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Chapter 9: Scaling Autonomous Execution Across Enterprise Services

9.1. Introduction

Enterprise information technology is at both a turning point and a crossroads. New capabilities spanning infrastructure, platforms, and software are now available to allow information technologies to autonomously manage and operate themselves autonomous execution. Autonomous execution in a service context refers to independently managing the provisioning, processing, and management of autonomous execution. Such self-management potentially carries substantial rewards—hotels can scale without any on-site staff, trades can be executed in fractions of a second, and, in extreme cases, entire cities are being built using economy-of-scale principles. But these rewards also bring substantial risks.

While autonomous execution is already being applied in a wide variety of operational contexts in enterprises, these initiatives are generally not based on clear design principles and architectural foundations, nor are the decisions being approached in a systematic way. What are the core principles for scaling autonomous execution, are those principles being followed by existing initiatives, and what are the implications of those decisions? As a step toward addressing these questions, examine the key principles for scaling autonomous execution in enterprise services, how those principles relate to existing frameworks for enterprise governance, risk, and security, and how those principles can be translated into a reference model for guiding the design of enterprise services capable of supporting autonomous execution.

9.1.1. Understanding the Role and Impact of Autonomous Execution in Enterprises

Autonomous execution covers a broad range of situations where activities are completed without human intervention. In a corporate environment, it applies to the execution of IT-related or business operations that are typically governed by some form of policy.

Decisions need to be made regarding when to execute; for the autonomy to be meaningful, the triggering and execution conditions should be automated and not solely depend on a human decision-maker.

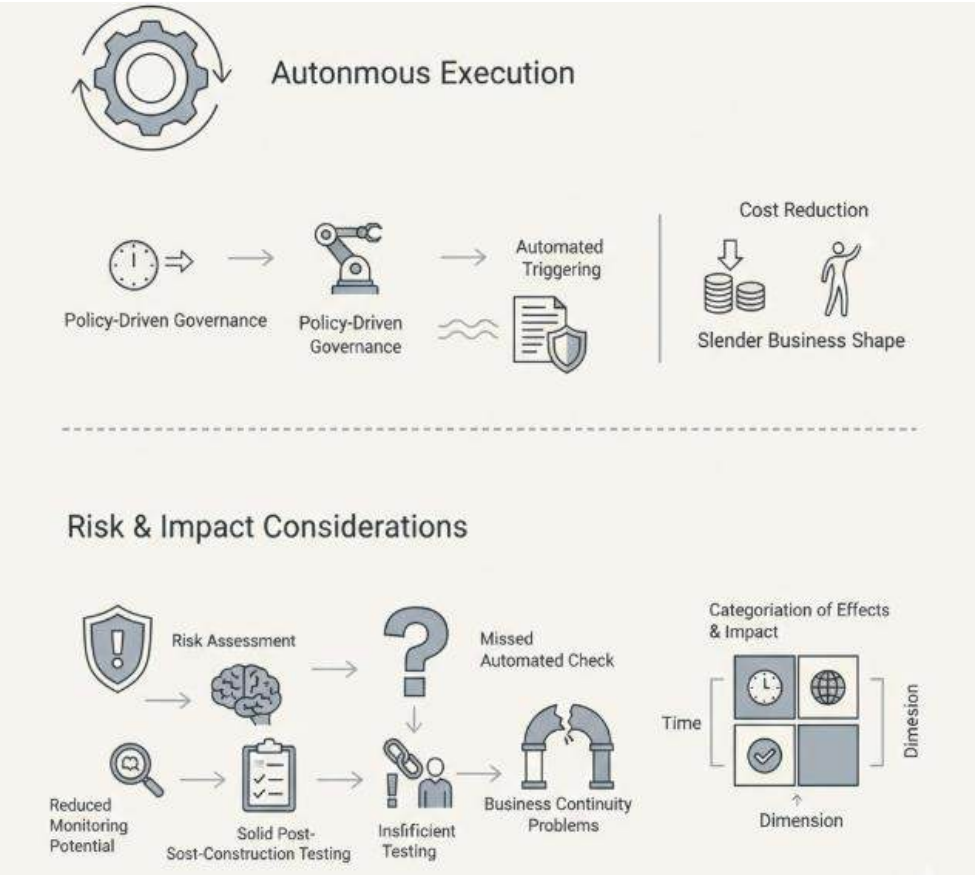

Fig 9.1: Governance Principles for Autonomous Execution: Balancing Policy-Driven Automation with Risk-Responsive Business Continuity

