Integrated Governance Model for Industry 4.0 Data Centers

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Abstract

Digital transitions are revolutionising industrial processes and services offered. The new arrangements introduce new risks across the entire value chain domain from planning to supply, production and delivery of services. State-of-the-art Enterprise Risk Management (ERM) provides the necessary elements to cover risk domains associated to cyber-physical systems interconnected by the operating technology in concert with Information Technology under Industry 4.0 paradigms Control mechanisms from ERM needs new support structure provided by the Data Centre Governance principles, in particular those linked to data quality, security, privacy and stewardship, for a coherent data preparation and management able to deliver the correct and timely analytics supporting the decision making.

The effort synthesises the integrated Enterprise Risk and the Data Centre Governance Framework, integrated with data quality requirements, applying the two best practice domains to the Industry 4.0 era. The underlying concept defined a layer governance structure able to cover day-to-day operate in the production/service delivery sites and the strategic management levels for the application to any organisation supporting the integrated risk management approach. The set of guiding principles is outlined consequently. Grounding elements are drawn from literature sources, the originals support description from the Centre for Internet Security, the Industrial Internet Consortium guiding principles and recommendations, five case studies of Industry 4.0 environments for Manufacturing and the integration of cloud technologies in data centres. The resulting work delivers an integrated structure capable to capture coherent data from the production/service area and to deliver the correct analytics behind the ERM risk management for any Industry 4.0 context.

Keywords: Enterprise Risk Management (ERM), Industry 4.0 Risk Systems, Data Center Governance, Cyber-Physical Risk Management, IT-OT Integration, Digital Risk Transformation, Data Quality Governance, Data Stewardship Models, Risk Analytics Frameworks, Operational Risk Management, Industrial Data Governance, Risk-Based Decision Systems, Integrated Risk Frameworks, Manufacturing Risk Analytics, Cloud-Integrated Risk Systems, Strategic Risk

Governance, Layered Governance Models, Industrial Cybersecurity, Data-Driven Risk Management, Industry 4.0 Governance.

1. Introduction

Increased dependence on digital technologies creates opportunities as well as risks for organizations. Cyber-attacks, data breaches, and disruptions of digital supply chains are just some of the increasing threats faced by organizations in all industries. The traditional approach of treating these different kinds of risk in isolation at best results in a partial view of the risk landscape. An integrated approach is essential and Enterprise Risk Management (ERM) provides the appropriate framework. However, applying the ERM process to a modern organization is not straightforward. Implementing this framework in a complex organization with a combination of operational technologies (OT) and information technologies (IT) requires careful thought. Organizing these risks at a strategic level, as proposed in the governance layer, provides a valuable blueprint for coordination.

Realizing this value is also essential in the transformation of the conventional industrial world toward Industry 4.0. Three key trends shape Industry 4.0: (1) The continuing convergence of the physical and digital worlds enables the tracking and monitoring of physical assets with unprecedented levels of granularity and detail; (2) The digital transformation and connectivity of factories and production systems create new opportunities for data collection and analysis; and (3) The growing usage of services within manufacturing companies is driving a change in focus toward the underlying supply chain and supplier risks. The literature also identifies OT/IT convergence as an important trend for Industry 4.0. These trends create new categories of cyber and information risks for organizations that are using Industry 4.0 technologies, which provide new directions for the improvement of ERM in these settings.

2. Theoretical Foundations of Enterprise Risk Management in Industry 4.0

Generating knowledge assets and achieving economic benefits through investments in data processing and management require an integrated approach to risk management across the entire enterprise, including the Data Center. Existing information systems in organizations constantly evolve in response to market trends, technological advances, changes in legislation, or customer requirements. These changes determine the participation of the Data Center in interconnected processes and the impact on other organizational processes. The introduction of

Cyber-Physical Systems (CPS) and the convergence of operational and information technologies (OT/IT) increase exposure to additional risk threats. Furthermore, the optimization of supply chains requires the ubiquitous movement of data. Risk management in this context must be connected with the use of these systems in supporting decision-making. Risk exposure, threat factors, and the risk assessment process must therefore connect with the decision-making process.

Foundational components of Enterprise Risk Management (ERM) in Industry 4.0 are examined. Enterprise risk space is presented as a source of risk-facing action for organizations. The development of an ontology of enterprise risk registers enables industry players to analyze risk exposure. The extension of the ERM process allows for appropriate risk assessment mapping and benchmarking of the register. Empirical evidence from aspects related to risk in smart industry environments provides further validation. Research topics within topical risk areas are proposed for further exploration.

2.1. Risk Taxonomies and Ontologies for Smart Industries

Taxonomies and ontologies for risk assessment and management, specifically for Industry 4.0, address the need for a holistic consideration of the Enterprise Risk Management (ERM) domain. Risk taxonomies group risks according to categories such as domain, impact, likelihood, and control mechanisms. A risk ontology maps the relations between categories and their properties and attributes. While standard ontologies exist for various components or for parts of ERM systems, an integrated ontology for the complete ERM domain does not yet appear to be in use for smart industries. This section therefore identifies the need for taxonomies and ontologies that encompass the complete Enterprise Risk Management domain and contribute to a comprehensive and integrated view of risk management for smart industries.

Although the focus is on smart industries, the development also offers an integrated ontological representation of risks for any modern enterprise. The development follows the principles of modern data governance: Data Governance comprises the processes and responsibilities that ensure the quality and protection of data used across the enterprise. Effective governance ensures appropriate access to data, its accuracy and completeness, its proper lineage, and compliance with data privacy laws and policies.

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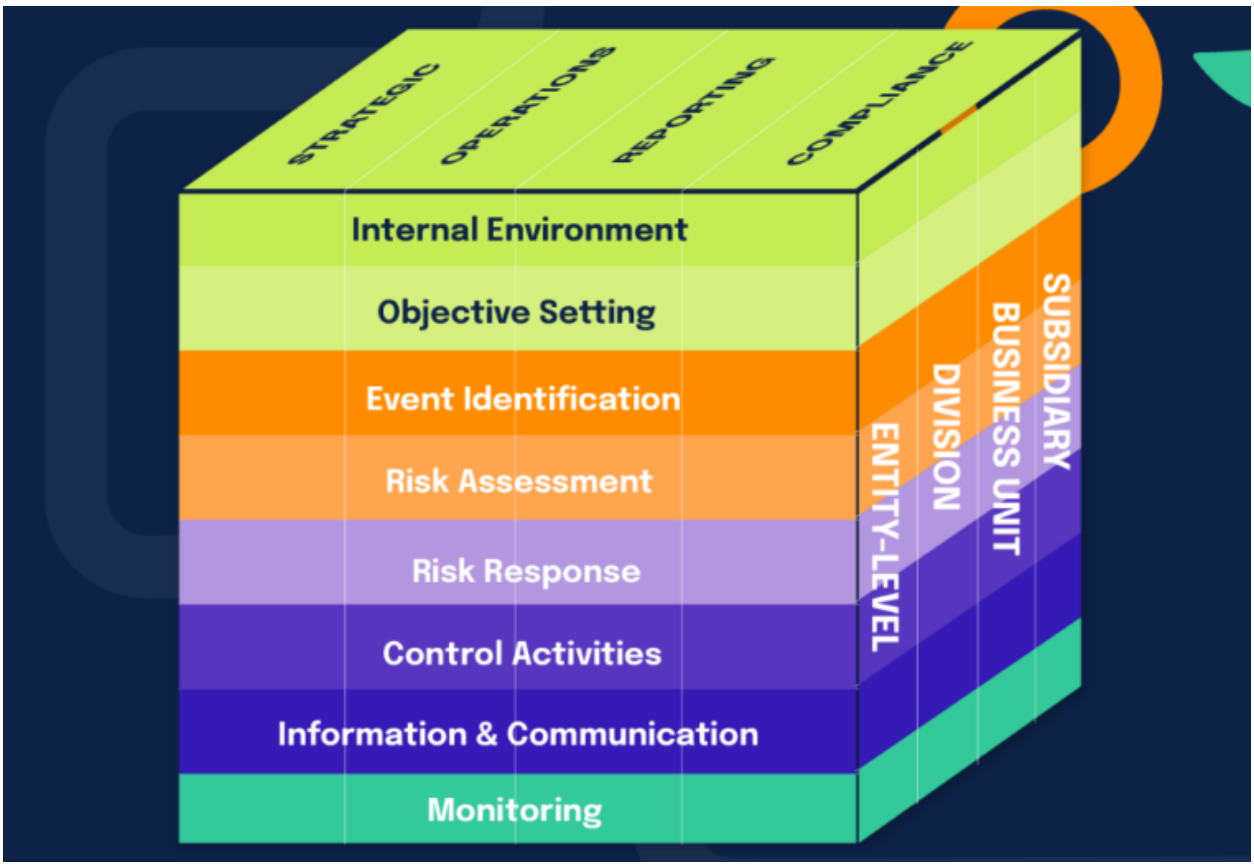

Fig 1: Enterprise Risk Management

2.2. Data Governance Principles in Modern Data Centers

In modern data centers, where data is the primary product, service, and unique distinguishing feature of a provider, enterprises must ensure that data is efficiently delivered, consistently managed for quality, protected from deliberate and unintended actions or errors, and retained for a defined period of time consistent with applicable laws, rules, and regulations. A data governance framework seeks to do all of the above, and five governing elements enable best-practice data governance, entrusted with responsibility for these elements ensures that the data center is managed as an asset, and have optimal quality as a product and service offering.

