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Chapter 2: Architecture of Integrated Systems for Modern Industries

2.1. Introduction

The rapid emergence and adoption of the Internet of Things, Edge Computing, Cyber-Physical Systems, Digital Twins, Artificial Intelligence, Blockchains, 5G Telecommunications, Quantum Computing, such as yet other radically new technology trends manifesting their effectiveness and potential to disrupt traditional approaches, is gradually reshaping the fabric of modern industries all over the globe. All these advancements are enabling the development of tailored systems fulfilling specific requirements, whether in manufacturing or energy, transportation or healthcare, environment or safety, security or finance or any other sector. The gradual implementation of such tailored systems constitutes what many refer to as the Industry 4.0 revolution paradigm shift. These trends and developments are presenting novel opportunities yet also introducing unprecedented challenges when it comes to implementing integrated systems that allow diverse technologies, plants, and services to work cohesively and appear as a single powerful facility to customers, for example.

To serve specialized, niche purposes yet work collectively as a more complex Super-System in a decentralized manner whenever possible, the industry-focused systems are best understood as a specific instance of What System of Systems encompass: a collection of independent and using different styles in terms of technology, infrastructure, and system integration approach to fulfil dedicated function(s) that can combine efforts at certain times yet also be utilized separately, when needed, in a truly scalable and flexible way. As such, the more special cases of theme-based industries represent then a resolution to the two-size-fit-all dilemma by allowing the deployment of specialized systems tailored for niche areas while also providing integration patterns that permit combining resources across the broader landscape when needed.

2.1.1. Overview of Integrated Systems and Their Importance

Integrated systems combine heterogeneous information and hardware systems integrating sensors, machines, and cloud services. The technological advances of the last decade allow the integration of a multitude of products, services, and sectors such that each product or service could be considered a multi-faceted System of Systems (SoS). The pace of change in business imperatives is accelerating and the need for adaptation and rapid reconfiguration of integrated systems is imperative. To cope with these challenges, some industries opt for a Digital Twin of Organization (DTO) strategy, leveraging a digital representation of their physical assets, resources, processes, relations, and business ecosystem to plan, monitor, react, and pre-empt changes in near real-time. DTO provides situational awareness by allowing industries to aggregate, monitor, and analyze incoming data, but a mere combination of the Industry Internet of Things (IIoT), Edge Computing and Cyber-Physical Systems (CPS) is not sufficient. A thorough architecture of the integrated system is essential to tackle the inherent and escalating complexity of integration.

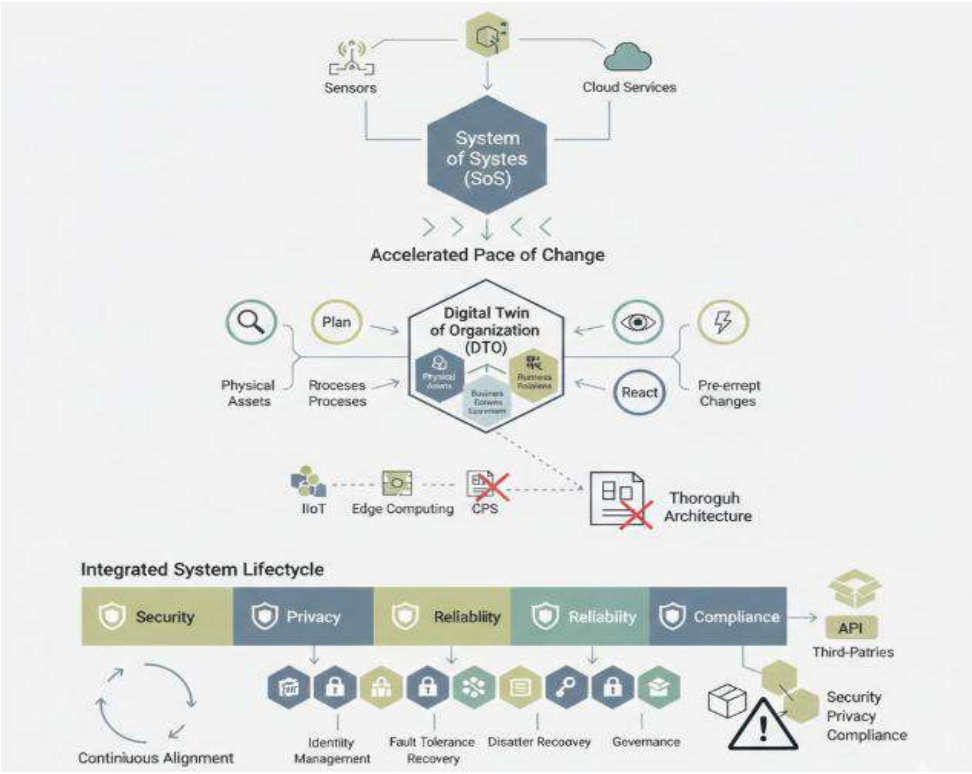

Fig 2.1: Architecting Adaptive Ecosystems: A Digital Twin of Organization (DTO) Framework for Secure and Compliant Systems of Systems

Integrated systems are increasingly addressing Security, Privacy, Reliability, and Compliance throughout their entire lifecycle. Stakeholders expect proper Identity

Management, Access Control and Auditability; high levels of resilience and fault tolerance; measures for Disaster Recovery; Governance and DevSecOps, to guarantee continuous alignment with laws, regulations and industry standards; and assurance of the Security, Privacy and Compliance of the whole integrated ecosystem. Integrated systems are becoming more and more open: exposed Services, mainly through APIs, allow third-parties to integrate their products and services, extending the COTS (Commercial Off-The-Shelf) offer, but in exchange put Security, Privacy and Compliance at risk.