The direct benefits of autonomous execution are cost reduction and slender business-shape. Keeping these benefits in mind, autonomous execution should be called for only where risk levels support this call, be it connected to reduced monitoring potential or because highly solid, post-construction testing cases indicate a high reliability in achieving the desired results. High autonomy in execution comes with a drawback; a missed automated check or insufficient testing by a control authority may lead to business continuity problems. To judge effects and impact properly, autonomous executions should be categorized in considerations affecting the enterprise in time and dimension of their impact on other enterprise activities.

9.2. Defining Autonomous Execution in Enterprise Contexts

What Exactly Is Autonomous Execution in the Enterprise, and How Is Its Application Delimited?

The following provides a formal definition of the concept—focusing on foundational aspects of the operation and its autonomous nature, and delineating how it interacts with human decision-making in contexts that are relevant to enterprises—as well as discussion of why the deployment of autonomous execution is deserving of more systematic and extensive application. The emphasis is on enterprise-scale operations, where the overall scope and feasibility of autonomous execution are strongly determined by enabling architecture rather than on the properties of the autonomous execution itself—although successful implementation is still clearly contingent upon the operational resilience and soundness of those autonomous execution operations.

Contemplating autonomous execution using an enterprise composition perspective leads to a model in which the control and decision-making authority of human personnel can be considered modifiable, and systems may be able to reach decisions and take actions without human intervention—for several different reasons, including cost reduction, improved accuracy, faster reaction times, and full 24x7 availability. In other works, this concept of operational autonomy does not generally encompass decision-making and control for the entire enterprise; instead, the control and decision-making abilities of personnel are considered for their importance to the risks associated with the level of control delegated to a particular operation, to achieve the same business objectives as without it and with the same controls and assurances in place.

9.2.1. Key Principles and Frameworks for Autonomous Execution

Key guiding principles for design and implementation are modularity, resilience, transparency, and integrity. Organization and control of autonomous execution can be mapped to existing enterprise governance frameworks: autonomy governance provides operational oversight, risk management defines limits and boundaries, security identifies acceptable threats and controls, and policy enforces constraints. An enterprise reference model captures the dimensions for successful scaling of autonomous execution.

The principle of modularity stipulates that services should be constructed as small, cohesive units supporting a specific capability. This requirement is a well-known design goal especially critical for automation, not just for making implementation easier but also for scaling and adaptation: microservices can grow, shrink, or be replaced as needed; a failed service can be redirected to a spare unit or to a load-balanced aggregate if one exists; a braking service can be temporarily suspended; and replacing a faulty service requires changes only at the interaction points. Service modularity underpins service-

oriented architecture definitions but is often too loosely applied—especially at the lowest levels—to provide the intended benefits.

9.3. Architectural Foundations for Scaling

Scaling autonomous execution across enterprise services requires careful design of key architectural foundations. The idea of autonomy is often associated with self-driving cars, aircraft, and other piloted vehicles under a variety of conditions, but these machines are only partially autonomous and still require significant human intervention and action even during fully autonomous operations.

Sufficiently scaled autonomous execution in enterprises demands more than a small number of autonomous systems. The architecture of services—how they are decomposed, how they interact, the capabilities and guarantees they offer, the means by which they are orchestrated, and how all of these aspects are protected and supported from an operational perspective—greatly affects scalability since most of the risks, costs, and governance needs are present to some extent at the service level. Telemetry, workforce substitution, cost, and business outcomes matter for any service being executed or consumed autonomously, but only a small subset of those factors is directly relevant for enterprise-wide and system-of-systems autonomy.

