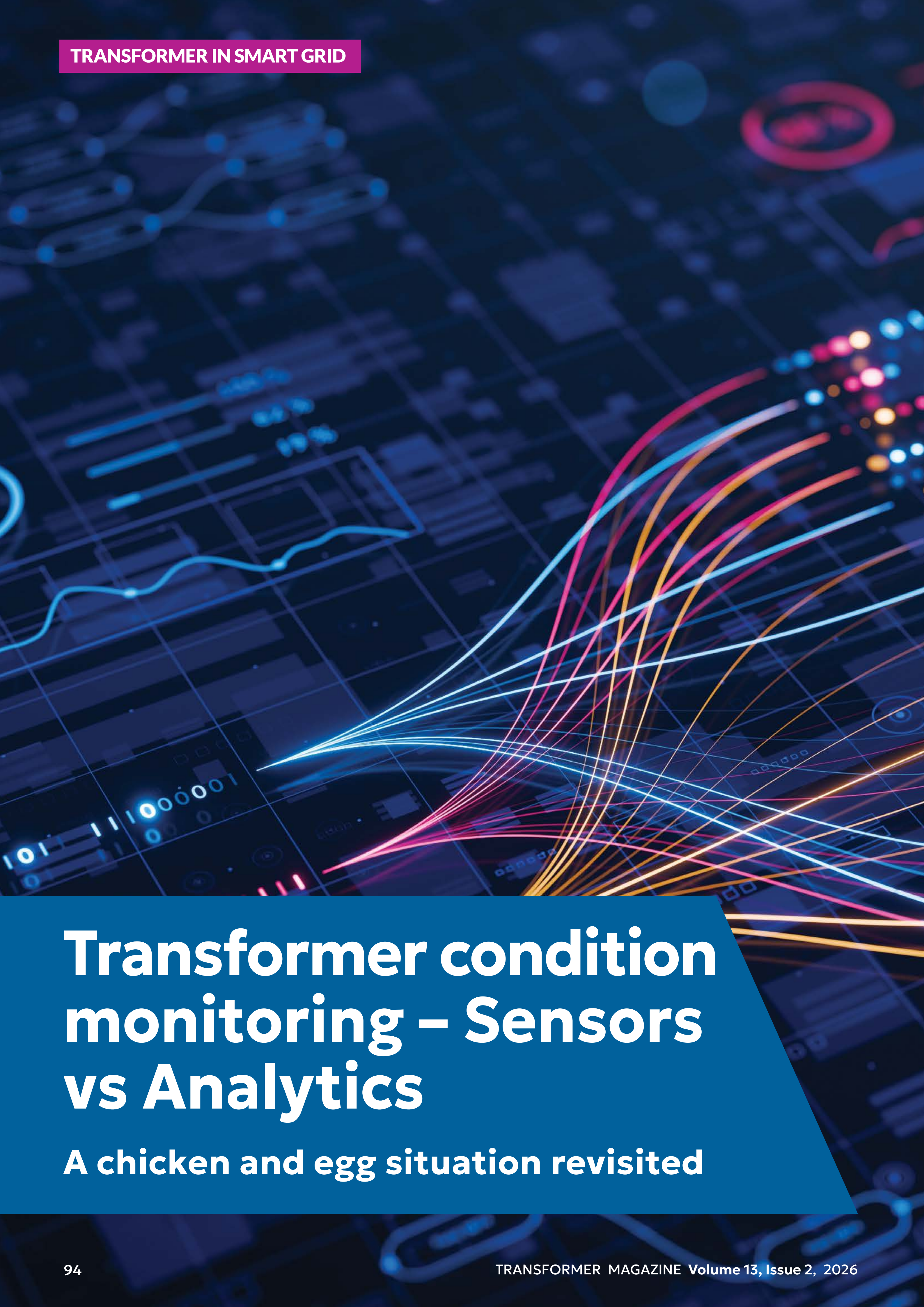
