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# Chapter 2: Architecture of Risk-Aware Operational Systems

## 2.1. Introduction

Announcing some important and potentially disruptive changes to regional risk that can impact an operational system's risk profile and its operations in real time, a risk-aware operational system architecture is proposed. The principal goal of this architecture is to support the design, construction, and ongoing operation of such systems. A risk-aware operational system architecture extends a domain-specific operational system architecture with operational system, risk, and external environmental change metrics. These metrics provide the ability to model an operational system's behavior as changes emanating from the external environment travel through the system and may impact any of its own components, behaviors, and attributes.

Research into risk-aware operational systems and their definition, architecture, simulation, decision-making pipelines, governance, security, compliance, and ethical implications is guided by questions concerning risk-aware architecture design. What methods, techniques, and concepts exist for qualitatively and quantitatively modeling risk in an operational system architecture, and what architectural decisions enable risk metrics, change benchmarks, and testing frameworks to support risk-aware decision making? By building on the risk-aware architecture, risk-aware decision-making pipelines and ongoing decision-making governance can also be defined. These enable changes in a manner described by the risk-aware architecture to trigger warning notifications, carry out dynamic risk assessments, and execute appropriate business decisions.

### 2.1.1. Metrics, benchmarks, and evaluation frameworks

A risk-aware architecture must be validated against operational benchmarks to determine whether the implemented objectives have been achieved and to inform adaptations to the architecture. Established testing methods from operational risk domains, such as military

and disaster response, should also be employed when testing risk-aware architectures using simulations or emulations. These tend to be expensive processes, due to the difficulty of realistically incorporating environmental uncertainties and transient faults, and cost–benefit assessments should therefore be part of the risk model.

The time, cost, and operational impacts of going live with an unfamiliar design must be carefully managed to avoid disasters or their excessively disruptive effects. A live test could occur during routine normal operations in such a way that deviations from the favourite service-path would be fully accommodated. An opportunistic live test, in which a live test runs connected to the service on the assumption that available risk reserves will be sufficient, should also be a low-cost low-impact option.