9.3.1. Service-Oriented and Microservice Architectures

Autonomous execution of IT operations and enterprise business processes relies on modularity to distribute operational tasks to highly responsible and accountable policy-based services. Although self-service empowers business users, the service provider retains overall control. Business agility can be achieved through external delegation of policy execution to third parties, and these external services can rely on dynamic event-driven choreography to address rapidly changing business scenarios.

Enterprise applications are increasingly implemented using services. Service-oriented architectures (SOA) supported by enterprise application integration and automation service recovery capabilities matured several years ago, while microservice architectures utilizing a constantly evolving set of cloud-native technologies are on the rise. Governance models for enterprise automation have led to the emergence of automation services that assist in the self-service execution of complex IT tasks. Autonomy remains an important design consideration. Services should not blindly deploy what they are told. Business risks must be considered, and decision pairs formed with Little's paradox approach: making the first decision independent of the controller of the second decision minimizes risk. However, the risk, effort, and skills required to deploy using automation

services should be much lower than not using them. This section explores service-oriented architecture (SOA) and microservice architecture patterns, considers their implications for autonomy, and outlines coupling strategies to enable autonomy across service-based applications.

Service-oriented architecture (SOA) emphasises enterprise-wide service composition, while microservice architecture seeks to maximise the speed and frequency of service delivery. The key principles of SOA–enterprise agility, improved service reuse, reduced integration complexity, simplified administration and maintenance, and business process alignment–resonate with the goals of enterprise automation. Hence, development teams should adopt SOA principles when applying enterprise automation, although the execution of automation tasks using external automation services can improve business agility and reduce risk.

9.3.2. Orchestration and Workflow Engines

Orchestration engines coordinate the actions of distributed services participating in a procedure without requiring close coupling. They execute a defined workflow by invoking services according to a sequence and sometimes directing the flow of control depending on conditions. Special-purpose engines for business processes extend the generic concept to provide capabilities such as long-running transaction support and connection to business activity monitoring, but the core aspects apply.

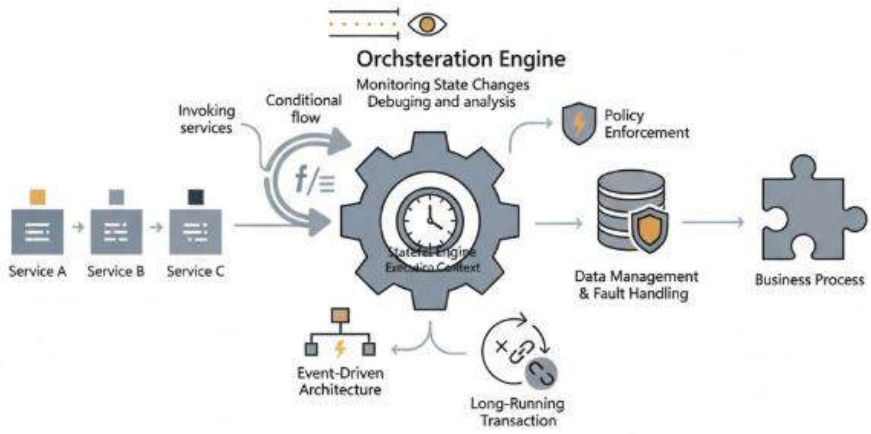

Fig 9.2: Orchestration of State-Persistent Workflows: A Framework for Long-Running Transactions and Decentralized Service Coordination

All stateful engines maintain a representation of the execution context. Lightweight implementations can defer state changes to external events, but service calls usually proceed synchronously, and the state must be updated to track service outcomes.

Monitoring all state changes enables efficient and effective debugging, incident analysis, and business activity monitoring.