Data Quality, Data Quality governs the quality characteristics of the data management and delivery processes. Data Quality orchestrates automated controls close to the point of data creation or use. Data quality Work Products define the quality properties required of the data managed and delivered by a data center, such as Information/Data Classification, Information Sharing Agreements, Metadata, Privacy Impact Assessments and Privacy Notices, a Data Quality Plan, Data Flow Interdependencies Diagrams, Data Quality Assurance and Control Requirements, Data Quality Strategy and Guidelines. Data Lineage, Data lineage governs the sources and history of data and the systems that require or create that data. Data lineage determines the path that the data must follow to fulfil a business requirement and delivers logical representations of that data path. Data lineage Work Products enable audit activities to trace the lineage of data elements, such as Data Origin Maps, Data Requirements Traceability Matrices, Data Lifecycle Models and Data Lineage Diagrams. Data Access, Data access governs who can use which data, when and under what conditions. Data access establishes the rights required, acts to fulfil those rights, and determines the mechanisms through which the access is delivered. Data access Work Products define Data Access controls that protect data from accidental and deliberate damage, loss or disclosure, data access Work Products include.

An access control framework, an Information Sharing Framework, a Data Access People Contract for People with Access Privileges, and Access Permissions Templates for Data Transaction Applications and Data Query Applications. Data Stewardship, Data stewardship oversees the other elements, fulfilling the responsibilities entrusted to ensure that each applies its risk-management and control processes effectively. Data stewardship also owns any data that is a sub-product of the data center, for example as residual data from data encryption processes. Data stewardship Work Products include Data Stewardship Plans, Training and Awareness Plans for Data Users, Data Stewardship Templates for Data Ingest, Data Functional Ownership Responsibilities and Data Service Delivery Lifecycle Responsibilities. Data Privacy, Data privacy assures that the information entrusted to an organization’s care, control and custody is protected in compliance with local privacy laws and regulations. Data privacy Work Products govern privacy-impact assessments, privacy notices for data subjects and privacy notifications for application users.

Equation 1. Basic risk score

Step 1: Define variables

Let

- L = likelihood score
- I = impact score

Usually both are on a scale such as 1 to 5.

Step 2: Combine them

If a risk becomes more likely, risk goes up.
If a risk becomes more severe, risk also goes up.
The simplest and most standard joint effect is multiplication:

$$R = L \times I$$

Step 3: Interpretation

If $L = 4$ and $I = 5$,

$$R = 4 \times 5 = 20$$

3. Methodology

Industry 4.0 governance rests on three pillars: supporting the overall strategy; integrating Enterprise Risk Management with data center resilience; and fostering the adoption of new technologies. The architecture defines the accountability structure, spanning a strategic layer that enables stakeholder oversight of the full risk profile and operational layers responsible for day-to-day mitigation activities.

The strategic governance layer establishes the policies and decision portfolio that enable stakeholder oversight of long-term risk management. The wide-ranging scope requires the

involvement of several enterprise functions, each responsible for a specific risk domain. Function heads have the authority to approve control-related investments and development initiatives within their remit. Portfolio-level decisions pose escalation paths where control paths cross functional borders or exceed limits. Specific roles for adopting new technologies—digital twins, models of a smart industry, and analytics for OT—help maintain focus in areas of strategic importance. Governance enables the organization to remain adaptable amid continuous transformation.

Data center design and operations are affected by all these trends, and a separate operational governance layer enforces an extended set of controls and processes. These cover day-to-day operations, incident response, and compliance with audits and regulations. High-level Remediation and Assurance Processes direct actions in response to specific risk-scoring outcomes or Data Quality Control scorecards.

Table 1. Core governance structure

Layer / Component	Main purpose	Main functions	Main outputs
Strategic Governance Layer	Long-term oversight of enterprise-wide risk	Risk appetite, tolerance, policy, portfolio decisions, escalation, investment direction	Policies, approved controls, strategic priorities, oversight decisions
Operational Governance Layer	Day-to-day execution of controls and response	Incident handling, compliance, monitoring, resilience operations, tactical adjustments	Alerts, mitigation actions, recovery actions, audit readiness
Data Governance Enablers	Ensure trusted data for decisions	Data quality, lineage, access, stewardship, privacy	Reliable data, traceability, controlled access, privacy compliance
Industry 4.0 Execution Context	Operational environment where risks occur	CPS, OT/IT convergence, telemetry, analytics, supply	Real-time signals, business services,

Layer / Component	Main purpose	Main functions	Main outputs
		chain integration, cloud/data center integration	production continuity, analytics support

3.1. Governance Layer for Strategic Oversight

Defining a layered structure for Enterprise Risk Management (ERM) helps integrate all risk domains, synchronizing controls and responding to risk drivers. A governance layer provides oversight and maintains strategic perspective. Senior decision-makers should establish the risk appetite and risk tolerance thresholds necessary for the organization to achieve its strategic targets. Controllers can then align the consolidated ERM portfolio with the strategic objectives and drive investments into controls that deliver the intended results.

The governance layer enables a long-term focus on risk issues and effective escalation of emerging threats and opportunities. Escalation paths ensure that decision rights are assigned to the appropriate governance body for each class of risk. For example, the board of directors might delegate liability-covering activity authorizations to an audit or risk committee, while other strategic investments are referred to an investment or portfolio committee. Operationally, this layer might task a risk management committee with monitoring processes and controls and availing guidance on risk assessment during the day-to-day operation of the integrated framework. A project management office could likewise be formed to consolidate responses to the most strategic risk issues at the portfolio level.

4. Objective of the Study

Industries adopt modern practices mainly to reduce production and operational costs, and to accelerate production without sacrificing quality and accuracy. An integrated risk management approach drives modern Industry 4.0 manufacturing, where dangers arise from cyber-physical systems, IT/OT convergence, and extended supply chains. However, organisations struggle to manage enterprise risk, and to combine data centre governance and risk management. Integrated risk management must also include data centre capabilities.

The study develops an Integrated Enterprise Risk and Data Centre Governance Framework for Industry 4.0 Environments, composed of three elements and achieving five

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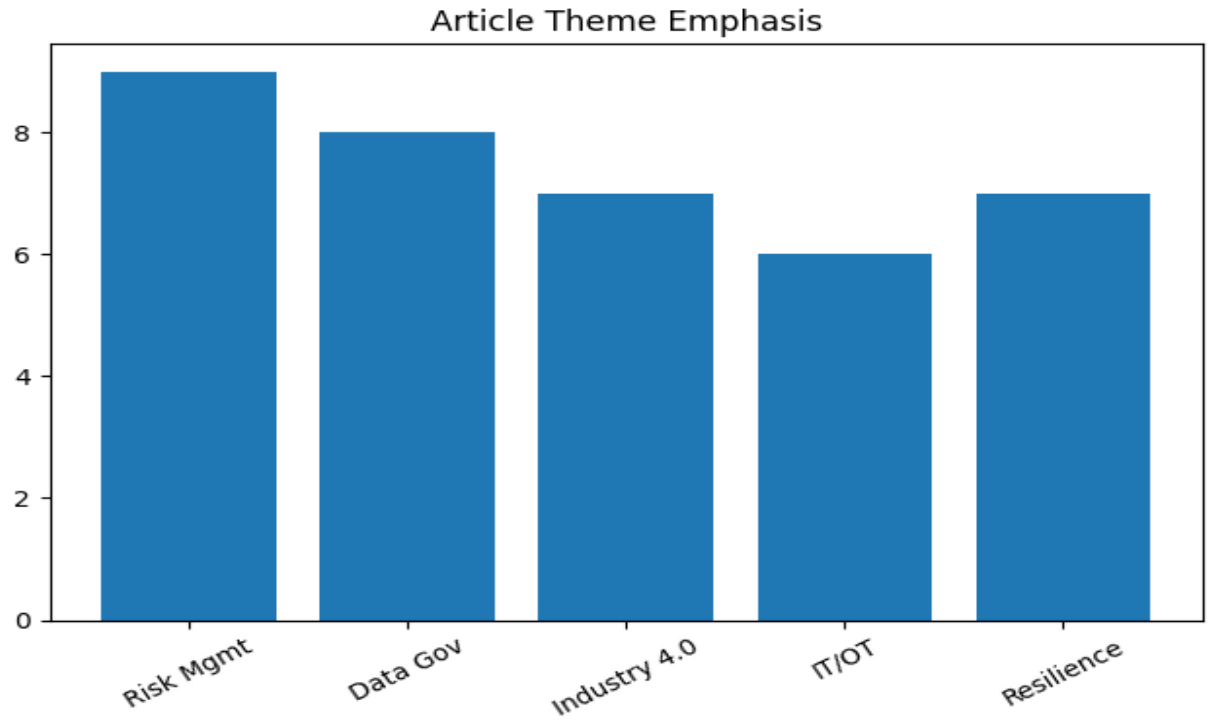
objectives. Seven research questions address Industry 4.0 components, and risk management requirements for data centres supporting Industry 4.0. The study proposes five hypotheses, success is defined in terms of academic and managerial contribution, and an integrated framework architecture aligns with scholarly guidance.



4.1. Aims and Goals of the Research

The objectives of the research are stated concisely, specifying the study's aims, the hypotheses driving the analysis, criteria for success, and expected contributions to theory, practice, and society. The overarching aim is to develop a governance architecture supporting the integrated management of risk in Industry 4.0 environments, with a layered structure encompassing strategic oversight, tactical monitoring, and operational execution of risk programs across multiple domains.

The first aim centers on conceptualizing an Integrated Enterprise Risk and Data Center Governance Framework. Supporting research questions examine how the framework allows risk management processes to be carried out in a coordinated and effective manner across the specific risk domains identified. The main hypothesis asserts that the absence of a holistic view and extended data center automation inhibits dynamic management of the wide variety of risks present in Industry 4.0 environments. Evidence gathered during the investigation shows that the combination of Cyber-Physical Systems (CPSs), different levels of Operational Technology (OT) and Information Technology (IT) convergence, and complex Supply Chains makes situational awareness even more transient and changeable. Therefore, the capacity of an organization to manage risk must also be dynamic.