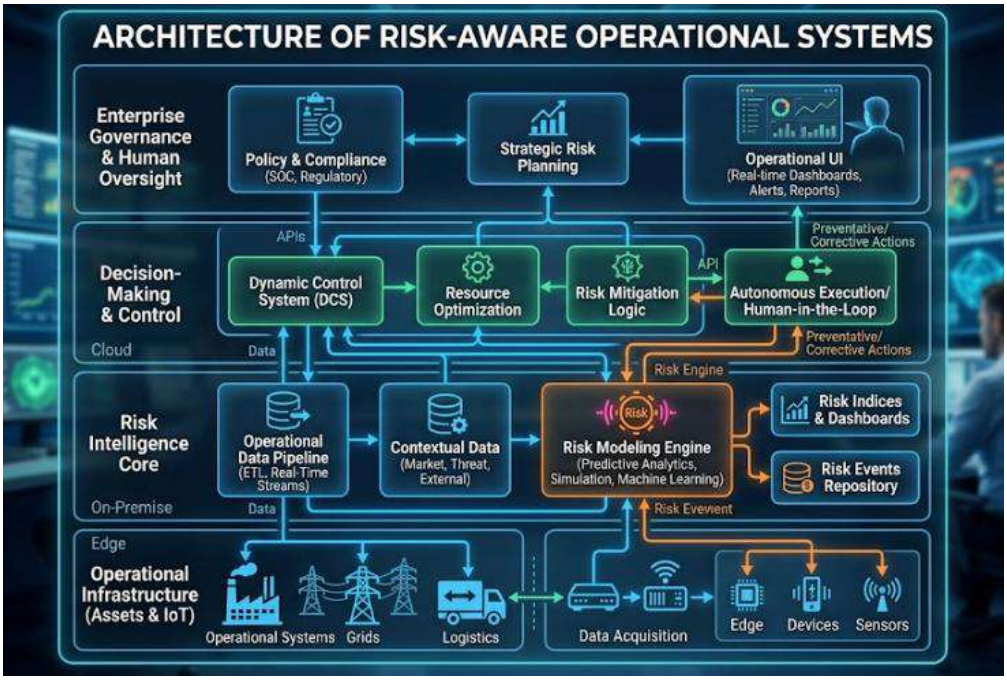


**Fig 2.1:** Architecture of risk-aware systems

### 2.1.2. Simulation, emulation, and live testing

Allocating error budgets and determining when to respond to detected anomalies are risks decision-makers routinely confront. Simulation is a technique used to assess possible outcomes of alternative pathway selections. Many types of simulation provide resilience testing and scorecard reporting. Such simulations may be as simple as taking an existing set of decisions and projecting them across a future landscape of changing conditions, in the manner of Monte Carlo analyses. It can also serve to determine

appropriate margins for safety through multiple runs to discover how many sources of failure a particular design can withstand with little or no cost increase. The Weather Company has long employed such simulations and is credited with having remarkably few severe failures of the their forecasts. Other types are also possible including geo-spatial analysis of decision impacts, black-swan scenario generation, and simply taking risks managers are inclined to overlook in order to test a decision framework's boundaries. When played as games including time pressure and scorekeeping, it can become testing of the bulk that sophisticated military command systems regularly handle and that The United Kingdom's Department of Defense has employed and monitored since the advent of social media. Gamification can assist with stimulate-the-stimulators architectures and integrating humans effectively into decision making pipelines.

Emulation is used where modelling is difficult or too costly. Its use is increasingly common where a sufficient suite of experimental equipment exists to allow tailor-building simulator-harvests containing all the components, data, and scenarios needed to recreate a current real-world system with minimal effort. One developing thread is to further provide automation such as children's toys do, so that such emulator-harvests can be employed easily anywhere at even little cost. Current navy plans to test autonomous ships and deployment functions against an emulated Israel Navy enclaved provide an example. Emulation can additionally be blended with the more standard stimulate-the-stimulators and appropriate-testing use of existing equipment. Such approaches can also be integrated with live-testing ("live" in that it touches a real-world prudential system) and pilot work designed into digital-twin and sustainment-acquisition pipelines; or simply maintained as parallel work files with associated gradual history-monitoring improvement.

## 2.2. Foundations of Risk-Aware Architecture

Research into risk-aware architecture for complex operational systems and adaptations to risk-aware contexts is enriched through evaluation of metrics, benchmarks, and frameworks. Metrices related to ownership, governance, and decision-making are identified as critical risk-aware building blocks. Risk-aware systems comprise formal (audit) trails qualified by related decision governance involved in change-theory detection as risk-aware decision pipelines. Risk-management automation connects risk-model-generated self-healing with operational systems via controls that provide a human-in-the-loop role.

Operational risk modeling capability enables sound application of the cyclic health–monitoring–auditing process that supports system resilience. Architecting the decision-making process captures complexity and contingency to weave risk-aware principles into the operational fabric. Concurrency, repeatability, and robust quality are essential

platforms for the design and lifespan of risk-aware systems. Regulations and controls ensure responsible use of personal data. Emerging data-management technologies provide affordances for private data governance, whereas data-use patterns contribute to auditability and explainability of the decision-making.

Operational-system architects follow a cyclic process of health monitoring and auditing to measure quantitative and qualitative traits. Compliance and business position serve as the framework for metrics, and operational risks provide supporting intelligence to aggregate the risks most applicable for service resilience. Operational decisions change processes, so the metrics support an audit trail that is owned by the business and guarantees risk-aware compliance for scale, repeatability, and automation of control actions.

### 2.2.1. Definitions and core concepts

Risk-aware architecture considers the architectural aspects of systems that are designed to create, discover, and leverage new opportunities or avenues for business. Risk-aware systems focus not only on the desire for maximizing value, but also on the necessity to understand risks associated with scenario developments, the data used to make decisions and the impacts of those decisions. Such systems are increasingly incorporating complex effects associated with the COVID-19 pandemic such as workforce shortages, the need for physical distancing, the unavailability of suppliers or service providers, and reduced or volatile demand.