The core control flow is expressed through one of the standard languages. Many engines are event-driven, moving a workflow towards its completion as events trigger the invocation of relevant service endpoints. Such designs can use the high-level business process modeling languages to implement the workflow, including state-preserving error recovery and sonar control without requiring low-level workflow languages. Policy enforcement can also be enforced through an event-driven architecture.

Data management architecture is critical for reliable integrated systems; appropriate fault handling and rollback semantics are nontrivial and need careful design consideration. The long-running transaction semantic governs the expected way of handling errors for long-running processes that cannot be rolled back; alternative strategies may expose inconsistent intermediate states, which can lead to an erroneous recovery.

A business process is a complex activity or set of activities pursued by an organization with a defined goal (for example, implementing a new product). A business process extends the notion of a long-running transaction, which involves coordinating the actions of separate services that do not share state, to a much larger scale, generally involving many more moving parts. Business process engines enable such coordination, often leveraging the long-running transaction semantics for fault handling and recovery.

9.4. Governance, Compliance, and Risk Management

Control mechanisms help detect and mitigate operational risks, ensuring that business value is realized. The autonomy of these systems must be balanced against the risk appetite of the organization and should be reflected and expressed in business objectives. Implementation decisions must therefore demonstrate how autonomy is governed, how risk is addressed, how control is exercised, and how compliance is assured.

The mechanisms that govern autonomous execution must support the disciplines concerned with risk management, security, and compliance. Risk management identifies and quantifies operational risks that may lead to service outages, data breaches, or non-compliance and reflects the organization’s risk appetite. Security addresses the risk of service outages and data compromise or data loss, ensuring that business side controls are in place to protect business resources. Compliance ensures that processes operate according to internal policies (e.g., information classification) and external regulations with respect to data protection and privacy. Taken as a whole, these control functions provide the required assurance that the deployed automation will fulfill business objectives with an acceptable level of risk. A summary of this mapping is shown in the table below.

9.4.1. Policy as Code and Automation governance

Policies define the acceptable parameters, constraints, and goals for automated operations and decision-making processes. These policies must be expressed, shared, validated, tested for correctness (to ensure both fitness-for-purpose and fitness-for-use), updated, and audited, and their enforcement must be checked to ensure the policy's intent is actually being adhered to by the autonomous components. The governance gates should therefore focus on these policy aspects. The lifecycle of automation-related policies follows the same general structure as any software development with additional characteristics, which arise from their separation from the operational code.

Policies must be represented in a compact and consistent format that is machine operationalizable and has a clear translation into the non-functional area of security, risk, and compliance. Policy validation should also expose any anomalies within the set, such as conflicting policies or non-permissive lists with no entries. Other forms of stress tests, such as breach and attack simulations, can be applied across the entire stack to highlight gaps and deficiencies. Testing for fitness for use is also an important aspect of advanced production-grade policy governance. This ensures that the policies currently in place actually allow the system to fulfil its expected role. Telemetry data can be fed into a policy testing framework to validate pre-defined rulesets, such as expected traffic flows.

Auditing is critical for tracking policy changes, especially when attempting to highlight any anomalies or patterns in a constant state of flux. When the need arises to review who changed a policy that provoked a dramatic shift in the operational reliability or security position, a simple variation report showing changes along with author attribution will aid the investigation.

9.4.2. Security, Privacy, and Regulatory Considerations

Identification of threat models, data protection mechanisms, access control measures, and mappings to regulatory obligations is a critical component of every enterprise operation, including those performed autonomously. Failure to consider security and privacy from the outset can lead to vulnerable or non-compliant automation, requiring tedious, expensive, and time-consuming fixes. Each service must therefore maintain a security risk assessment that identifies potential malicious or inadvertent threats, the data it manipulates (e.g. personal, financial, intellectual property), how the data is regularly protected, and the use of policies or technology to ensure authorized access only to the appropriate information for each role.