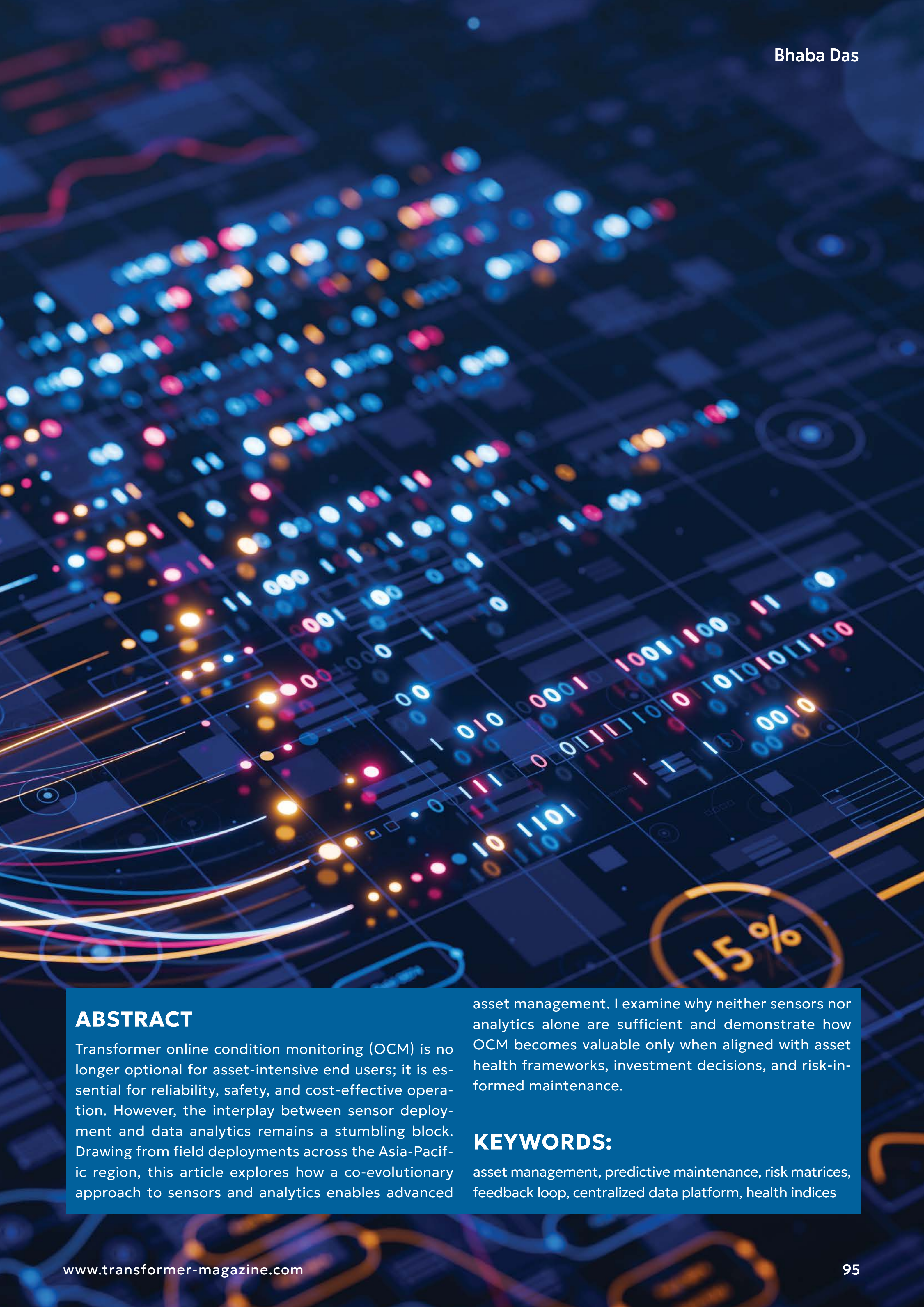