The notion of risk-aware architecture emerged in the context of risk-aware operational systems for business, a challenge that addresses the risk of making very bad decisions that a standard risk-neutral business model might entail. Risk-aware architectures therefore aim at preserving the risk-aware nature of the operational systems being constructed. They focus on creating risk-aware decision pipelines in those operational systems through which all decisions pass. A risk-aware operational system can emerge from a multitude of risk-neutral decision pipelines, but a risk-neutral operational system cannot be risk-aware if a risk-aware decision pipeline is embedded within it. Risk-aware architecture seeks to understand, identify, and describe the elements that add risk-awareness to an operational system.

### 2.2.2. Stakeholders and governance

Dependable operational systems ultimately serve actors that can be categorized as customers, suppliers, or regulators. Business and government customers typically appoint trusted managers to oversee the control and governance functions. Although

these roles may be assumed by one or more persons, it is essential that the specific authorities for each decision be clearly defined. A regulator can be a stakeholder defined for the limited parts of the system that fall under the authority of legislation. For other parts of the system and for the system in its entirety, a regulator can be considered as forming part of the customer group. In both instances, governance must strike a balance between protecting public interests and allowing sufficient creativity and flexibility for the producer to operate successfully. Such consideration becomes ever more eminent when new technologies are brought to market. A clear division of responsibilities between regulators and customers is thus essential for the successful delivery of a new idea or service.

Risk-aware systems architecture introduces risk as a primary concept for business and operational decisions. The provisioning of reliable and dependable operational environments capable of sustaining required levels of function, correct operation, and performance also decreases risk exposure. Safeguarding the system agents responsible for risk-aware decisions from potential risk is one of the driving forces behind the design of risk-aware systems architecture. Clearly defined risk governance pipelines allow risk to be detected at its source and communicated upwards for consideration associated with the key goals of reduced impact (exposure) and reduced frequency. The simple definition of risk provides an easily understandable basis from which risk modeling can be performed and enables both quantitative and qualitative assessment techniques to be applied in a consistent manner across the decision pipeline.

## 2.3. Architectural Principles and Patterns

Key architectural principles and patterns that aid coherence aim to reduce overall system complexity or manage complexity within the main operational path. Separation of concerns and modularity target the first objective, while resilience and robustness design address the second. Most systems under examine have decided on a modular structure of some sort, primarily for separation of concerns and developing security controls mostly independently, often as a sidecar. At the same time, some aspects of system resilience and robustness especially those concerning continuous operation are becoming increasingly important due to users' heightened risk awareness. Political implications or source code ownership and control are acknowledged but out of scope.

Separation of concerns and modularity. Separation of concerns is a foundational architectural principle. It aims to make software easier to plan, develop, test, deploy, and operate by isolating cognitive and operational burdens. No clear principle exists on the acceptable number of concerns. Specialization for one concern is often convenient. Concerns of less importance may be combined into a module by an architect or one of the developers freely exercising architectural choice. The acceptance of additional,

architecture-related concerns, such as mitigating security risks, constitutes a tightening rather than a release of the principle. As a consequence, most architectures have functional or logical modularity along with these dedicated sidecars.

### 2.3.1. Separation of concerns and modularity

Separation of concerns and modularity are fundamental design principles. Relevant patterns implemented in an architecture include single responsibility, separation of models, microservices, and multi-tenant designs. When these principles are effectively executed, the architecture of the risk-aware system is more understandable, easier to develop and test, and the individual modules are easier to deploy and replace independently.

The single responsibility principle states that a component should have one, and only one, reason to change. A component may possess more responsibilities, but multiple reasons to change implies a risk that the component will have to change when a different responsibility changes. The separation of models principle states that a model viewed from one perspective should be administratively unrelated to a model viewed from another perspective. When one perspective requires a change in a model that does not affect the other perspective, an error may occur if a change is made when it is not actually needed. In such cases, having separate, administratively unrelated models for the same object increases the risks and costs of maintaining the models. The microservices model extends the single responsibility principle to services: each service should implement only one function or business capability. With a multi-tenant design, a single deployment of the software runs on a server and serves multiple hosting organizations.