In contemporary enterprises, the cybersecurity and data privacy breath of responsibility is broad and comprehensive. It covers traditional areas of concern such as data secrecy, confidentiality, and availability, but incorporates many more aspects in orders to address

the ubiquitous threat of cyberattack; the more specific requirements of data privacy and protection, encompassing both the risks of allowing inappropriate access and those of gathering sensitive data for machine-learning operations; and the provision of suitable oversight of automated services across the enterprise. Mitigation strategies span the entire range of security and data privacy and regulatory concerns, not only limited to human-controlled operations; consequently, risk assessments for automation will be similarly far-reaching.

9.5. Operationalization and Deployment strategies

Automating processes is just the first step towards achieving autonomy. Autonomous systems must be operationalized and deployed in production environments where robustness, reliability, governance, and compliance needs deter the execution of manual processes. The patterns outlined below enhance production readiness and accelerate both the rollout of new services and the ongoing refinement of existing services. The discussion focuses on autonomous IT services but is equally applicable to business-process automation solutions. To underscore this, the general CI/CD pipeline model uses a generic term, “service,” which encompasses any form of autonomous service.

Continuous integration and deployment pipelines automate the testing, validation, and deployment of code changes. For autonomous services, these pipelines must include additional steps that optimize the cost of cloud-based deployments, check the accuracy of policies governing the operation of the service as a whole, and validate those governing its interaction with specific cloud provider resources. They must also cover preproduction environments designed for the purpose of simulating deployments and executing non-business-critical tasks. Constraints addressing control, compliance, and risk must be enforced at appropriate stages of the pipeline.

9.5.1. Automation Pipelines and CI/CD for Autonomous Services

Productionizing a service for autonomous execution requires more than a working implementation. An automation pipeline, akin to the continuous integration and continuous delivery (CI/CD) pipelines of software development, is necessary to equip the service with the capabilities that maximize its quality and operational readiness. The absence of telemetry, policy checks, auditing, and other safeguards undermines the competitive advantage of harnessing autonomous execution. Each stage of the pipeline should be defined and integrated to guarantee that the service’s operational quality is continuously maintained and maximized. The automation pipeline typically consists of the following stages:

1. Verify: Unit or component tests validate the operation of the service and its components in isolation, without external dependencies. These may be complemented with a mock or stub implementation of the external services that the service calls. The service's defining interface contract allows well-defined mocks and stubs to be implemented, thus allowing tests to focus on the contract of the service with external consumers. The use of mocks or stubs supports the execution of larger integration tests that test multiple components working together without performing full end-to-end tests.

2. Test: Integration tests validate the operation of one or more components of the service with external dependencies. These tests verify the correctness of the integration of components by performing operations that cross the defined interfaces. The tests are usually performed against test or validation environments but may also be executed against the production environment under certain conditions.

3. Policy checks: Policies for automation services are considered as code (policy as code) and should therefore be validated when the policies undergo changes. The different types of policy checks involve syntax validation against the chosen representation language (for example, JSON, JSON Schema, or Open Policy Agent) and dry-run of the validation of test data. Every change in the service should trigger check of the policies to validate if the changes affect the policies or if new policies should be added.

4. Auditing: Changes or additions in control policies should be reviewed before they are applied in production environments and should therefore be recorded in an auditing mechanism. The auditing mechanism and access control in policy checking could be integrated, allowing special roles to bypass the policy verification process.

5. Rollback: An automation service is a business-critical component and should follow good practices normally associated with software delivery in production. Changes deployed in production should therefore allow rollback to a previous version in case of service degradation.

The effectiveness of the automation pipeline determines the reliability and quality of the service and the overall benefits from deploying the automation service.

9.5.2. Observability, Telemetry, and SRE in Autonomous Systems

An effective strategy for monitoring and understanding autonomous systems involves observability and telemetry combined with principles derived from site reliability engineering. Observability implies that key reliability-related properties and metrics of a system can be determined from its external behavior—typically seen in its logs, tracers, and detectors—without requiring access to the source code. Traditional reliability measurement strategies are (almost) not applicable to autonomously executing systems;

instead of being directly measured and taken into account at design time, system reliability is emergent and is inferred from post-failure observation of incident behavior. Thus, directly measuring system fault frequency and cost remains elusive, but availability and reliability goals may indeed manifest as meme-like focuses of engineering effort.