# Transformer condition monitoring – Sensors vs Analytics

## A chicken and egg situation revisited

Bhaba Das



## ABSTRACT

Transformer online condition monitoring (OCM) is no longer optional for asset-intensive end users; it is essential for reliability, safety, and cost-effective operation. However, the interplay between sensor deployment and data analytics remains a stumbling block. Drawing from field deployments across the Asia-Pacific region, this article explores how a co-evolutionary approach to sensors and analytics enables advanced asset management. I examine why neither sensors nor analytics alone are sufficient and demonstrate how OCM becomes valuable only when aligned with asset health frameworks, investment decisions, and risk-informed maintenance.

## KEYWORDS:

asset management, predictive maintenance, risk matrices, feedback loop, centralized data platform, health indices

Should end users deploy sensors first and figure out analytics later, or should they define analytics models and then procure sensors?

## 1. Introduction

Online Condition Monitoring (OCM) has matured significantly in the past decade, with a wide range of commercial sensors available for transformers, such as: Electronic Temperature Monitors (ETM), Dissolved Gas Analysis (DGA) units, Bushing, Tap Changer (OLTC), Partial Discharge (PD) monitors, and other sensors. Yet, during numerous customer engagements, I have witnessed a similar pattern: transformers have monitors installed, but asset managers are still making decisions based on time-based schedules, nameplate data, or gut feel. This reveals a disconnect not between people and technology, but between monitoring data and asset management processes.

Should end users deploy sensors first and figure out analytics later, or should they define analytics models and then procure sensors? What about establishing communications between sensors and the analytical model? How do they respond to alarms?

This article unpacks this dilemma and shows how the real answer lies in asset management-driven integration – the feedback loop.

### 1.1 Asset management in the context of transformers

Transformer asset management is the systematic coordination of practices that balance cost, performance, and risk across the transformer's lifecycle. For utilities and large industrial power users, transformers are not only capital-intensive but are also long-life, failure-critical components with major implications for reliability, safety, and regulatory compliance.

Asset management encompasses the entire lifecycle of a transformer as listed in Table 1:

Table 1. Transformer lifecycle phases: Asset management considerations

| Phase | Key considerations |
|---|---|
| Planning and procurement | Specification, cost, loading expectations, redundancy levels, design life, factory acceptance. |
| Installation and commissioning | Site condition verification, site acceptance tests, correct energization procedures. |
| Operation and monitoring | Online/offline diagnostics, real-time condition data. |
| Maintenance | Time-based vs condition-based decision maintenance, risk-based prioritization |
| Life extension | Refurbishment, derating, load shifting and others. |
| Replacement/disposal | End-of-life planning, recycling strategy |

Each stage involves trade-offs between technical health, economic cost, and operational risk, and OCM plays a growing role in optimizing those trade-offs. OCM is not asset management by itself, but it is a critical enabler.

OCM systems provide:

- Real-time insights into degradation mechanisms.
- Evidence-based support for repair vs replace decisions.
- Data continuity to validate and improve health models.
- Dynamic information to support loading decisions (e.g., solar variability, contingency ops).

But for this to be effective, sensor data must be processed through analytics and linked into decision frameworks, like transformer health indices, risk matrices, etc.

Sensor data must be processed through analytics and linked into decision frameworks, like transformer health indices, risk matrices, etc.

So, what decisions do end users want help with?

**Manage failure risk**

- Quantify the probability of failure (PoF) using analytics based on DGA, thermal trends, partial discharge, etc results from OCM.
- Link PoF with consequence of failure (CoF) e.g., grid impact, customer outage, environmental damage.

**Support cost-efficient maintenance**

- Complement periodic offline testing with predictive maintenance triggered by OCM data.
- Reduce unnecessary interventions while preventing catastrophic failures.

**Ensure regulatory and insurance compliance**

- Use OCM data to demonstrate proactive risk control.
- Reduce insurance premiums by demonstrating condition-based reliability.

**Enable informed investment planning**

- Justify transformer replacement based on actual degradation rather than age.
- Use digital health indices for capital budgeting and rate-case submissions.

**Maximize useful life**

- Extend transformer life through insulation preservation, cooling optimization, and load balancing.
- Use condition trends to delay capital replacement.

Transformer asset management is about much more than repair and replace. It is about making risk-informed, data-driven decisions over decades. OCM provides the pulse, but asset management is the decision-making brain. Only when both are connected can end users extract full value from their monitoring investments.