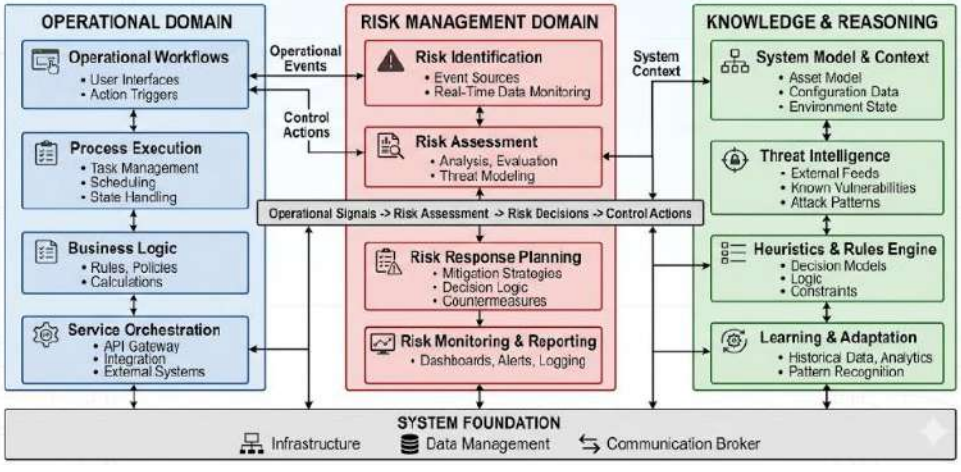


**Fig 2.2:** Separation of concerns in architecture

### 2.3.2. Resilience and robustness design

An essential aspect of risk-aware architecture is resilience – the ability of a system to withstand perturbations while retaining core capabilities. Architectures can thus be developed to deliberately resist specific perturbations, reducing the probability of failure. Roles and functions within a risk-aware architecture can also be grouped into those that are intended to ensure the continuous provision of operational capabilities, and those that may be interrupted or fail entirely without substantially disrupting ongoing operations.

As with resilience, robustness also addresses the impact of perturbations on functionality. Robust architectures resist changes in function or capability when faced with anticipated disturbances, undertaking additional activity only when required for emergency response and recovery within established intervals. Indeed, these two concepts are complementary, supporting different dimensions of operational design.

## 2.4. Modeling Risk in System Architectures

Risk considerations often surface late in the architecture process, at the engineering stage or during pre-production testing, when trade-offs are typically tested against budget, schedule, reliability, robustness, and other engineering attributes. Risk modeling techniques offer methods for incorporating considerations of risk complexly, early, and throughout the architecture process. They can be applied to assess, analyse, or evaluate often in a comparative manner key enablers, successful or alertable failure modes, and offset strengths. Both quantitative and qualitative assessment approaches are surveyed.

Adverse consequences on stakeholders not on failure per se are the key drivers of risk, and risk management prioritises consequential risks that are in fact severe. Practitioners therefore tend to assess risk by focusing on bad conveniently measurable things that can happen to systems, such as calamities, broken things, or out-of-requirement-performance things, rather than by directly modelling stakeholder consequences at every stage and from first principles. Quantitative approaches therefore show risk as the product of likelihood and consequence, with high-risk conditions seen as those with an unacceptable product level. Qualitative approaches use associated terms such as low acceptable risk or cater to risk-averse or reluctant-acceptance stakeholders.

### 2.4.1. risk modeling techniques

Risk has different forms and distinct modeling techniques are generally applied to capture each form. The approaches discussed cover the common sources of risk against perceived value over time. They are interest rate risk (with a value-at-risk and expected shortfall focus), market risk (judged through a Black-Scholes modeling approach), credit

limit risk, enterprise risk (hedged via an on-balance-sheet strategy), inflation risk (quantified using a Fisher relationship), foreign currency risk (established using an appropriate F/X hedge), liquidity risk, and operational risk.