Telemetries like tracing, logging, and alerting convey the operational quality of service of an autonomous system via its monitoring interface, informing an engineering team whether an incident is currently occurring and what may have gone wrong. Service level objectives and their error budgets govern teams that develop and deploy services, assuring that particular key quality properties are built and maintained at desired levels of risk and cost.

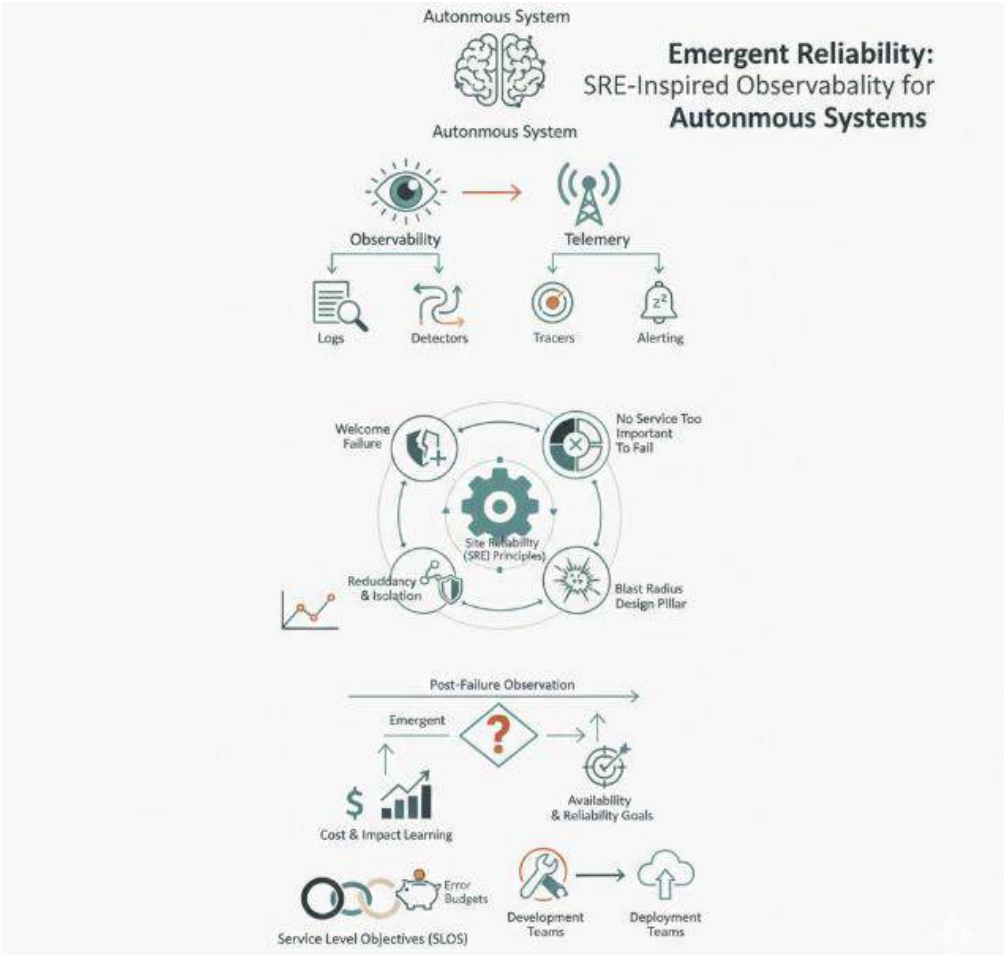

Fig 9.3: Emergent Reliability: An SRE-Based Framework for Observability and Blast Radius Mitigation in Autonomous Systems

SRE possesses especially useful ground rules for autonomous services. For instance, SREs explicitly welcome failure, rather than pretending failure is impossible or unacceptable. No service should be too important to fail (in the sense of too important). An autonomous service that causes too much distress (in terms of cost or impact to customers) when it fails does not have enough redundancy or isolation. Any important service that cannot be designed to withstand the failure of its entire implementation should be allocated to a dedicated team that can respond to its failures within acceptable time frames—and the time spent responding to its failures should not be considered on-call duty. Per using, learning from, and promoting blast radius as a design pillar.