Success is gauged through the definition of a risk governance architecture that supports the proper integration of controls over a wide variety of risk domains, supplemented by evidence from literature and real-life case studies. Expected contributions provide specific insights for the areas of governance, risk management, and Academy–Industry collaboration, as well as offering general indications concerning public safety, education, and sustainable development.

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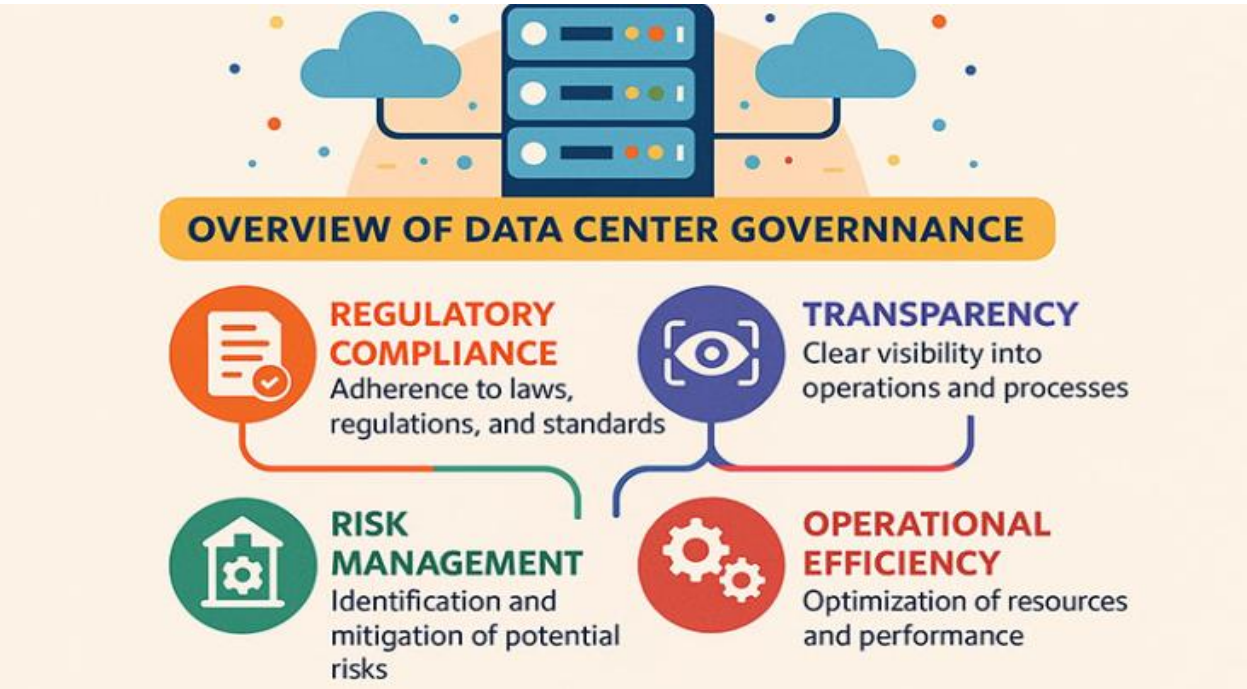

Fig 2: Data Center Governance

5. Research Summary

A layered governance architecture enables the oversight of Integrated Enterprise Risk Management across all domains of enterprise risk. The topmost layer embodies the strategic governance of enterprise risk, providing the direction, structure, and framework for redefining portfolios, generating risk-aware strategies, and ensuring regulatory compliance. The strategic enterprise risk governance architects define roles and assign relevant responsibilities, articulating the decision-making rights of each role and the required escalation paths. Strategic enterprise risk oversight is entrusted to an enterprise risk committee comprising the chief executive, chief operations, corporate social responsibility, chief information, and chief finance officers. Risk analyses are presented at the committee level for portfolio adjustments, regulatory compliance, and long-term stakeholder acceptability. The strategic horizon extends beyond the strategic plan and must consider the rapidity of other organisations in the ecosystem.

The second layer governs the operational integration of risk domains into routine processes, assuring the cancelling of risk owners' risk liabilities during the daily rhythm. The orchestration of the Integrated Enterprise Risk Management system assures that integrated operational risk flows are aligned with the support processes for detection, investigation, control, mitigation, and recovery. Such processes cover day-to-day risk detection, announcement of risk detection, investigation of investigations, management of detected incidents, management and support of(ii continual) recovery of the ecosystem from past incidents, process lifecycle management, and an independent evaluation of the integrated operational risk flow.

Equation 2. Weighted risk score with governance emphasis

Step 1: Start with the base score

$$R = L \times I$$

Step 2: Add a strategic weight

Let w be the governance or portfolio weight.

$$R_w = w \times L \times I$$

Step 3: Meaning

- $w > 1$: strategically more important risk
- $w = 1$: standard importance
- $w < 1$: lower strategic priority

Example

If $w = 1.3$, $L = 4$, $I = 5$,

$$R_w = 1.3 \times 4 \times 5 = 26$$

5.1. Governance Architecture for Integrated Risk Management

Integrated risk management is realized through six governance components. The risk and data governance frameworks operate in adjacent layers of the architecture, enabling joint consideration of risk and data issues across the enterprise and its supply chain. Risk management and data stewardship measures converge in the management of the data center's physical security, cyberspace defenses, and access controls. The risk and data domain controls are integrated into a cohesive set of day-to-day measures that safeguard the business activities and support compliance with external requirements, while also serving the enterprise's and the supply chain's risk management and data stewardship needs. A long-term focus on heavy-asset investments, newsworthy risk events, and the board-treasurer risk dialogue incorporates risk and data issues into the investment portfolio planning process. Risk management is augmented by active RM in the data domain and by the RM research, development, and application capabilities embedded in the data center.

Evidence from Industry 4.0 manufacturing environments underlines the importance of a governance architecture that supports integrated risk management. Security, compliance, and data are important domains of enterprise risk; however, their collective treatment remains underexplored in the literature. The analysis accentuates the linkages between Industry 4.0 technologies, the emerging sources of risk, and the changing requirements for integrated risk management. Business, governmental, and regulatory stakeholders are driving the convergence of operational technology and information technology. This trend shapes Industry 4.0 data ecosystems that integrate suppliers' and customers' data, enabling new analytics-driven business models.

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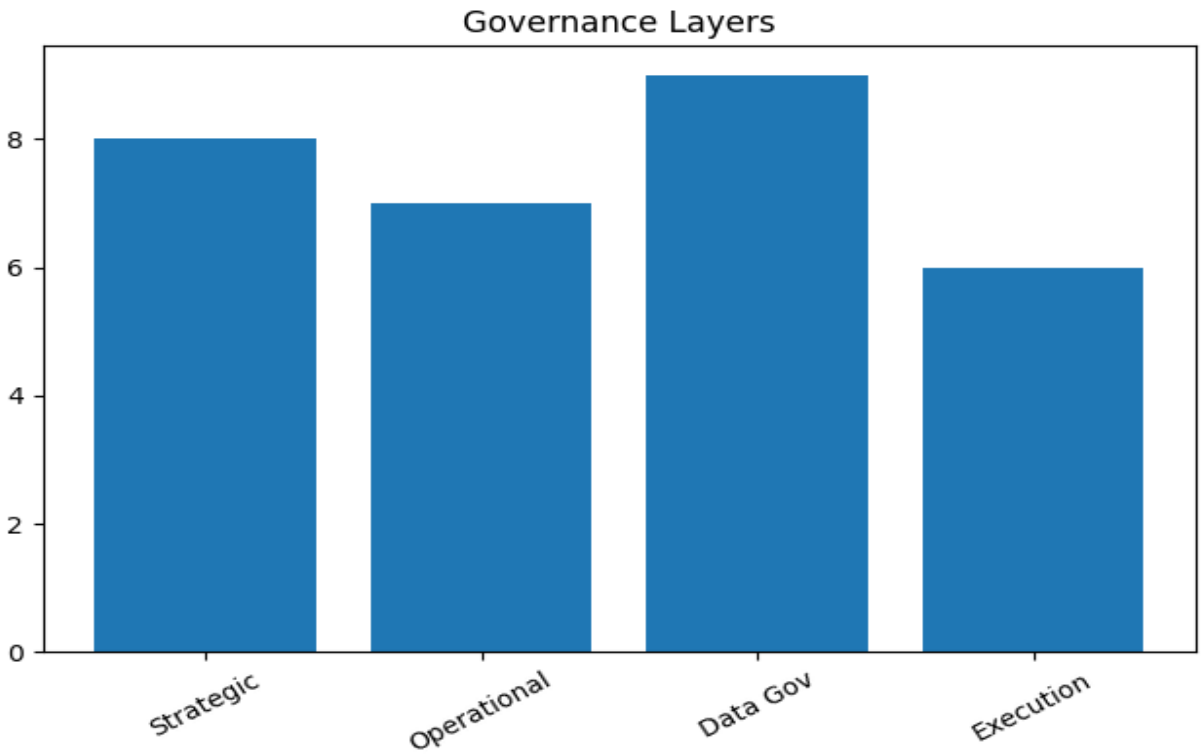

6. Governance Framework Architecture

The governance framework architecture comprises four main components organized in a layered structure for systematized risk management and integration with data center operations. The resulting architecture articulates the objectives, essential elements, and anticipated outcomes of data center risk governance. The strategic governance layer shapes overall policy and direction, while the operational layer oversees day-to-day activities and incident response.