1. Interest Rate Risk

The risk to the amount and timing of expected future cash flows inherent in an asset with a specific maturity is referred to as interest rate risk. Financial theory supports the view that interest risk is best judged in relation to value-at-risk (VaR) and expected shortfall (ES) concepts. Value-at-risk measures the potential in a gain or a loss of an asset over a specified time period and at a given level of statistical confidence. For most forecast horizons (one day, ten days, etc.), value-at-risk behaves asymmetrically. Financial models suggest that the potential for loss is greater than the potential for gain. When the asymmetry property of value-at-risk is quantified, expected shortfall emerges as the more interesting risk measure.

2. Market Risk

Market risk is often used in a trading environment. Indeed, some financial institutions deal only in trading activity. Generally acknowledged to be the most profitable area for financial institutions engaged in trading, the risk is inherently a trading limit risk. Indeed, the author's adjusted capital allocation methodology attempts to perform such a function. But the adoption of a simple Black-Scholes model introduces a much broader set of considerations that go beyond trading limit usage.

3. Credit Risk

There is a tendency in derivatives pricing to view credit risk as a type of quality risk inherent in any loan activity. That risk is particular to the type of financial institution actually granting the derivative, rather than for those transacting in the derivative's trading market. The market makers in credit derivatives make prof- it by ensuring that any credit risk inherent in the derivative products they trade does not generate actual credit losses. They accordingly allocate capital to the credit risk exposure they underwrite.

### 2.4.2. Quantitative versus qualitative assessment

Implementation of specific quantitative metrics for the management of complex adaptive systems and operational systems is a long-time aspiration of the ATM community. The aspirations of a simplified formulaic risk metric leading to simpler decision making is noted, although it remains a long way off. The Financial Industry presents notable examples of the use of a very simple metric applied across many aspects of operational and decision making. In ATM, the established formula of Safety Risk = Probability x

Severity is a great advantage for verbal rather than mathematical reasoned assessment. Verifications that use some aspect of that very simple Safety Risk metric occur at almost all levels of operation, from Strategic to Tactical and Real Time.

Quantification of ANS risk is a difficult challenge and probably not achievable in the near short term for any but a limited number of significant decisions. Probability of an accident combined with severity are essential metrics but outwardly it is illogical for, pretending to contrast nature, it could be rationally argued that ATM is an accident-free environment with indeed unpredictably very serious consequences. Risk-aware attributes for the ATM community that can further be quantitatively assessed are therefore limited. Some of risk-aware attributes need to be defined or expanded within a specific Risk Framework and Committees created to achieve them exist or are established at both European and German levels.

## 2.5. Architecture for Risk-Aware Decision Making

An operational architecture tackling risk factors requires an embedded decision-making process. This must begin with gathering intelligence based on the configuration of the architecture, including facilities predictions. Second, it must allocate governance responsibilities among stakeholders and define roles along the decision pipeline according to risk assessment levels. Third, specialized offices must review control mechanisms pertinent to various risk parameters. Fourth, it must determine the possibility of automating execution through alerting systems and control mechanisms.

The phases of the architecture reflect a risk-aware governance model. The decision pipeline, a core mechanism from risk management, is applied to a domain of operational architecture design. The pipeline defines intelligence-gathering processes, the allocation of governance responsibility, the evaluation of risk-reducing control mechanisms, and the possibility of automating execution through alerting systems. Risk control and crisis management offices support the decision pipeline by assessing risks and establishing the risk levels that trigger alert systems for automated execution. With these insights, automated architecture control emerges as a risk-aware component of design and realization.

The decision pipeline integrates automated and non-automated architectural risk response. Risk control and crisis management offices examine all identified risks, determining the steps and procedures necessary to effectively minimize different risk entities. Such preventive measures are embedded within the architecture and must be clearly communicated to the operations teams. Processes, procedures, and action plans relevant for addressing extreme or high-risk events require more attention and clarity. The architecture must proactively speak to these during the operations cycle.

