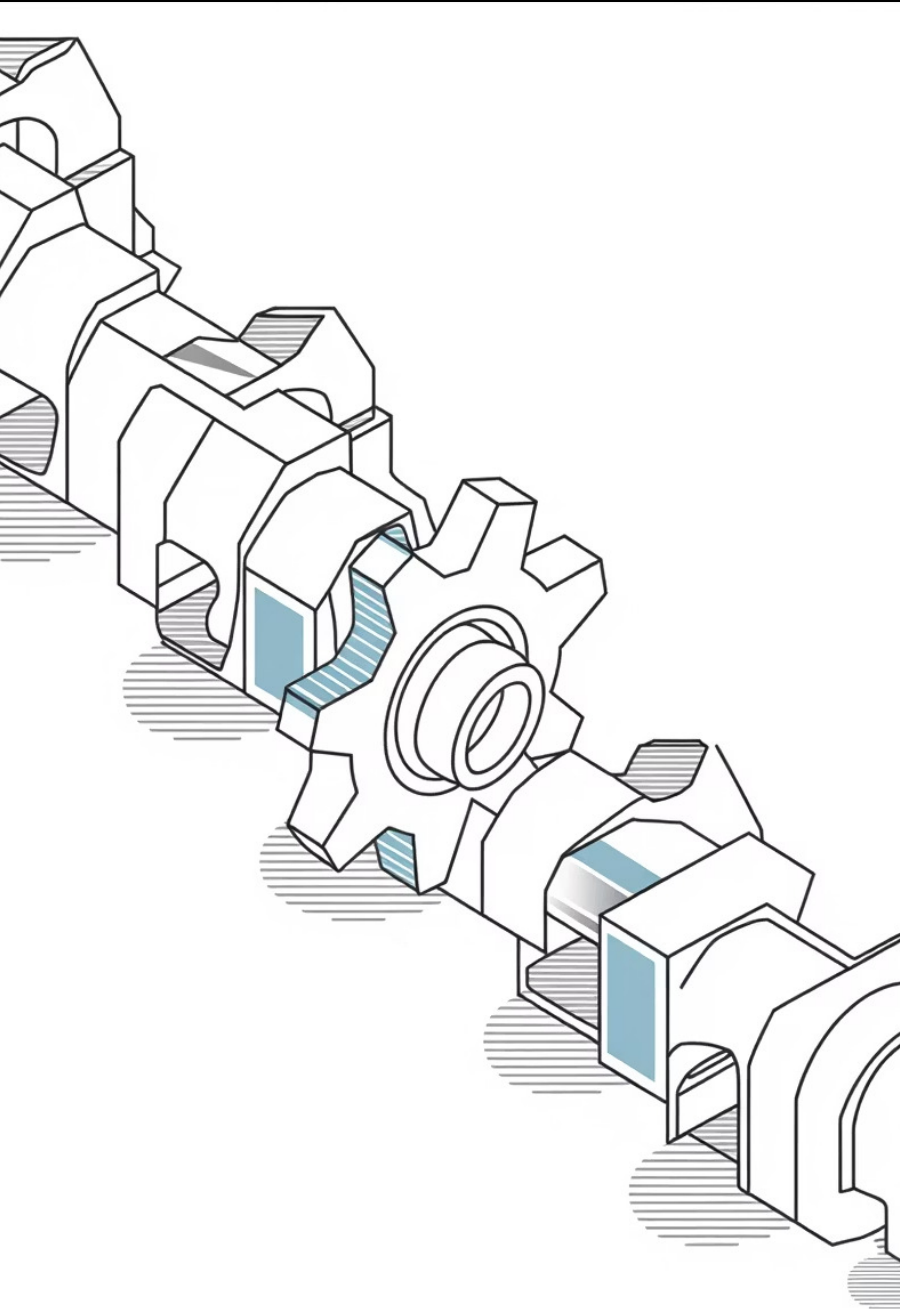
The availability, lead time, and storage costs of spare parts significantly impact maintenance strategy. Critical components with long procurement cycles may require maintaining safety stock, while others might use just-in-time ordering. Spare parts inventory optimization becomes an integral component of system maintenance modeling, balancing carrying costs against stockout risks.