**OCM provides the pulse, but asset management is the decision-making brain, and only when both are connected can end users extract full value from their monitoring investments**

## 2. My experience in the Asia Pacific

### 2.1 The sensor-heavy approach: What happens in the field

In many Asia-Pacific end users, the initial push for condition monitoring is driven by the installation of sensors, field trials, proof of concept, etc. This often leads to the installation of:

- Predominantly, multi-gas DGA sensors
- In some cases, bushing monitors
- Top oil and winding temperature sensors
- PD monitoring is requested, but implementation is still far from ideal.

This approach is usually pursued because:

- Ease of procurement: Turnkey projects include sensors by default; minimal internal effort needed.
- Perceived risk reduction: Installing sensors is seen as a visible form of “doing something” to improve reliability.
- Vendor recommendations: Original equipment manufacturers (OEM) promote their monitoring packages as part of asset lifecycle service agreements.
- Insurance or regulator pressure: Premium discounts or compliance may drive sensor installations.

Yet in multiple instances, I have seen end users unable to answer a basic question: *What actions have been taken in the last 12 months based on OCM data?* The majority answer is that we don’t have communication with the device established to investigate the data, we don’t have dedicated asset management engineers, and the fragmented vendor ecosystems prevent us from having a common dashboard.

In one end user I visited in Southeast Asia, over 30 transformers had online DGA monitoring installed. Yet only two asset managers were responsible for re-

**Without appropriate data infrastructure, analytics tools, and asset management integration, sensor-heavy approaches often lead to disappointing returns on investment**

viewing all alerts, leading to months-long delays in response and missed warning signs in at least one actual failure case.

In another site, a solar farm's Generator Step Up (GSU) transformer had fibre optic temperature sensors installed, but the temperature data was not used for dynamic loading decisions because no one had developed a model to translate hot-spot data into safe dynamic limits!

#### 2.1.1 The resulting gaps

Without appropriate data infrastructure, analytics tools, and asset management integration, sensor-heavy approaches often lead to disappointing returns on investment. Key challenges include:

- Operational data overload: Operators receive more alarms than they can realistically triage. Which alarms are critical, which are optional, and which are not well defined. This leads to alarm fatigue.
- Lack of contextualization: Raw values are not linked to transformer loading, location, or risk profiles. Online sensors sometimes provide incorrect readings due to issues in sensor systems.
- Poor return on investments (ROI) justification: OCM investment is seen as a nice-to-have rather than a reliability tool.
- Lack of operational buy-in: Field and maintenance teams usually do not trust or understand what OCM data means. Condition insights are ignored. Manual override of alarms or bypassing of sensors happens in practice.

The sensor-heavy approach is not inherently flawed, but without a strategic framework that includes data interpretation, decision-making processes, and integration into asset risk models, its value remains largely unrealized. Sensors alone don't improve reliability; decisions based on their outputs do.

### 2.2 The analytics-first approach: Incomplete without sensors

The analytics-first approach starts with the development of models, algorithms, or condition indices, before real-time monitoring systems or sensors are in place. While this strategy can demonstrate thought leadership and long-term planning, it often runs into practical and structural limitations during implementation. Analytics first approach is usually pursued because:

- Data availability: Historical offline test results (DGA, oil quality, IR scans, load records) already exist.
- Fleet-wide analysis: Enables high-level prioritization across a large population of assets.
- Decision Support: Offers a preliminary basis for replacement deferral,

refurbishment, or maintenance prioritization.
- Budget constraints: Analytical models are seen as a lower-cost entry point compared to full-scale OCM deployments.

**The analytics-first approach starts with the development of models, algorithms, or condition indices, before real-time monitoring systems or sensors are in place**

In one project I was involved in, an asset manager built a transformer remaining useful life (RUL) model based on oil test data. But due to test intervals (3-4 years) and missing key trends such as variation in temperature, moisture, etc, the RUL model did not meet the intended objective and was eventually discarded.