### 2.5.1. Decision pipelines and governance

Both automated and human-in-the-loop pipelines for governing risk-aware decisions are common in operational and information systems. Automated pipelines use alerts, triggers, and feedback loops tailored to support a specific risk-aware decision. Alerts inform stakeholders when a pre-determined threshold has been reached, enabling them to decide whether to escalate an issue or handle it at a lower level. Triggers initiate a predetermined action in response to an event, such as redirecting a connection attempt due to a database compromise. Feedback loops are designed to ensure continued effectiveness, e.g., an alert enabling change detection and response in a system designed to handle a dynamic challenge. Automated response pipelines can provide faster reactions, but the response must be designed and approved in advance.

Human-in-the-loop pipelines are often used for situations that exceed a system's confidence level for handling a decision autonomously. The triggered alert contains a formal description of the situation and an explicit recommendation, facilitating the human decision. Since a human must verify or challenge the system's assessment before proceeding, the decision tends to take longer than an automated control. The need for such intervention, therefore, also acts as a load limiter on the risk-aware system.

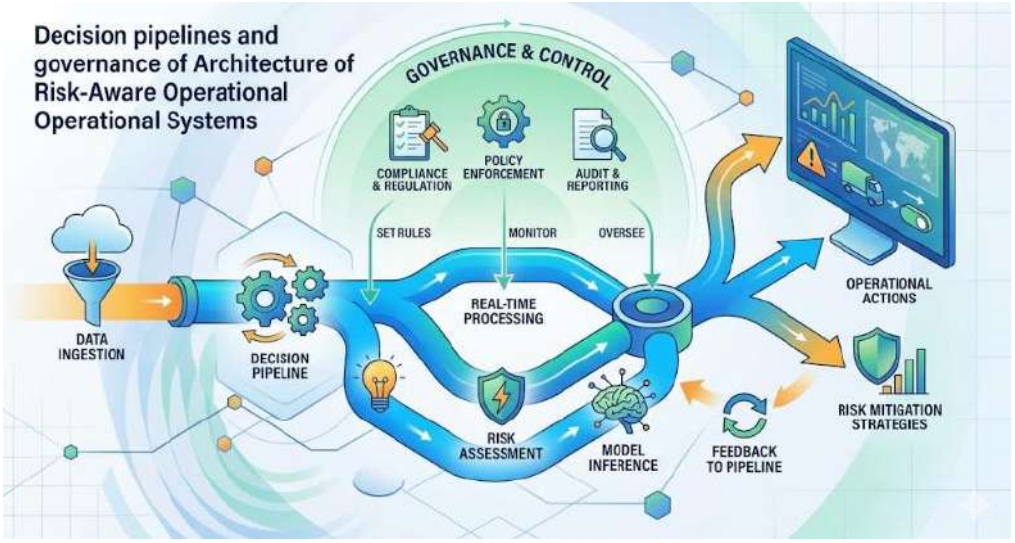


**Fig 2.3:** Architecture of risk-aware systems

### 2.5.2. Automated controls and human-in-the-loop

Automated controls are decision pipelines designed to maintain designated aspects of a complex operational system near desired levels, without human intervention. The

achievement of operational goals may require continuous control or control over multiple coupled variables. While automated controls can manipulate trajectory and timing of actions in the operations, they are incapable of dynamically evaluating the conditions, risks and trade-offs involved in achieving them.

These decisions rely on more sophisticated decision pipelines that may account for risk and trade-offs in design, development or operations. However, independent of their ownership, significant risk is assumed by the automated decisions: should the outcomes not conform to a preset tolerance envelope, responsibility for the ensuing behaviours and consequences rests with the human party owning the pipeline. Therefore, it is critical to establish and to communicate the suitablity or lack of it of the automated decisions for the given situation, risk-control threshold, time and environment.

Human-in-the-loop decision processes acknowledge that intelligent human beings (the loop) are part of the decision-making process, both supplying data and context to the automated control as well as forming an important part of the risk management process of the automated controls. It is clear that the specifications of the automated control must provide the humans with sufficient information on risks taken, conditions and rationale behind the decisions made. This requires judicious choice of data sources, data bundling for display and the timing of decisions and communications.