9.6. Economic and Organizational Implications

Technical decisions impact the business bottom line and often require changes in organizational structure, roles, and processes. Computing resources are no longer a scarce commodity but vary in price by geography and time, opening up the decision of where workloads run to optimization. Many cloud platforms offer auto-scaling facilities that increase capacity in times of high demand and decrease it when demand falls. Data storage is cheap but data extraction and transfer costs can be large. Organizations that use cloud or on-premises service instances often pay for underutilized infrastructure.

Autonomous execution can replace the current incremental models of product development and operational support with a concept analogous to the shift to continuous integration and deployment, providing an always-up-to-date, always-ready-to-run service in production, with no special effort involved for end-users. Creating and executing a significant number of production-ready autonomous services is hard work and in many organizations requires new skills, roles, and collaboration models across infrastructure, development, and operational teams.

9.6.1. Compute, Storage, and Cost Management

In orthodox enterprise IT patterns, consumption is constrained to real-time demand, and units are leased. Consequently, the overall cost remains limited. In the proposed model, the effect of autonomous execution on consumption and cost must be analyzed, related to the enterprise architecture and the runtime business needs: to what extent does a typical period of autonomous behavior lead to a higher cost for that service—be it identified as an increase in a line of the business budget, which combined will eventually reflect a higher percentage on the overall consumption, or at least a predictable waste—in terms of consuming resources without direct use?

Though a more extensive model will encompass the orchestrated group of automations composing a larger autonomous episode (for instance, performing risk management), at this level, the effect in terms of total cost of ownership simply increases linearly with the number of independent standalone and ready-for-production implementations being triggered continuously. Such behavior can lead to resource consumption that far exceeds the level offered, driving costs up and having a severe effect on the runtime execution. But it does not bring in even a sign of compensation. Thus, patterns must be established aimed at autonomously defining resource capacity and budget management on a continuous basis, as execution frequency starts producing identifiable patterns over time, becoming the business-as-usual behavior. Such capacity and budget management must also provide guidelines about when and how to auto-scale the entire set of autonomous automations combined, for example, being perfectly suitable for a 5, 10, or 15-minute service.

9.6.2. Skill Sets, Roles, and Collaboration Models

A novel approach to leveraging machine learning capabilities, such as reinforcement learning, deep learning, and boosted trees, to predict and prescribe cost-efficient resource usage is explored. The automation of adaptation planning and execution on a transient infrastructure is proposed. The model-driven specification of user stories and the articulation of domain knowledge are also highlighted. Enterprises are encouraged to create specialized teams combining the technology and domain knowledge to accelerate the automation of task execution over business processes.