### 2.2.1 The resulting gaps

The analytics-first approach carries structural and operational limitations that can reduce its effectiveness if not addressed:

- Low resolution and delayed data: Offline testing lacks the temporal granularity to detect rapid deterioration or sudden dissolved gas spikes.
- Lack of real-time validation: Predictions cannot be verified or corrected by live events, leading to uncertainty in model accuracy.
- Exclusion of dynamic factors: Models often omit or simplify actual transformer loading, ambient variation, and even tap changer operations, key contributors to issues.
- Generic thresholds and assumptions: Reliance on static guidelines (e.g., DGA limits from standards) leads to fleet-wide assumptions that don't reflect individual unit histories.
- Limited stakeholder trust: Operators and field teams may question outputs as they cannot link them to live conditions or visible equipment behaviour.
- Missed opportunities for early warning: Without real-time sensing, fast-developing faults (e.g., electrical arcing) may be discovered too late for cost-effective intervention.

The analytics-first approach can be a strong starting point for transformer fleet modernization, but only when viewed as a transition phase, not an end state. Without integration with OCM, its predictive power is limited, and its outputs risk being disconnected from real-world asset behaviour.

## 2.3 Fragmented vendor ecosystems in transformer monitoring

As transformer condition monitoring systems evolve, many utilities and industrial asset owners find themselves grappling with "fragmentation" - a situation where different transformers, substations, or system components are monitored using sensors and platforms from multiple, incompatible vendors. This fragmentation creates barriers to consistent analytics, centralized risk tracking, and strategic asset management.

Fragmentation typically results from procurement patterns, not technical design:

- Procurement diversity: In theory, procurement diversity has valid and strategic objectives: competitive pricing, supply chain resilience, and flexibility. However, without clear synergy, they create a patchwork of incompatible systems.
- Open-ended specifications: When transformer specifications are open-ended, the purchase includes different vendor OCM systems depending on the lowest cost of monitoring equipment.
- Project-based procurement: EPC contractors choose sensors independently, often based on the lowest cost or local availability.
- Legacy integration attempts: Older transformers retrofitted with sensors using proprietary protocols.

For many end users, this leads to a fleet of transformers where no two units are monitored in the same way, thus creating inconsistency in data quality, format, accessibility, and interpretation.

### 2.3.1 The resulting gaps

- Multiple dashboards, no central visibility - Different vendor portals for DGA, thermal, OLTC, or PD data. Operators must log into separate systems per site or vendor. This makes it hard to build fleet-wide condition maps!
- Higher training and maintenance burden - Field and operations staff must be trained on different systems. This leads to spare parts, support contacts, and documentation varying across vendors.
- Inconsistent data formats and protocols - Data normalization becomes difficult, requiring middleware or custom interfaces.
- Limited interoperability with analytics platforms - OCM data can't be easily ingested by enterprise analytics tools. Sometimes, a lack of Application Programming Interface (APIs) or export features blocks integration.

In one end user I interacted with, the asset health manager had access to four different dashboards for monitoring just 20 transformers with DGA monitors. None of the systems shared a common interface, and each vendor used different alarm thresholds for "high" gas levels, making it impossible to standardize alerts. As a result, asset risk scoring had to rely on outdated offline test data instead of the real-time OCM systems already installed!

**Fragmentation leads to a fleet of transformers where no two units are monitored in the same way, thus creating inconsistency in data quality, format, accessibility, and interpretation**

The reason "diversity in procurement" - particularly in the context of OCM

**When not aligned with a broader asset management or analytics strategy, diverse procurement can unintentionally lead to data silos, integration headaches, and diluted insights**

systems is often seen as a mark of competitive sourcing and commercial neutrality. However, when not aligned with a broader asset management or analytics strategy, diverse procurement can unintentionally lead to data silos, integration headaches, and diluted insights, as highlighted above.

### 2.4 Procurement diversity

Procurement diversity means sourcing OCM solutions which includes hardware, software, integration, and services from a variety of suppliers with differing capabilities, ownership backgrounds, sizes, and regions. This approach strengthens resilience and promotes innovation. In theory, these are all valid and strategic objectives. However, without clear guidelines on the goal, they can create a patchwork of incompatible systems.