## 2.6. Infrastructure and Operational Considerations

Risk-aware operational systems rely on infrastructure and platform choices that minimize risk for given resource budgets. Each resource compute, storage, bandwidth, skilled personnel has a natural availability, but the requirement could be quantified on an as-needed basis using benchmarks, testing, or a combination, favoring quantification with higher-level operational status when possible. In general terms, all systems are antifragile at the runtime level.

The architecture of a risk-aware operational system reflects considerations for the support platforms and environments in addition to the operating system. On the technology side, multiple options are available for each of the enabling capabilities: physical, virtual, and cloud platforms support compute resources; block and object store, conventional and NoSQL databases serve data storage; and dedicated, virtual, and CDN networks assist with traffic delivery. Semi-automated use of the preferred option for a specific capability reduces risk exposure during that specific operation; however, they are often reserved as a last resort because of the corresponding cost. A hybrid operational architecture with separate risk-optimized layers level 1, dedicated resources to quantify service dynamics and to implement semiautomated response controls; level 2, platform-independent coordination of status and control signals; level 3, risk-optimized public-

cloud-based resources for on-demand additional capacity can minimize costs while retaining service resilience.

### 2.6.1. Platform choices and runtime environments

Platform choices and runtime environment selections impact reliability, availability, maintainability, and scalability of systems. These trade-offs are complex and context-dependent, but a risk-aware architecture can aid their exploration, noting those points which generate opportunities or pose particular risks.

The choice of hardware and software platforms has wide-reaching consequences. The cheapest solution may save money but carries a high risk of failure due to low reliability, especially if complex hardware supports a mission-critical system. For safety-critical systems, only platforms that meet the relevant standards should be approved, with alternatives assessed under rigorous certification processes. Generally, software middleware, hardware virtualization, or container environments, all of which add layers of abstraction to the platform, are tolerated only where the most appealing advantage is resilience to component failures.

### 2.6.2. Reliability, availability, and scalability trade-offs

Many aspects of risk-aware architecture design depend on the application and operational environment. The design of the perfect car is governed by highly different requirements than the design of the perfect airliner. Yet, one aspect that risks being overlooked is the dependence of risk-aware architectures not only on the domain of application but also, in particular, on the infrastructure on which they run. Indeed, a decision-pipeline architecture that performs a formal analysis on small data samples with a significant amount of human-in-the-loop supervision can be seamlessly hosted on a smaller infrastructure and have lower reliability than an architecture that uses machine-learning models trained on big data for detection of fake news in a live feed at worldwide scale.

Nonetheless, it is important to put into perspective the pros and cons of three key aspects of modern IT platforms: reliability, scalability, and availability. The more reliable, available and scalable the platform, the lower the lifetime probability of a failure of the architecture hosted on top of it. Hence, one of the goals of a risk-aware architecture is to maximize the number of operational risk scenarios in which the impact of asset malfunctioning is negligible. Availability and reliability of sensing components also have a direct implication on how risk-aware the architecture is. When the assets actively

contributing to the decision-pipeline function properly as expected, an external event or human error may trigger some risk scenario, but this may not be cause for too much alert.

## 2.7. Compliance, Ethics, and Legal Implications

Governance implications associated with the operational architecture may include requirements stemming from applicable laws, regulations, and ethical considerations. Key concerns in non-technical domains include protectiveness of stakeholders' entrusted data and the possibility to expose wrongdoing and ethical concerns during normal operations. Data governance arrangements should therefore provide substantive, formalized protection against mission and performance impairments associated with data breaches and data misuse.

Within the operational domain of risk-aware systems, the data protection goal is commonly realized through diverse technical implementations associated with data access controls. Ownership and usage rights of external data sources, as well as the resulting usage restrictions and constraints, are formalized and recognized by the operational architecture. Risk-aware design patterns ensure that protected data can neither be shared nor combined with other data that may result in privacy-sensitive information without violating the defined access controls.

In highly visible domains, such as crime and tax investigations, higher demands for auditability, explainability, and non-repudiation are typically imposed than in normal information system environments. Concerning privacy, the GDPR stipulates strong guarantees against the undesired exposure of individuals' private information by systems' operations. In these architectures, data controllers must demonstrate that technical audits yield as little sensitive information as feasible during normal operations while still providing sufficient control to the auditors.