Shifting the focus to the strategic governance layer, key roles, decision rights, and escalation paths are defined. Clarifying the decision-making structure generates confidence among stakeholders and ensures the governance process effectively delivers risk management system performance, funding, and licensing outcomes. Long-term risk management also

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demands shared understanding and verification that the risk portfolio aligns with cyber-physical system risk tolerance, Industry 4.0 goals, and short-term targets set at the operational layer.

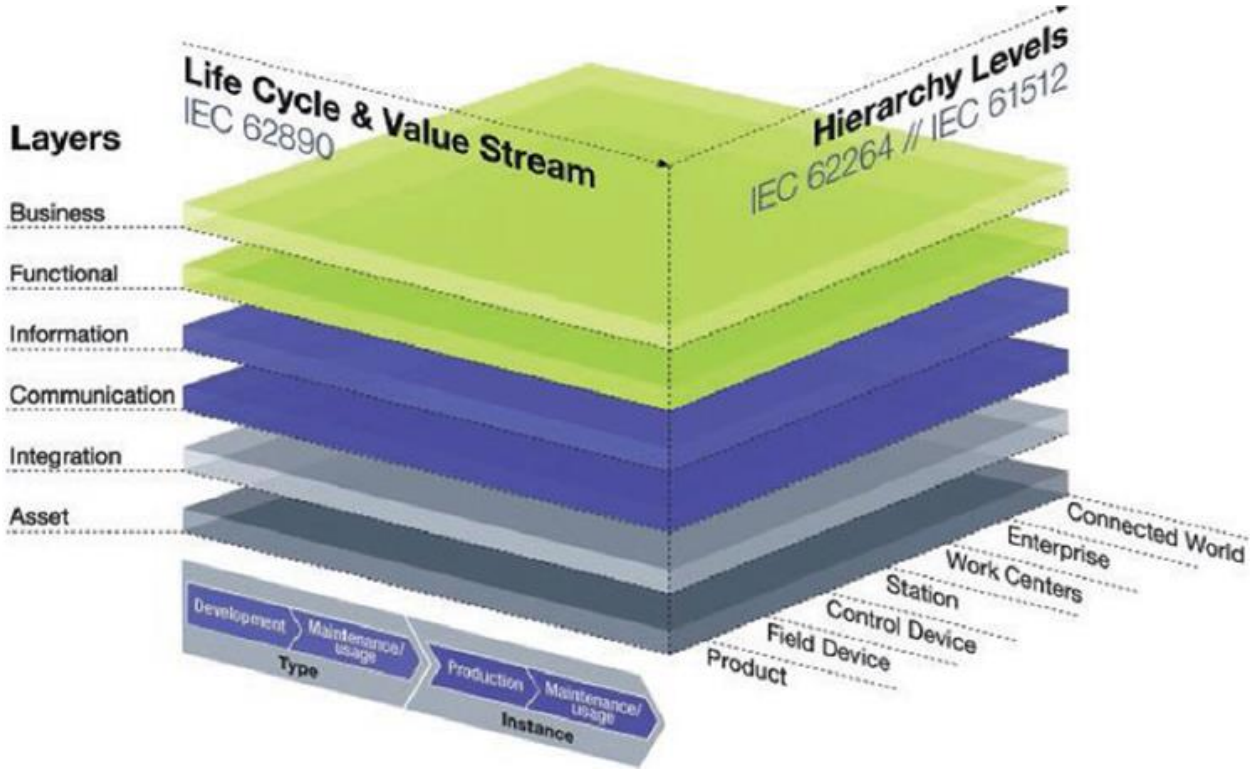

Fig 3: Enterprise Integration and Interoperability for Big Data-Driven Processes

6.1. Strategic Governance Layer

Governance, at every management level, must establish clear policies, work allocation within the governance framework, and a vigilant eye on the long-term risk horizon in order to meet enterprise goals. Silent decisions taken by the executioners at the tactical level eventually impact the enterprise at its strategic level. With finances and profits swinging in both directions, a strong yet prudent risk management policy must rule the enterprise portfolio. Therefore, the strategic layer of the integrated ERM framework is aligned with the governance components, principles, and objectives of the portfolio enterprise.

The first consideration of the portfolio in the era of Industry 4.0 is to be the keeper of the enterprise core values, which cannot be debated or compromised under any circumstances, such as the Daimler motto “the best or nothing.” This must govern the decision-making process and steer the entire enterprise towards the right direction for the right products and services. While corporate policies set non-negotiable top thresholds, it is the business leaders of various business units who seize and convert opportunities into reality.

6.2. Operational Governance Layer

While policy-makers set the high-level enterprise strategy and risk appetite to create long-term value through a balanced portfolio of risk and opportunity, the operational governance layer is responsible for day-to-day execution and tactical adjustments within that framework. It handles the implementation of controls to contain the risks identified by the risk governance layer, directs incident-handling processes, and oversees compliance with laws, regulations, and contractual agreements. Having the right capabilities, roles, and workflows in place to perform these functions and maintain continuous operational resilience while supporting the demands of Industry 4.0 is critical. An adequate level of resource and capability allocation—and the use of an efficient enterprise architecture—ensure that the controls required to mitigate operational risk are fit-for-purpose. The continuous management of the physical security and cyber defense functions, resilience planning, and ongoing performance of the risk and control monitoring processes help to maintain assurance that the operational environment remains capable of withstanding shocks to the service continuity and data breach security properties. Data quality, privacy, and security are core operational requirements that, when not ensured, can completely undermine the benefits of decisions driven by artificial intelligence and other advanced analysis techniques.

Properly defined telemetry capabilities, real-time analytics, and well-crafted decision-support and situational-awareness mechanisms further define the operational needs of risk mitigation and opportunity maximization. These capabilities provide the information needed for alerts and dashboards, allow for the life-cycle analytics of the monitored physical and logical systems within the service environment, and support the simulation of crises and the assessment of new opportunities posed by changing market demands and conditions. A focus on data integrity, open standards, and public-sector interoperability supports the creation of solutions that are vendor-neutral and that address the broader needs of operations without creating costly vendor-lock dependencies.

Equation 3. Residual risk after controls

Step 1: Start with inherent risk

$$R_i = L \times I$$

Step 2: Define control effectiveness

Let C be control effectiveness, where

$$0 \leq C \leq 1$$

- $C = 0$: no reduction
- $C = 1$: perfect reduction

Step 3: Residual risk

The remaining fraction of risk is $1 - C$. Therefore,

$$R_r = R_i(1 - C)$$

Example

If $R_i = 20$ and $C = 0.40$,

$$R_r = 20(1 - 0.40) = 20(0.60) = 12$$

7. Risk Management Processes and Workflows

Risks must be identified and assessed before mitigation design can begin. The risk assessment process, which categorizes risks based on impact and likelihood, provides the basis for control selection. The approach combines risk scoring and prioritization with scenario analysis to augment traditional list-based assessments. Identified treatment mechanisms and supporting process controls are described. Workflows for integrating support processes,

controlling operations, managing incidents, and ensuring compliance complete the risk management definition.

Risks are identified by engaging stakeholder knowledge through structured interviews and documented incident histories. The identified risk list provides the context for applying a scoring methodology that assesses impact, likelihood, and existing controls. A prioritization process then ranks the risks, highlighting potential gaps that require additional attention. A deeper dive into the highest-priority risks supports robust mitigation design. Scenario analysis is used to encourage out-of-the-box thinking, identify key assumptions and dependencies, and reveal unforeseen consequences. β-Trees bring a rigor to scenario analysis that forces a dependence focus critical to avoiding miscalculations.

Table 2. Five data governance elements

Data governance element	Meaning in the article	Typical work products mentioned
Data Quality	Ensures data is correct, complete, usable, and timely	Classification, metadata, data quality plan, assurance/control requirements
Data Lineage	Tracks data source, movement, and transformations	Data origin maps, traceability matrices, lifecycle models, lineage diagrams
Data Access	Governs who can access which data and under what conditions	Access control framework, permissions templates, information sharing framework
Data Stewardship	Oversees the other data governance functions	Stewardship plans, training plans, ingest templates, ownership responsibilities
Data Privacy	Protects entrusted information in line with law and policy	Privacy impact assessments, privacy notices, privacy notifications

7.1. Risk Identification and Assessment

Risk identification determines the risks threatening the enterprise and their potential impact. This step involves listing and assessing the key risks, prioritizing them according to likelihood and severity, and analyzing them in detail. Together, scoring, prioritization, and

scenario analyses ensure the most relevant risks receive the highest attention. A scoring method that assigns weights to the likelihood of occurrence and potential impact is typically used.

Likelihood is the estimated probability of risk occurrence based on historical and forward-looking data. A scoring scale (for example, 1 to 5) helps quantify it, and the score is multiplied by the risk impact estimate. The most critical risks — whether with a high risk score or high likelihood and impact — should be the focus of scenario analysis. Scoring and prioritization help determine which risks need detailed analysis to establish severity, root cause, exposure, and mitigative actions. Based on the top global risks identified in the literature review, scenario analysis evaluates the consequences of cyberattacks and local supply chain failure.

Organizations, industries, and regions face risks that significantly differ in likelihood and impact due to unique factors such as location and business models. For example, the Covid pandemic favored remote work opportunities more than terror activities, while for airlines, travel bans had a far larger impact than cyberattacks. These specific conditions should be considered, and the identified critical risks should include ones that directly and severely affect the organization. A second method for risk identification can therefore focus on these critical risks, designing scenarios for detailed analysis and detection of causes and impact.