## Specialized Equipment

Many maintenance activities require specialized tools, diagnostic equipment, or heavy machinery that may be limited in availability or expensive to mobilize. The sharing of these resources across multiple maintenance activities creates scheduling dependencies that must be carefully coordinated. Equipment constraints often drive the grouping of maintenance activities to maximize utilization efficiency.

- ❑ The operational reality of maintenance extends beyond theoretical reliability models to include these practical constraints. Effective system-level maintenance planning must integrate these constraints into optimization models, often requiring complex optimization approaches. Ignoring these constraints leads to mathematically optimal but practically infeasible maintenance schedules that cannot be implemented in real-world settings.



# Why Dependencies Matter

# Why Dependencies Matter

Dependencies among components lead to **non-linear interactions** that invalidate simple component-level models.

- **Failure dependence** increases hazard rates of other components:

$$h_i(t) = h_i^0(t) + \sum_{j \neq i} \alpha_{ij} \cdot \mathbf{1}_{\{C_j \text{ failed}\}}$$

- Results in potential **cascading failures** and “domino effects”.
- Studies show that ignoring interdependencies lowers prediction accuracy; incorporating them improved F1-score by ~7%.
- In complex, tightly coupled systems, even **small faults escalate** quickly (*Normal Accidents Theory*).

# Why Simple Threshold Rules Fail

At the component level, a common maintenance decision rule is based on a critical degradation threshold:

$$X(t) \geq D_{\text{crit}} \Rightarrow \text{Repair}$$

The fundamental problem with this approach is that it assumes components are **independent**. In reality, **interdependencies** significantly distort component degradation paths and elevate failure risks.

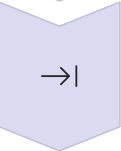
## Example: Interdependent Components

Consider a scenario where the failure of one component directly impacts another:



### Component A Failure

If **Component A** fails at time  $t_A$ .



### Impact on Component B

It increases the hazard rate of **Component B**.

$$h_B(t) = h_B^0(t) + \alpha \cdot \mathbf{1}_{\{t \geq t_A\}}$$

Even if Component B's degradation  $X_B(t)$  has not yet reached its critical threshold  $D_{\text{crit}}$ , the increased hazard may cause it to fail **prematurely**.

## Consequences

Relying solely on individual component degradation thresholds for intervention:



Underestimates the **true urgency** of maintenance interventions for interdependent components.



Leads to **cascading failures** and extended system downtime.

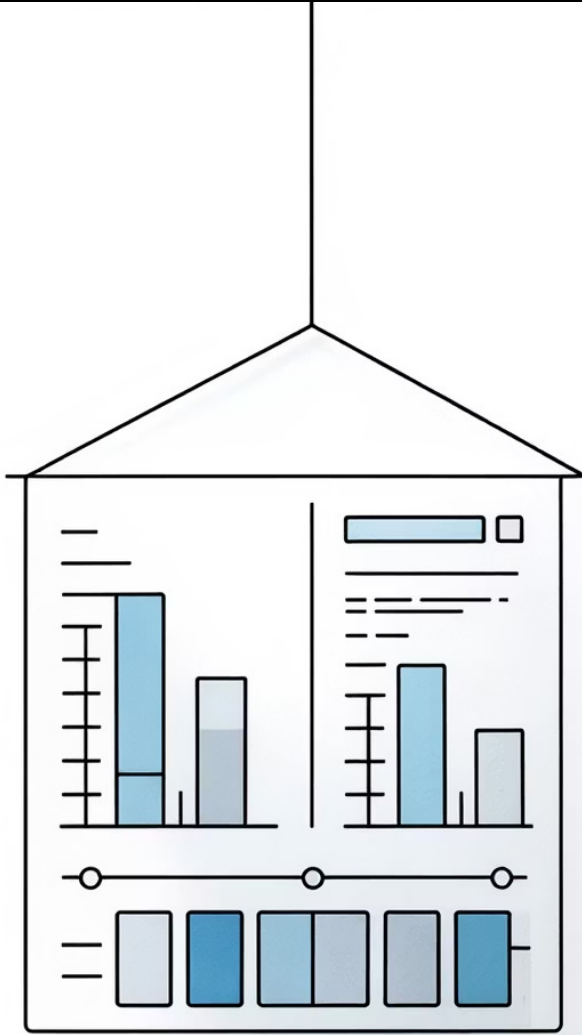


Produces misleading Key Performance Indicators (KPIs) for system availability and operational costs.