Some of the perceived advantages are listed in Table 2:

#### 2.4.1 The resulting gaps

- Integration complexity: Different sensors use different communication protocols and data formats (Modbus, DNP3, IEC 61850, or vendor-specific protocol). Building a unified analytics layer becomes technically challenging and costly.
- Uneven data quality: Sensor calibration, resolution, and accuracy vary across vendors, making it hard to benchmark fleet-wide health.
- Alarm and threshold inconsistency: Gas limits, thermal models, and criticality scoring vary, leading to inconsistent responses for the same technical condition.
- Training and support overload: Maintenance teams must learn and maintain multiple systems and interfaces. Spare parts and vendor support contacts multiply!
- Reduced predictive power: Predictive models rely on consistent data structures. Inconsistent sensor types make fleet-wide machine learning (ML) or statistical analysis weaker.

Procurement diversity should not be confused with strategic flexibility. While allowing choice and innovation is important, a successful transformer asset management requires controlled standardization, strong integration policies, and procurement processes that serve long-term asset health goals. Asset managers must work closely with procurement and engineering teams to ensure that every new sensor or system contributes meaningfully to the fleet-wide monitoring vision.

Table 2. Advantages of procurement diversity

| Advantage | Description |
|---|---|
| Competitive pricing | Keeps vendors honest and avoids monopolistic pricing models. |
| Access to innovation | Newer or niche players may offer advanced technologies. |
| Supply chain resilience | Avoids over-reliance on one vendor for spares, support, or upgrades. |
| Project flexibility | Allows customization based on geography, asset criticality, or environmental conditions. |

## 3. The feedback loop

Modern transformer OCM is not just about observing asset behaviour it's about establishing a closed feedback loop between monitoring, decision-making, and asset action. The feedback loop provides a framework for achieving continuous improvement in transformer reliability and asset performance through interconnected data, analytics, and operations.

The "feedback loop" in asset management represents a cyclical, real-time relationship between:

1. Data collection (sensors): Online and offline measurements (e.g., DGA, moisture, temperature, partial discharge)
2. Data interpretation (analytics): Models that assess risk, trend degradation, and classify failure modes
3. Asset decision-making (asset management): Maintenance, life-extension, replacement, or loading decisions
4. Operational and strategic action: Execution of work orders, capital planning, grid operation adjustments
5. Feedback into monitoring strategy: Sensor recalibration, model refinement, and future specification improvements

This loop ensures that data is not the end-product, but a means to refine how we operate and manage transformers!

Many transformer fleets operate in open-loop mode due to:

- Procurement diversity creating silos.
- Fragmented vendor systems (no centralized data ingestion).

**When end users close the loop between sensors, analytics, and action, they unlock the full potential of digitalization of transformers.**

- No formal process to integrate OCM insights into maintenance planning.
- OCM seen as “alarm generators” instead of decision enablers.
- Analytics outsourced with no learning loop to improve analytical models.

In such cases, the OCM system becomes informational, not transformational, and is a missed opportunity.

**While allowing choice and innovation is important, a successful transformer asset management requires controlled standardization**

### 3.1 Enablers of the feedback loop

To implement this model effectively, several key capabilities are required:

- Cross-functional teams: Procurement, asset managers, maintenance planners, and data analysts must work in tandem.
- Centralized data platform: All sensor and offline data must feed into one ecosystem, enabling correlation and learning.
- Event and outcome tracking: Maintenance outcomes, asset failures, and operational responses must be recorded and analysed to improve models.
- Closed-loop integration: Output from analytics tools must connect to Enterprise Asset Management (EAM), or strategic investment platforms.
- Feedback policies: Establish formal processes to review OCM insights, update risk models, and align monitoring upgrades.

The feedback loop elevates condition monitoring from passive data collection to active asset governance. When end users close the loop between sensors, analytics, and action, they unlock the full potential of digitalization of transformers. Without this loop, even the most sophisticated monitoring tools become underutilized (and expensive) diagnostic accessories.

## 4. Unlocking the full value

Based on my engagement and analytical work across various end users in the Asia Pacific region, some of my recommendations would be:

- Start with asset objectives, not just sensor specs.
- Don’t install more sensors than you can process.
- Integrate OCM with EAM and financial systems.
- Use analytics to justify every step: upgrades, replacements, maintenance.
- Treat condition data as a living input, not a reporting formality.
- Train operators on interpretation - Alarms need to be contextualized, not just acknowledged.