7.2. Risk Mitigation and Control Design

Risk controls encompass mitigation measures and processes for addressing risks that materialize despite being in control. Each risk is assigned one or more configured controls responsible for its management. Controls could include preventive measures to reduce the risk likelihood, as well as detective measures to increase the probability of detecting an incident before considerable loss or damage is experienced. For instance, in the event of a security breach, having a very robust access control list with proper monitoring and alerts in place may prevent possible theft or damage.

The design of controls proceeds by selecting mitigation mechanisms and linking them to roles and responsibilities, policies, procedures, and other activities that assist in the implementation of the controls. The totality of the controls configured to manage the risks constitutes the risk treatment plan, indicated in the tool as risk treatment. For risk treatment, the identification of control owners is essential, as these owners are responsible for ensuring that the configured controls will function as expected. The owner of the control is usually tasked with

verifying the control through actual testing and, in the case of a testing failure, with providing corrective actions for the failure detected. To facilitate the successful implementation of controls, they can be linked to relevant non-risk security management documentation, such as policies, procedures, and standard operating procedures.

8. Data Center Infrastructure and Operational Resilience

Commonly perceived as vulnerable support elements, data center infrastructure and operation must provide resilience to withstand unplanned disruptive events. This integrated consideration raises the need to formulate a framework combining data center physical and cybersecurity within a common, consolidated, multi-layered resiliency approach. Such resilience is not about preventing failure, but preparing for it and mitigating its business impact through avoidance, diversion, containment or toleration.

Understanding the various service elements across a comprehensive data center risk profile facilitates physical security, cyber-defense and user access control integration, permitting alignment with enterprise IT continuity planning and execution. Specific recovery strategies, procedures, objectives and testing are also defined as part of an overall multi-layered risk management governance framework.

Combining physical and cyber operating environment resilience for data center-related service elements is essential. Business continuity, disaster recovery and resilience strategies must adequately encapsulate the full risk exposure profile of infrastructure services, ensuring that a common and comprehensive strategy is developed. The scope should also incorporate areas of physical security and user access control risk relating to data center facilities outside of the cyber framework.

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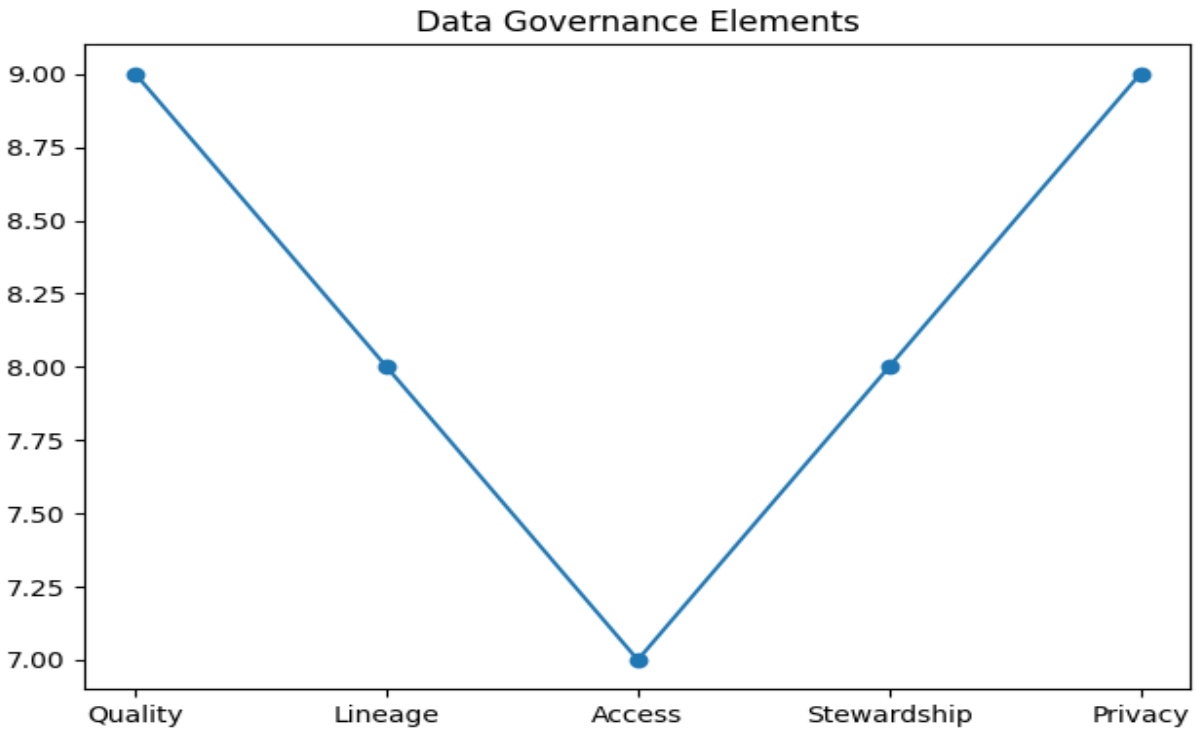

8.1. Physical and Cybersecurity Integration

Cybersecurity and physical security have been treated as separate domains, with different responsibilities, technologies, and specialists. Different specialists have created different algorithms for access control to the facility, but their separation could often lead to reduced overall security. The gathering of information in a data center will reflect the operational risks and physical security, and therefore, physical security and cyber risk should converge. The physical security plan should include cyber defense and access control at the information technology (IT) level.

In general, when it comes to planning a security solution to a building, each Security Expert has its own cognitive framework (known as mental model) that takes into account the inputs available to him and the areas of expertise developed over the years. A researcher

involved in the physical security of a working facility will focus his/her attention on issues such as Access Controls, Perimeter Protection, Intrusion Detection and Fire Protection, among many others, seeking to keep unauthorized people out of the facility, monitoring its surroundings and, if someone is inside that shouldn't be, notify and/or trigger a reaction. An IT Security Specialist, in turn, will try to avoid people from exploring and/or breaking into the Computer Room(s), stealing data, stealing bandwidth, or triggering attacks.

Although both functions have different areas of expertise and are looking in different directions, they share the same goal: protecting the resources inside the environment. A cyber-attack with the computer environment not being protected could cause a Denial of Service or stealing of information, e.g. It is possible to mix analytic algorithms for the two protection groups and come up with a solution for both like choosing who comes into the building, monitoring the perimeter and inside area, and Protecting the IT area as a privileged area in case of group get detected.

Equation 4. Preventive + detective control model

Step 1: Let

- C_p = preventive control effectiveness
- C_d = detective/response effectiveness

Step 2: Preventive controls mainly reduce likelihood

$$L' = L(1 - C_p)$$

Step 3: Detective controls mainly reduce realized impact

$$I' = I(1 - C_d)$$

Step 4: Residual risk after both control classes

$$R' = L' \times I' = L(1 - C_p) \times I(1 - C_d)$$

Expanded form

$$R' = LI\left(1 - C_p\right)(1 - C_d)$$

Example

If $L = 4$, $I = 5$, $C_p = 0.25$, $C_d = 0.30$,

$$R' = 4(0.75) \times 5(0.70) = 3 \times 3.5 = 10.5$$

8.2. Resilient Architecture and Recovery Capabilities

Certain major incidents necessitate the loss of data, most importantly during natural disasters. A natural disaster is without doubt correlated to the adverse weather conditions which may destroy both buildings and the IBM mainframes which are used to safeguard highly sensitive and important information. Security and even physical data should focus in order to mitigate the effects of those major accidents as less as possible. To minimize the risks into the future, hot sites should be found, and the cost of the hot and warm sites is useful to find out whether additional sites are economically justified. Thus, the cost of hot and warm site support makes additional sites justified. Therefore, planned maintenance is needed in order to verify the RPO, RTO, and RTO testing of the data apart from other processes involved for information assurance and risk analysis.

The backlog of many transactions should also be taken into consideration especially when trying to follow disaster recovery strategies in which RPO and RTO testing can be assured and even followed properly. The loss of business opportunity can also be associated with a major natural disaster as it affects the company reputation and strategy within the market and with customers. At longer intervals and at a very low frequency, it might also be necessary to take into account the possibility that an external client requests that areas of the data centre are tested for security. At a more frequent time interval, it might be worthwhile to evaluate the need for a household crisis or full approach test of the facility from a Disaster Recovery or Business Continuity planning perspective. Testing can also take place to satisfy control of operations' business and legal requirements.

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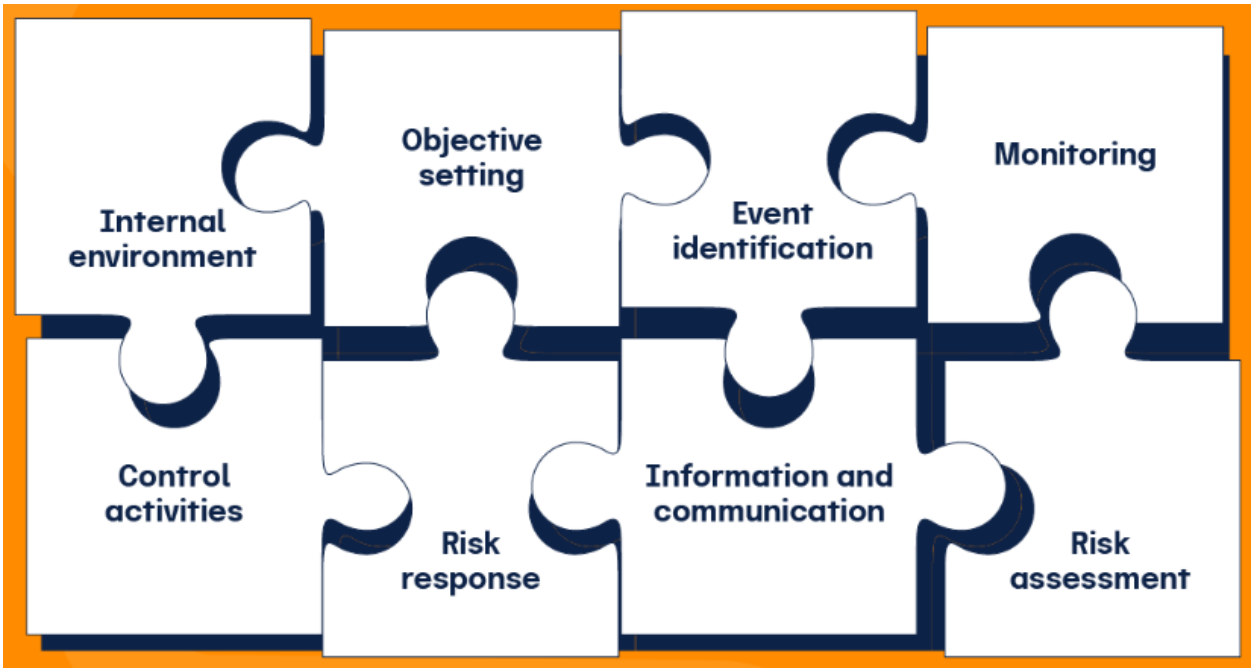