### 2.7.1. Data governance and privacy

To enable responsible use of risk-aware operational systems, frameworks and platforms must have the necessary supporting processes in place. A specific focus is on compliance and thus satisfactions of legal obligations while avoiding loss of trust due to ethical failures. Legal obligations mainly arise from regulations covering data protection and privacy. Key risks are the so-called party risks, meaning risks of violating or not demonstrating compliance with obligations towards parties of systems that use data in risky ways. Data governance is thus a significant aspect of it because it should ensure that the data that is being processed can indeed be processed by the operational systems.

The main privacy regulation governing the processing of personal data is the General Data Protection Regulation (GDPR). A general understanding of what privacy is and what the GDPR means with it is useful to derive its implications for operational systems. With that it can be stated which data processing principles the underlying control systems should cover, enabling a more concrete definition of compliance monitoring and capability auditing. Finally, the adequacy of the data processed by a system according to the GDPR can be considered; thus their association to the processing has been shown to be potentially risky. The data processing principles driving the obligations of controllers and processors are individual consent, limitation to purposes, data retention limitation, data minimisation and data accuracy. Potential violations stemming from or emerging from possible failures in risk-aware operational systems should be assessed in an architecture review stage as part of its risk assessment.

### 2.7.2. Auditability and explainability

Risk-aware architecture supports risk-aware decision pipelines. Such pipelines may contain dynamically orchestrated composite services providing answers for concrete risk questions, but their quality relies on the fulfilment of the associated input quality metrics. Poorly assessed or insufficiently governed input data introduces the risk of incorrect answers, failures of automated responses, and issues caused by a human in the loop. The answers must satisfy specific qualitative properties relevant in risk-aware contexts.

Risk-aware architectures support auditability to recreate the full evolution of the system, including the inputs of the decision pipelines, the decisions and responsible actors, and the resultant actions and effects. Auditability enables the follow-up of incidents to evaluate how they happened and improve robustness based on lessons learned. Auditability also facilitates the adoption of digital forensic methods to provide evidence to support the mitigation of legal risks and organize cyber insurance claims. Sensemaking techniques that produce explanations improve preventive actions and enable incident responders to fix damages faster and more efficiently.

## 2.8. Conclusion

Risk-aware operational architectures represent a growing area of interest for central banks, financial regulators, law enforcement agencies, intelligence communities, emergency services, and military organizations, and involve three broad themes. First, methods and metrics for evaluating risk common forms of risk acceptance, risk tolerance, and risk appetite should be defined in accordance with the legal, governance, and policy context of a risk-aware architecture. Second, components of a risk-aware operational architecture should be addressed, focusing primarily on the components

most relevant for risk-aware decision-making. Finally, the principle of risk as a first-class consideration in decision-making should be formally stated in order to form part of a risk-aware architectural pattern.

Emerging trends point to the growing need for operational systems with these capabilities, either explicitly or as an emergent property. Historically, risk management decisions followed mostly qualitative paths. However, increased focus on risk management including enterprise risk management, semi-quantitative scoring mechanisms, and requirements for precise know-your-customer (KYC) procedures means that risk-aware operational decision-making is now expected to occur within risk-aware operational systems. These risk-aware architectures are beginning to be developed for operational contexts where they have not previously been present, yet their design is still tacit. During this period, it is therefore useful to explicit the requirements for operational components, address the operation of one of the most common operational types a decision pipeline and note the risk as a first-class consideration.

### 2.8.1. Emerging Trends

A better understanding of external threats, evolving technology ecosystems, changing consumer behavior, combinations of existing technologies, and disrupted supply chains have prompted increased investments in the research, development, and integration of risk-aware architectures into production systems. While a significant literature exists in the specialized domains of operational risk management, many academic fields and industry verticals tend to consider various aspects of technological and business systems in relative isolation rather than as components of an integrated architecture that facilitates cross-organizational and cross-technology-rank decision making.

Risk-aware architecture addresses these gaps by providing decision makers with the quantitative and qualitative assessment and decision support capabilities required to respond to the emerging threat landscape. .

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