✗ **System-Level Maintenance Models** are essential. They must explicitly integrate interdependencies to accurately capture and mitigate these hidden risks, moving beyond isolated component perspectives.

# Consequences of Ignoring Dependencies

| Risk                    | Impact on Maintenance Planning                  |
|-------------------------|-------------------------------------------------|
| Underestimating urgency | Failures propagate faster — late interventions. |
| Cascading failures      | One fault overloads others, halting the system. |
| Misleading KPIs         | Availability overestimated at component level.  |
| Cost overruns           | Higher corrective costs and lost production.    |



# **Economic Trade- Offs in System-Level Maintenance**

# Economic Analysis of Joint vs. Separate Maintenance

## Cost Structure Analysis

The economic trade-offs in system maintenance can be quantified by comparing the costs of separate versus grouped interventions:

### Separate Maintenance Approach:

$$C_{\text{separate}} = \sum_{i=1}^n C_i = \sum_{i=1}^n (C_{i,\text{setup}} + C_{i,\text{parts}} + C_{i,\text{labor}} + C_{i,\text{downtime}})$$

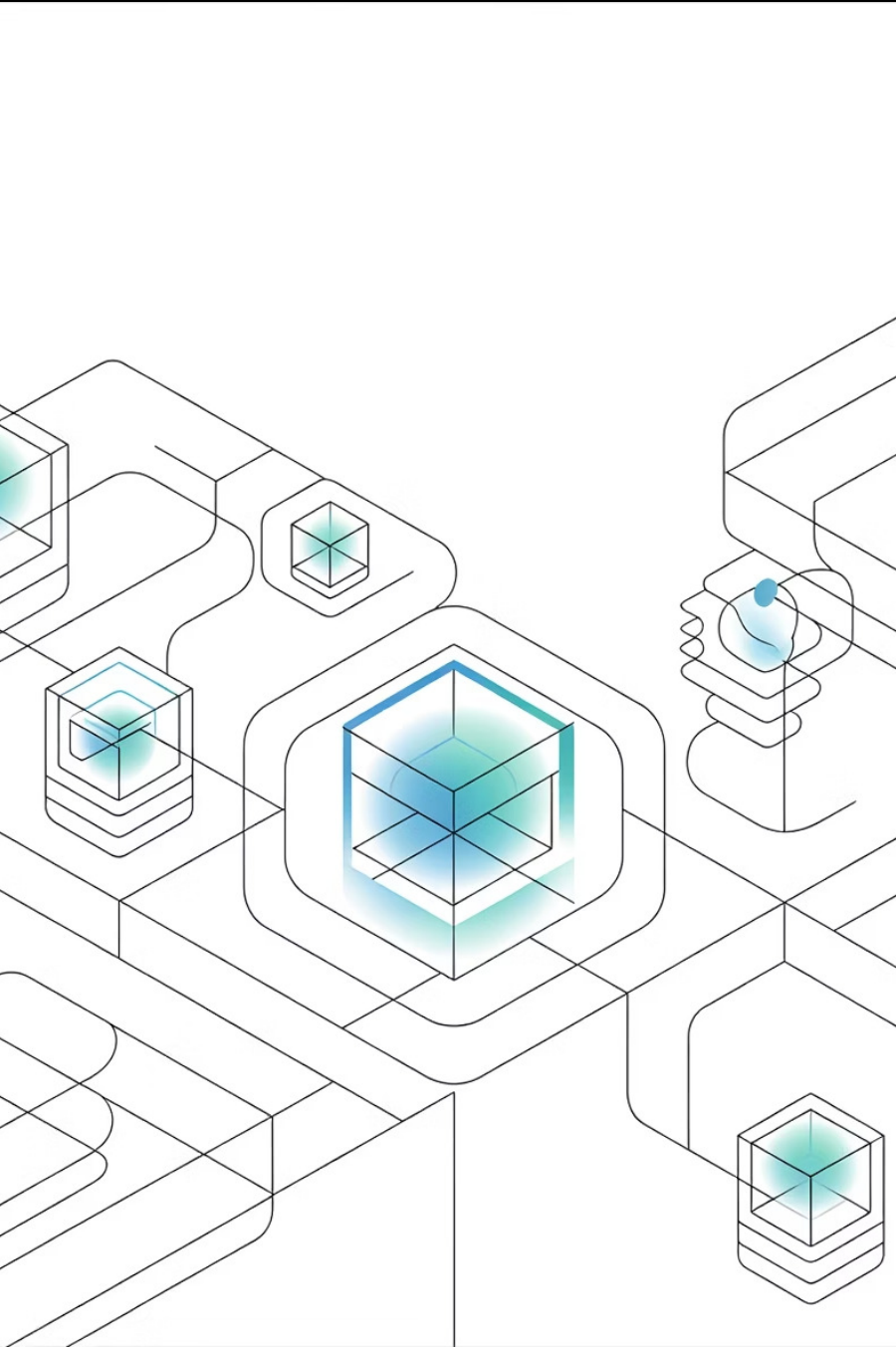
### Grouped Maintenance Approach:

$$C_{\text{group}} = C_{\text{setup}} + \sum_{i=1}^n C_{i,\text{marginal}} = C_{\text{setup}} + \sum_{i=1}^n (C_{i,\text{parts}} + C_{i,\text{labor}}) + C_{\text{downtime}}$$

The economic advantage of grouping arises from sharing setup costs and downtime across multiple maintenance activities. However, this advantage must be balanced against the potential cost of prematurely replacing components that still have remaining useful life.

### Factors Affecting Economic Decisions:

- **Setup Cost Ratio:** Higher setup costs relative to component costs favor grouping
- **Downtime Penalty:** Higher production loss costs favor grouping
- **Component Correlation:** Similar degradation patterns favor grouping
- **Skill Requirements:** Similar skill needs favor grouping



# **The Need for Advanced System- Level Models**

# Advanced Modeling Approaches



## System Structure Representation

Modern system maintenance models must capture complex structures beyond simple series-parallel configurations. Techniques include:

- **Reliability Block Diagrams (RBDs):** Graphical representations of system reliability structure
- **Fault Trees:** Top-down logical representations of failure paths
- **Petri Nets:** Mathematical modeling for concurrent system behavior

These approaches enable accurate representation of k-out-of-n systems, load-sharing structures, and standby redundancies that characterize modern engineering systems.



## Multi-Dimensional Dependencies

Advanced models must integrate multiple dependency types simultaneously:

- **Copula Functions:** For modeling stochastic dependencies between component lifetimes
- **Influence Diagrams:** For representing conditional degradation processes
- **Bayesian Networks:** For capturing complex causal relationships between components

These mathematical tools allow for more realistic representation of how components influence each other's degradation patterns in complex systems.



## Optimization Algorithms

Finding optimal system maintenance policies requires sophisticated computational approaches:

- **Genetic Algorithms:** For handling large solution spaces with complex constraints
- **Reinforcement Learning:** For adaptive policies that respond to changing conditions
- **Approximate Dynamic Programming:** For handling the "curse of dimensionality" in large-scale systems

These algorithms enable solution of otherwise intractable maintenance optimization problems that arise at the system level.



## Digital Twin Integration

The future of system maintenance modeling lies in digital twin technology:

- **Real-time Condition Monitoring:** Continuous updating of component health indices
- **Physics-based Simulation:** For predicting degradation propagation
- **Integrated Decision Support:** Combining maintenance optimization with production planning

Digital twins enable dynamic maintenance planning that adapts to evolving system conditions and operational requirements.

As we look toward the next lecture on grouping strategies, it's important to recognize that effective system-level maintenance requires sophisticated modeling approaches that capture the full complexity of modern engineering systems. The field continues to evolve, with increasing integration of artificial intelligence, Internet of Things (IoT) technologies, and advanced optimization algorithms that promise to further improve maintenance decision-making and system performance.