Fig 4: The 8 components of enterprise risk management

9. Information Technology and OT Convergence

For data centers, convergence delivers a different value proposition. Although all three convergence themes remain relevant, the focus shifts to telemetry data, analytics, and integration with decision-support systems. The integration of Operational Technology (OT) and Information Technology (IT) environments introduces new operating models and blurs the traditional boundaries between IT and OT service providers. On the one hand, there is an increasing need for FedRAMP or FISMA-compliant cloud service providers to offer SECaaS, Cyber Security as a Service, capability. Such offerings should include the provision of continuous network scanning, 24/7 monitoring, incident detection and response, and security information and event management capabilities. On the other hand, companies that own or control their OT equipment require strong telecommunication links for telemetry data to feed algorithms and speed up the process of capturing incidents and providing corrections. In this case, the value for the OT world is the speed and quality of the telemetry data — not just price.

To deliver the necessary performance and speed in data analytics, cross-domain data flows, analytics, and dashboards tracking operational performance are required. Dashboards need to provide strong alerts whenever predefined thresholds are reached. Moreover, a reduced time to react is also possible when data flows are based on telemetry data from the OT structure. If the flow is based on periodic batch updates, alerts to deviations could take longer than anticipated. Identifying the best sources of data that contribute to the best analytic outcomes across the organization requires a thorough analysis. Identifying the data flows behind devices' telemetry, the frequency of those data flows, and how they contribute to better business performance and auditing before an incident happens can greatly enhance business performance through the use of AI.

Interoperability and standardization between vendors or products from different vendors become paramount. Standardized protocols and data models should be defined to enhance the collection, storage, and processing of telemetry data. Vendor-neutral optical splits, for example, are cost-effective solutions that deal with redundancy and the interaction with several vendors' devices in an easy way.

Table 3. Risk process sequence described

Step	Description	Why it matters
Risk Identification	List threats from interviews, incidents, and stakeholder knowledge	Creates the risk universe
Risk Assessment	Score likelihood and impact	Converts risk into comparable values
Prioritization	Rank risks using scores and criticality	Focuses effort on the most important risks
Scenario Analysis	Examine consequences, dependencies, and assumptions	Reveals hidden exposure and root causes
Mitigation / Control Design	Assign preventive and detective controls	Reduces likelihood and/or impact
Monitoring / Recovery	Track controls, incidents, continuity, and resilience	Maintains assurance over time

9.1. Telemetry, Analytics, and Decision Support

Dependent on the previous element, the integration of Operational Technologies (OT) and Information Technologies (IT) provides opportunities for operational and infrastructure improvement. Telemetry and analytics are particularly useful for detecting emerging malfunctions or risks. Automated alerting and decision support capabilities thereby facilitate timely operational intervention.

Management and operational decision support depends on continuous and standardized data streams from devices, sensors, and application logs throughout operations. Data analytics for trends, anomaly detection, and forecasting—as well as dashboarding—are integral to decision support. Alignment of operational practices and technology infrastructure underpins the availability, quality, and usability of business-sensitive telemetry.

Ongoing capture, analysis, and display of the health of physical and IT assets in real-time improves operation and maintenance decision making. Analytics of physical asset telemetry—like humidity, pressure, vibrations, and performance states—enables anticipation of component failure or health degradation. Detection and response to threats across cyberspace, OT environments, and associated supply chains are normally assisted by standard practice, supported by telemetry and analysis.

9.2. Interoperability and Standardization

Interoperability promotes a fluid flow of information across systems, subsystems, and components manufactured by various suppliers. Standardized interfaces, communication protocols, data representations, and models simplify integration. Achieving interoperability in Industry 4.0 systems is an ongoing challenge, as many devices, machines, and applications were developed individually and built on vendor-specific technologies. Industry 4.0 aims to break down data silos, allowing rapid analysis and aggregate decision-making. Interoperability depends not only on technology but also on data availability, format, and quality, public and private data governance, as well as appropriate analytics. The breadth and depth of data integration are often dictated by data models and standards.

Telemetry, monitoring, and integration of telemetry flows, especially those based on OT and third-party systems, are critical for incident detection and decision-making for physical emergencies and cyber incidents. The volume of real-time telemetry that can be processed is

limited, and automated dashboards for incident management support are critical. Triaging of events, alerts, and anomalies is optionally performed by a second level of alert management for a correspondent decision support view. Sources of high-frequency telemetry for operational optimization of machines, production, physical security, and emission monitoring are identified, and proper data delivery, storage length, and analytical pipelines are proposed.

10. Metrics, KPIs, and Assurance Frameworks

Integrating ERM within strategic objectives enables measurement of risk exposure in strategic portfolios and projects. Risk metrics and maturity models assess actual vs. desired levels. Individual risks are monitored using specific risk indicators, data quality metrics align with governance principles, and data privacy and security are tracked using established dimensions.

Governance outcomes measure the effectiveness of compliance controls (e.g. test results and coverage) and risk-ownership delegation (e.g. assignment of controls, control monitoring frequency, mitigation activity completion, and control verification progress). Finally, assurance activities related to risk management processes provide a comprehensive view of process effectiveness.

The appropriate balance between structured and autonomous data governance activities can be assessed using a business-maturity model that includes dimensions such as awareness, operations, responsibility structures, data quality, security, technical control environment, and performance metrics. The maturity assessment yields a baseline and specific goals and can be enriched with business-area benchmarking.

Risk Assessment and Mitigation

A multi-phase and multi-step risk assessment process defines roles, responsibilities, and escalation paths. Risk assessment commences with a qualitative evaluation of likelihood and impact, complemented by quantitative scenario analysis for priority risks. Results inform control and mitigation design, which maps controls to responsibilities and verification activities. Separate, dedicated processes tackle the remaining phases of the risk control cycle.

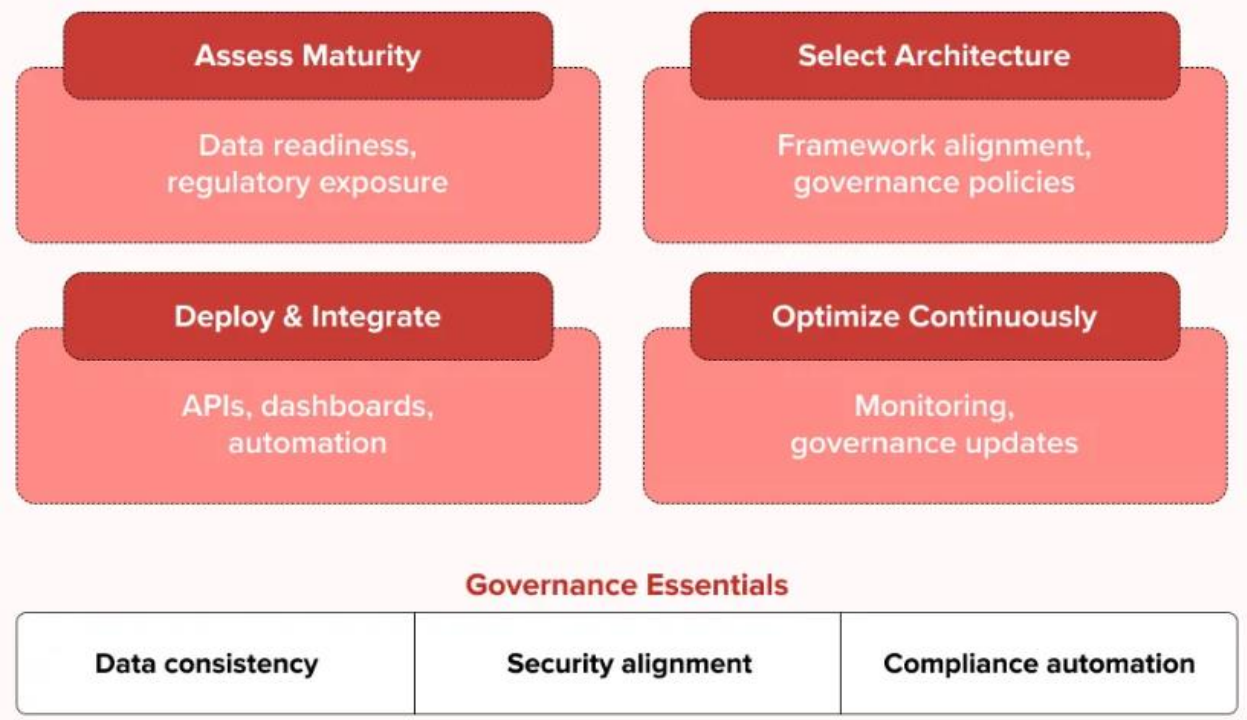

Fig 6: Enterprise Risk Implementation Roadmap

10.1. Risk Metrics and Maturity Models

Risk-related metrics and maturity models play a critical role in integrated enterprise risk management and in robust data center governance. By monitoring selected metrics, an enterprise can determine whether it is willing and able to accept the risk it faces in its operations and has a plan in place if operating at risk levels beyond its appetite. Likewise, a maturity model enables the enterprise to establish risk level targets and prioritize actions to address gaps. A baseline provides a starting point to meet defined targets, while benchmarking against external peers or independently defined criteria provides further perspective.