Following CIGRE Study Committees A2 (Transformers) and D1 (Materials & Diagnostics), which are increasingly focused on:

- Asset management alignment with OCM.
- Standardizing health indices based on real-time data.
- Digital twins for aging assets.
- Linking diagnostics with reliability-centred maintenance (RCM).

> The chicken-and-egg dilemma of sensors versus analytics in transformer monitoring is resolved only when viewed through the lens of asset management

As the global energy landscape evolves, CIGRE continues to play a pivotal role in shaping the direction, consensus, and knowledge-sharing surrounding transformer OCM, diagnostics, and asset management. Through its Study Committees, Working Groups, and international symposiums, CIGRE provides an independent and deeply technical platform that connects utilities, manufacturers, academics, and technology providers.

CIGRE is well-positioned to lead the industry in:

- Defining interoperability frameworks for multi-vendor OCM systems.
- Promoting cross-disciplinary collaboration between electrical engineering and data science.
- Publishing evidence-based ROI metrics from long-term OCM deployments.
- Enhancing tools for fleet-level asset health visualization and predictive maintenance.

By continuing its mission to promote technical excellence and neutrality, CIGRE remains essential in helping the industry navigate the evolving transformer monitoring landscape ensuring that both sensors and analytics deliver real value to asset owners.

Industry publications such as ***Transformer Magazine*** play a critical complementary role in disseminating applied knowledge, accelerating innovation visibility, and fostering global dialogue in the field of transformer OCM. ***Transformer Magazine*** has become a go-to resource for transformer professionals, providing a unique mix of:

- Peer-reviewed technical articles.
- Vendor-neutral case studies.
- Interviews and opinion pieces.
- Market trend analysis and CM technology overviews.

In the domain of OCM, this publication provides a practical lens on emerging techniques, system implementations, and commercial evolutions that may not yet be codified in standards or CIGRE brochures. It has helped democratize access to innovation, particularly for mid-sized utilities and asset owners who may not have the resources to participate directly in international working groups. As condition monitoring moves from an engineering concern to a strategic business function, the role of industry media will be even more critical in supporting the transition.

> Industry publications such as Transformer Magazine play a critical complementary role in disseminating applied knowledge

## 5. Conclusion

The chicken-and-egg dilemma of sensors versus analytics in transformer monitoring is resolved only when viewed through the lens of asset management. Sensors without analytics provide noise; analytics without sensors lack grounding. The debate between deploying sensors first or developing analytics first is no longer binary.

In my experience, success lies in treating condition monitoring as an evolving system. Sensors generate the signals, but analytics give them meaning. A feedback loop approach: where early data informs analytics, and analytics justify actions, ensures both technical performance and financial returns. As transformer fleets age and grid complexity increases, this co-evolution is not just preferable, it is essential.

While OCM holds great promise for improving transformer asset management, the reality in many end-user environments reveals a range of technical, operational, organizational, and financial barriers. Without proper integration into asset management, analytics platforms, maintenance workflows, and organizational culture, even the most advanced OCM tools will fail to deliver value.

CIGRE Study Committees and International Working Groups are already pushing for increased interoperability and standardization of OCM systems, recognizing some of the biggest obstacles to effective asset management. Industry publications such as Transformer Magazine play a critical complementary role. ■

PEER REVIEWED

### Author

**Dr. Bhaba P. Das** is the Regional Manager (Asia Pacific) for Dynamic Ratings Australia, based in Wellington, New Zealand.

He is a Senior Member of IEEE, Young Professional of IEC, Member CIGRE NZ A2 panel, Member of Engineering New Zealand and Executive Editor of Transformer Magazine. He has published 40+ technical articles in various peer reviewed international journals and magazines. He has three patents in New Zealand & Australia related to condition monitoring. He has been awarded the best author of 2023 by voters of Transformer Magazine, a leading worldwide publication on transformers.

He has previously worked at Hitachi Energy Transformers Business Unit in Singapore & ETEL Transformers Ltd in Auckland, New Zealand. He has completed his PhD in Electrical Engineering from the University of Canterbury, New Zealand and Bachelors Degree in Electrical Engineering from University of Gauhati, Assam, India.