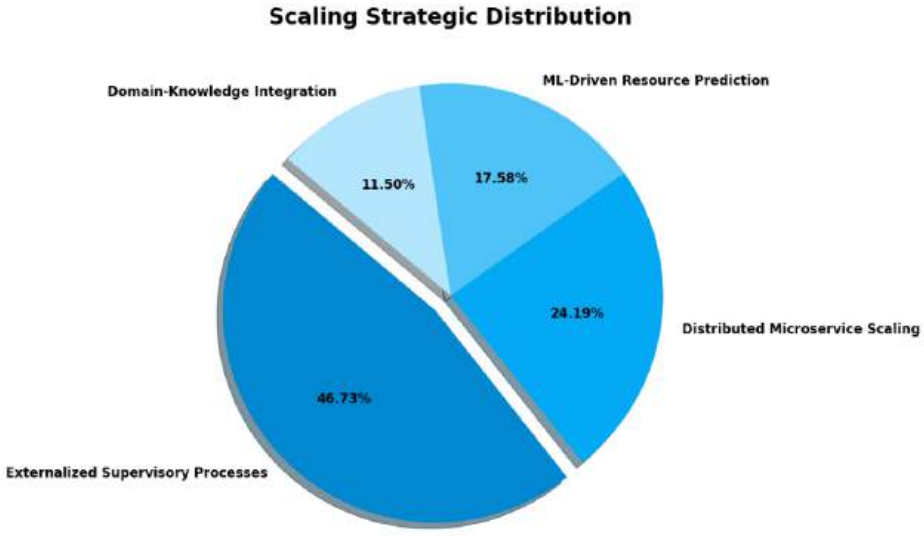

Fig 9.4: Scaling Strategic Distribution

Certain cloud-native architecting and engineering practices can facilitate the scaling of autonomous computing capabilities, especially in service-oriented and microservice-based application environments. Adopting a distributed architecture and deploying autonomously operable yet interdependent components enable separating autonomy-awareness from orchestration, externalizing high-level supervisory processes from actual task execution, delegating decision-making to the task-execution level, and simplifying observations, real-time response, and auditability.

9.7. Conclusion

Enterprise operations naturally encompass functions that differ in complexity and risk. Hence, some functions within these operations can be executed autonomously, and in many cases should be executed autonomously, or at least, the set of functions that can be executed autonomously should be expanded as much as possible. Autonomous execution brings certain measurable benefits, but also carries some inherent risks and is not yet possible for all areas of enterprise operations. In some areas, such as infrastructure management, policy enforcement, and security, organizations have been actively pursuing increased levels of autonomous execution for years. In other areas, such as marketing, enterprise resource planning and non-infrastructure business process management, the notion of autonomous execution has not yet been integrated into the mainstream thinking; however, the resulting benefits from truly autonomous autonomous execution of enterprise operations are so significant that pursuing some level of autonomous execution in all areas is beginning to gain traction.

The operationalization of a first enterprise function for which autonomous execution is natural and for which it has already been widely adopted outside of enterprise is a natural starting point. Supporting that operationalization requires careful definition of the required execution environment, identification of all non-functional requirements, addressing of the most important governance and risk management considerations, and definition of clear patterns for moving the function into production and maintaining it on an ongoing basis. Such patterns also serve as a foundation for operationalizing many other enterprise functions and remaining non-functional requirements for those functions supporting a more principled approach. This work outcome lays the groundwork for analyzing and addressing those aspects of those other enterprise functions that should be autonomously executed.

9.7.1. Final Thoughts and Future Directions

Scaling autonomous execution across enterprise services offers a coherent, evidence-based, formal articulation of the policy, military, architectural, and organizational

considerations necessary to facilitate be-any time, be-anywhere ownership, management, and execution of enterprise services. Future directions address two pressing areas: social and economic models that realize labor automation at all levels, and a practical, production-ready framework that connects Critical Signals, Operational Policies, and Autonomous Systems.

Achieving the next level of autonomy, enabling the enterprise to support be-any-time, be-any-where ownership, management, and execution of any enterprise service by any service consumer, progressively scaled from the people, processes, technology, and partners involved in the initial implementations, depends on a more realistic simulation of enterprise service consumption and execution than current test and staging environments provide, especially the visibility of confidence levels associated with the Critical Signals that control flows through supporting Autonomous Systems (e.g., a failure condition discovered only by running the production service without a run-book that stitches the status and fault business processes together). A production rollout approach that involves simulated consumption of planned changes through a Continuous Integration/Continuous Deployment pipeline also resolving production-significant Operations Requirement Signals for later consumption by the Operate Operations Policy and/or Autonomous System, rather than the Operation team, may further alleviate concerns that invariably arise during production rollout of such high-stakes solutions.

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