The list of risk metrics supporting enterprise risk management should be tailored to the specific enterprise and regularly reviewed to ensure that it remains relevant. A comprehensive risk metrics framework can be derived from the major areas of enterprise risk management

detailed above. Maturity models, offering a reference framework for measuring an enterprise's overall focus and effectiveness in any of these areas, can then be incorporated into the risk metrics framework. For each area, criteria for three or four maturity levels can be established, together with qualitative statements. These levels and statements form the basis for a maturity assessment and can serve as a guide for risk remediation efforts. The resulting risk framework thus provides a basis for articulating risk appetite and setting concrete targets.

10.2. Data Quality, Privacy, and Security Metrics

Data quality affects many aspects of everyday business and the functioning of smart organizations. When data must be shared across different parts of the ecosystem, for example in the context of distributed decisions, data quality takes on a crucial role. Defective or incomplete data leads to missed business opportunities, loss of customers, damaged reputation, and ultimately financial loss. Data loss due to privacy breaches can also harm all business partners in the ecosystem; a telemetry vendor may suffer reputational damage and loss of customers as a result of using unsafe data-sharing practices. Monitoring data quality in the simplest scenarios is difficult; in inter-enterprise contexts, it is even harder. Data-sharing agreements may define rules for some data quality aspects, but not for all. Therefore, it is important to monitor data quality indicators in dynamic ecosystems with intermittent data exchange for which no specific agreements are set.

Data quality and privacy are closely tied to customer trust. Data privacy indicators specify requirements and checks for legal compliance. Noncompliance entails financial penalties, loss of customers, and reputational damage. Stakeholders should negotiate privacy agreements before establishing a partnership; lapses in privacy standards can harm all business partners. Insufficient protection of personally identifiable information significantly reduces customer loyalty and repetitiveness. As attackers become more qualified, organizations must invest in security, starting from monitoring and assessing the protection level and aligning investments with the actual risk level. Monitoring investment in security against third-party breaches spotlights excessive investment. Companies performing constant risk analysis may save costs; adapting security investments to the season (increases in sales, strategic partnerships) allows dynamic allocation of financial resources.

Privacy requires special care and monitoring of the deployed protection measures. Privacy impact assessments identify privacy risks in new systems or processes. Distributed

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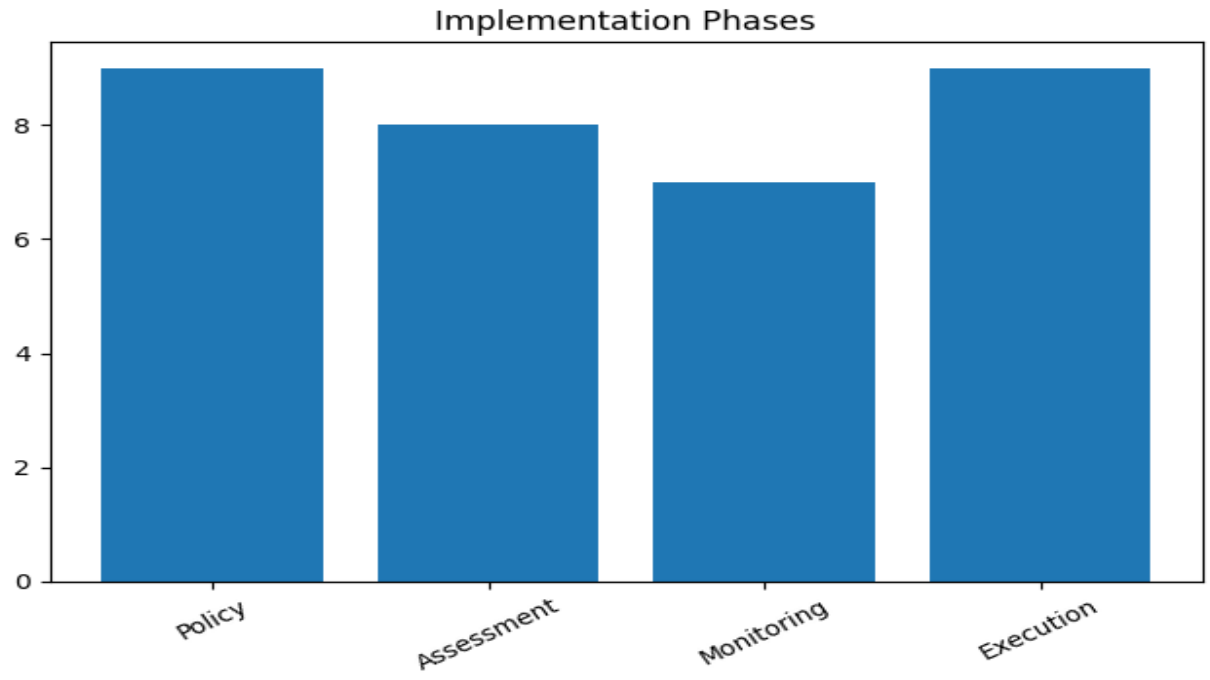
scenarios demand careful checking of privacy agreements for each business partnership. Such agreements should encompass operation aspects and detail the security methods applied. Neglecting these two aspects can damage customers' sales and distribution on a large scale. External security audits may be costly but support customers and prospects' trust.



11. Governance in Practice: Case Studies and Scenarios

The governance framework in this study manifests itself in practice through multiple case studies and scenarios. Lessons learned from two Industry 4.0 Manufacturing case Studies are extracted to assist enterprises in their NIS2 Directive risk governance and compliance initiatives. Two additional scenarios cover a data center consolidation and cloud integration journey. They reveal how such strategic data center initiatives affect the risk profile of enterprises and their NIS2 Directive compliance obligations, clarifying the resulting need for enhanced NIS NIS2 risk management governance. This knowledge directly benefits organizations in their consolidation and cloud integration decision-making.

Manufacturing Case Studies. The global cyber-attack catalyzed by the exploitation of vulnerabilities in the SolarWinds IT monitoring and management system in late 2020 underscored the urgent industry need to recalibrate risk priorities and controls. This evolving ask is particularly pressing for enterprises in critical sectors (NIS2 Directive) and for services (e.g., Managed Security Service Providers) supporting such sectors Recent analysis of Infrastructure Sector Report published by the United States Cybersecurity and Infrastructure Security Agency found that a considerable portion of physical infrastructure continues to be controlled and operated without sufficient cybersecurity integration, formulaic telemetry and analytics capability, and truly resilient architecture and control processes providing assurance of continuity, quality, integrity, privacy, and protection of both the critical service and the data shared with customers. The information recorded, monitored, and analyzed by physical security and OT equipment is enormously important for cyber defense, but remains largely untapped. A counter-telemetry attack on SCADA would be impossible to prove right now and may later be successfully denied without recording and preserving the information. Without adequate standards being defined, such telemetry capabilities continue to be explored only on a one-off basis. As long as they remain a competitive differentiator, vendors are incentivized to not publish the associated data models that would make their SCADA/NMS telemetry data consumable and create demand for the use of third-party data aggregators and correlation engines.

Equation 5. Composite data quality score

Step 1: Define dimensions

Let

- A = accuracy
- C = completeness
- S = consistency
- T = timeliness

All can be measured on 0 to 1 or 0 to 100 scale.

Step 2: Assign weights

Let weights be w_A, w_C, w_S, w_T, with

$$w_A + w_C + w_S + w_T = 1$$

Step 3: Build the score

$$DQ = w_A A + w_C C + w_S S + w_T T$$

Example

If

$$A = 0.95, \quad C = 0.88, \quad S = 0.90, \quad T = 0.85$$

and equal weights 0.25,

$$DQ = 0.25(0.95 + 0.88 + 0.90 + 0.85) = 0.25(3.58) = 0.895$$

So the composite data quality score is

$$DQ = 0.895$$

11.1. Industry 4.0 Manufacturing

The risk governance framework is applied to an intelligent manufacturing environment, transforming a traditional supply chain into an Industry 4.0 setup. Complementing the manufacturing case study, the current exploration reveals additional lessons, insights, and recommendations for establishing a research and innovation ecosystem supporting emerging trends in strategic manufacturing throughout Israel.

Industry 4.0 heralds the next wave of significant technological change in manufacturing, powered by recent developments in the Internet of Things (IoT). These capabilities allow manufacturers to change how they design, build, and deliver products to customers by shifting the entire value chain into a digitally-enabled cyber-physical environment. Such advanced manufacturing involves integrating new technology into every aspect of a product's lifecycle,

from design to supply chain to end-use and service. A telemetry sensor monitoring all systems in real-time and gathering data enables predictive analysis and informs internal stakeholders (engineers, researchers) and external stakeholders (OEMs and end-customers) on the operational condition of the asset in the field over its full lifecycle, thus enhancing the customer experience. Moreover, this core information is a powerful business opportunity in itself that creates new revenue streams and changes the nature of the business from being a pure manufacturer to a Smart Product-as-a-Service provider in a Smart Industrial Ecosystem.

The approach proceeds as follows. First, an overview of the proposed framework is provided. Then, the case study is introduced together with lessons learnt and recommendations for refining the risk governance structure, supported by a dedicated analysis of the case using the recently proposed integrated risk governance approach tailored for data center environments. The case illustrates the framework in action within the strategic governance layer, demonstrating its purpose and expected integration enablement.

Table 4. Four implementation phases from the roadmap

Phase	Description	Relative effort
1. Policy and risk framework definition	Define governance architecture, ownership, and principles	Very high
2. Risk assessment and mitigation plans	Assess risk and define treatment plans	High
3. Risk operation and monitoring planning	Plan routine controls, workflows, dashboards, assurance	Medium
4. Execution of the plans	Run operations, monitoring, testing, and continuous improvement	Very high

11.2. Data Center Consolidation and Cloud Integration

As enterprise IT continues to advance toward PaaS and SaaS delivery models, many organizations are still at earlier stages of public or private cloud implementation, where internal cloud resources are deployed and managed in data centers within their own enterprise. At this internal cloud stage, organizations are focusing on the added value of a cloud concept—self-

service access, elasticity, pay-per-use—integrating virtualization and cloud solutions at the IaaS layer. The provisioning of internal cloud resources is typically based on a data center consolidation and optimization initiative, where underutilized physical servers are consolidated into a smaller number of physical servers that are massively virtualized. Internal cloud is quickly becoming the transitional model for many organizations. The move from the current IaaS state to a fully functioning public cloud service provider is similar to the evolution depicted in the SOA (service-oriented architecture) journey and introduces a new set of factors, risks, and governance considerations for the successful architecture and execution of an internal cloud. Data center consolidation is certainly not a new phenomenon; however, the concept of a data center consolidation, optimization, and internal cloud strategy remains an acutely relevant area of focus for many organizations. The move from traditional physical servers to massively virtualized resource pools tightly integrated and managed through cloud service orchestration adds new dimensions to this initiative. Furthermore, many organizations are at the early stages of initiating their internal cloud strategy, and for them this topic provides useful direction for planning and architecture.

Cloud Computing: Why Now? Enterprise IT delivering services through a public or private cloud is the most significant shift underway in the technology and service delivery market. The concept has now penetrated a significant number of enterprises with talk of readiness and migration well above the level actually experienced. Enterprises are considering either implementing a cloud computing capability in-house, engaging an external cloud computing provider like Amazon or Google, or both. Many organizations have taken their first steps to offer computing services to internal or external customers through a more traditional leasing approach. Many organizations are implementing the technology stack to enable cloud computing and are actively considering design and implementation decisions. The expectation is that the delivery by service providers of cloud computing technology will eventually lead to a spiraling down of these costs and development times.

12. Implementation Roadmap and Roadmap Governance

An implementation roadmap provides an overview of phases, milestones, resources, and accountabilities, while roadmap governance specifies stakeholder roles and communication structures. The roadmap indicated below consists of the first three phases of the broader Industry 4.0 agenda, with steps, sequencing, expected effort, and resource allocation. Each element is assessed to determine the responsible and accountable parties.

The roadmap supports an integrated approach to risk management by enabling oversight of securities, controls, and incident handling across interconnected risk domains. Two executive directors have primary responsibility for the areas of business compliance and security, including data center consolidation and cloud moves. Four additional governance committees: Cyber Security & Privacy, OT/IT Risk, Business Resilience, and Quality—together with their designated leads—fulfil oversight roles in these domains. Integrating assessment findings, status reports, and assurance metrics from these functions into a coherent narrative provides the accountability and transparency sought by the Enterprise Risk Management Framework (ERMF) and Enterprise Data Governance Policy (EDGP).

12.1. Phases, Milestones, and Resource Allocation

Implementing the Enterprise Risk and Data Center Governance Framework comprises multiple phases, along with a dedicated focus on phases, milestones, and resource allocation. The framework leads to a designated area of responsibility (to assign everyone an accountable owner) and recognizes that not all activities can be executed at once. Furthermore, a phased approach allows for incremental investment, which is especially helpful for organizations with limited resources.

The implementation process consists of four main phases:

1. Policy and risk framework definition

2. Risk assessment and mitigation plans

3. Risk operation and monitoring planning

4. Execution of the plans

While policies and framework design require the most significant resource allocations, clear milestones build confidence in stakeholders and resource managers. Moreover, all phases should be completed well in advance of the start of actual execution for the operational business-as-usual activities, such as ongoing risk monitoring and day-to-day integrations. Risk monitoring is inherent in the risk assessment and mitigation plan execution phase. Future industry developments and new requests then justify the remaining investments.

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Putting this risk governance architecture into practice requires dedicated owners accountable for completion and evolution over time through the periodic executions of the risk management processes.

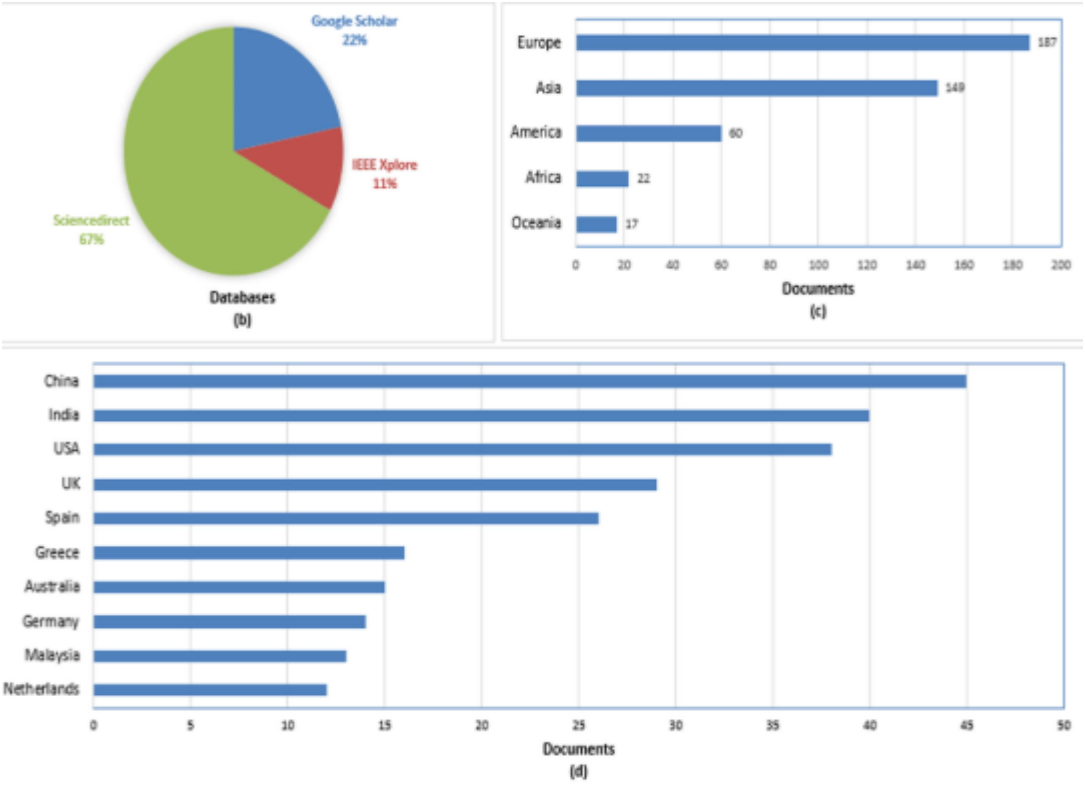

Fig 6: A big data framework for E-Government in Industry 4.0

12.2. Stakeholder Roles and Responsibilities

Clearly defining the responsibilities of those involved in the governance of enterprise risk and data center operations is essential to achieving the desired outcomes. A number of stakeholders have a vested interest in ensuring the adequate protection of sensitive data in IT and OT environments during Industry 4.0 transformations. An enterprise-wide data-handling policy provides the framework for these roles, principles, and responsibilities, which can be grouped

into four main areas: executive oversight, data handling, data protection, and data handling enablement.

Executive oversight of enterprise risk and data-handling operations is typically provided by the board, with the group CEO holding ultimate accountability, and a designated sponsor overseeing the enterprise risk governance program. Day-to-day controls are implemented by the management teams of both business and technology divisions, with the enterprise data governance council — which comprises representatives from both divisions — serving as the principal decision-making body for data governance and stewardship. Responsibility for adherance to data policies rests with all employees, who can be subjected to disciplinary action for breaches. Data protection responsibilities are assigned to data owners — usually senior executives with the appropriate level of authority and business expertise — and data custodians, who administer established security controls. Finally, enterprise risk management and data handling enablement roles concentrate on training, awareness campaigns, and the provision of tools and infrastructure.

13. Conclusion

The academic investigation presented an integrated enterprise risk and data center governance framework explicitly designed for the Industry 4.0 environment. The research was prompted by the accelerating evolution of business models introduced by Industry 4.0 technologies, the integration of cyber-physical systems, cloud computing, and the significance of these innovations; pressures for fusion with operational technology in relation to control risk, environmental authority concerns, and global supply chain premises. The proposed foundation integrates a governing architecture for Extreme-4.0 data centers that support global business solutions.

Enterprise Risk Management (ERM) frameworks and Data Center Infrastructure Management (DCIM) best practices provide theoretical enablers for a holistic view of risk originating from fusion with operational technology, environmental control risk, and global supply chain externalities. Two recommendations are pertinent: thorough knowledge of an Integrated Risk Management Process is imperative for governance in practice. It is highly advisable that Industry 4.0 data centers are designed and validated for these definitions to guarantee efficiency and the validity of predictive analytics.

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