2.2. Foundations of Integrated Systems

Integrated systems for modern industries are characterized by a deepened notion of system-of-systems, requiring hybrid cyber-physical and digital information assurance properties and supporting integrated mission patterns. Interoperability is both at the core of the definition and at the heart of the challenge of integrated systems for modern industries, made employable by established layered architectural models translated into a syntax foundation for integrated system design. Integrated systems enable advanced and smart applications by realizing integration and supporting complex interactions and regulations of multiple systems spanning business, operational technology, and information technology. The core models of system design for industry from industry are used and include the industrial internet of things and edge computing, cyber-physical systems and digital twins, event-driven and messaging-based architectures, the service-oriented and microservices models, and composite system-of-systems patterns and interaction models.

These design foundations are then complemented with security and privacy aspects, referring to identity, access, and auditability and extended by resilience, security-by-design, and disaster-proof considerations. The refinement is concluded by governance design supportive of the constitution of the integrated system. Existing industry standards and policies complement the synthesis. The complex design and operational requirements combine aspects of governance, structural, and functional design patterns that realize an enterprise-enabled system suitable for modern industry needs and far beyond.

2.2.1. System-of-Systems and Interoperability

Integrated Systems may be viewed as instances of the System-of-Systems concept. A System-of-Systems is defined as a collection of independent and useful systems that jointly provide a capability too complex for any individual system. The constituent systems functionally interact yet retain operational independence. For Integrated

Systems, operational independence is clearly determined by business objectives: participation is voluntary, and systems exist because they satisfy their owners.

The creation of Integrated Systems aims at supporting business imperatives while satisfying a set of non-functional requirements that guide system design. The Integrated Systems non-functional requirements emphasize openness and interoperability across system boundaries. Openness means the ability of participants to discover partners who can support their needs and to connect and interact with them. Interoperability implies the ability to exchange and interpret data and to comply with operation requests. Supporting openness and interoperability makes Integrated Systems particularly challenging. Openness leads to knowledge and operational asymmetries among participants. Interoperability demands continuous updates to the information about partners and to the mediation logics needed to manage interactions.

2.2.2. Layered Architectural Models

Layered architectural models define different abstraction levels necessary for designing a system. In the case of integrated systems, it is important to use a layered approach for system design in order to address the complexity of the integration and the heterogeneity of the technology landscape. One obvious choice is the ISO/OSI model applied to the integrated system network communications. Resources in integrated systems are composed of other integrated systems. This property enables resource description following an architectural hierarchy.

Integrated systems supporting complex environments usually connect to numerous third-party systems that interact with middleware solutions (commonly used in SOA). Such architecture usually depends on event-driven communications to ensure reactive responses. As nodes in integrated systems are usually constrained devices, special care should be taken to ensure that resource connections and disconnections do not overwhelm the limited processing power and memory. In any environment, cleaning up messages and subscriptions is important for optimal resource use. Therefore, a watchdog should check periodically whether a node is still operational. When a failure is detected, a message about its disconnection should be relayed to the middleware, responsible for propagating connection and disconnection events to the proper subscribers.

2.3. Reference Architectures for Modern Industry

Integrated systems are being developed for fields such as smart cities, smart factories, and smart agriculture. Emerging reference architectures for the industrial Internet of

Things (IIoT) and edge computing, cyber-physical systems, and digital twins constitute a basis for deriving integrated systems within these domains.

Industries have been integrating information technology and operational technology for several decades, especially in the automation of manufacturing processes. However, developments and trends over the last decade (e.g., the industrial Internet, Industry 4.0, IoT, big data analytics, artificial intelligence, cloud computing, and edge computing) have led to the accelerated development of industrial internet-enabled integrated platforms. The advent of cloud services enables businesses of all sizes, from start-ups to enterprises, to build, test, deploy, and manage applications using cloud services. These services enhance availability and reliability for applications.

Cybersecurity risks, privacy breaches, and data governance have emerged as critical issues for businesses. Added to these are the unique privacy needs of data owners, especially in the smart city sector. As users, developers, managers, and maintainers move to the cloud, there is increasing demand for more responsive, flexible, and scalable applications. Major vendors are deploying cloud services across multiple geographic areas and horizons to meet this demand. These developments offer opportunities for tier-two or tier-three vendors to rent these services for the development of vertical-domain applications and solutions. Important short-term trends in the IIoT ecosystem include the delivery of innovative and new solutions using artificial intelligence/machine learning, seamless interoperability, deployment of data, prevention of data hoarding, and better system support to enable compliance with regulatory and legal requirements.

2.3.1. Industrial Internet of Things and Edge Computing

Accelerating digitalization in modern industries leads to the continuous emergence of new systems, applications, and products that share enormous volumes of data across an extended use-life to improve performance and security by means of Artificial Intelligence and Machine Learning. Such systems comprise the so-called, yet unstructured, cyber-physical industry ecosystem, which is commonly represented as a modern system-of-systems.

The often-cited Internet of Things connects these devices in a way that integrates them into any system of interest. The largest part of IoT-specific infrastructure is designed to meet the needs of consumers—the so-called Internet of Everything. The Cyber-Physical Systems vision highlights the need for a similar new infrastructure for industry and critical infrastructure in general, which is sometimes referred to as the Industrial Internet or more recently the Industrial Internet of Things. It envisions a system-of-systems composed of industry-based things that implements an industry-specific IoT-to-Cloud infrastructure to manage the relevant data over its service life, which often spans

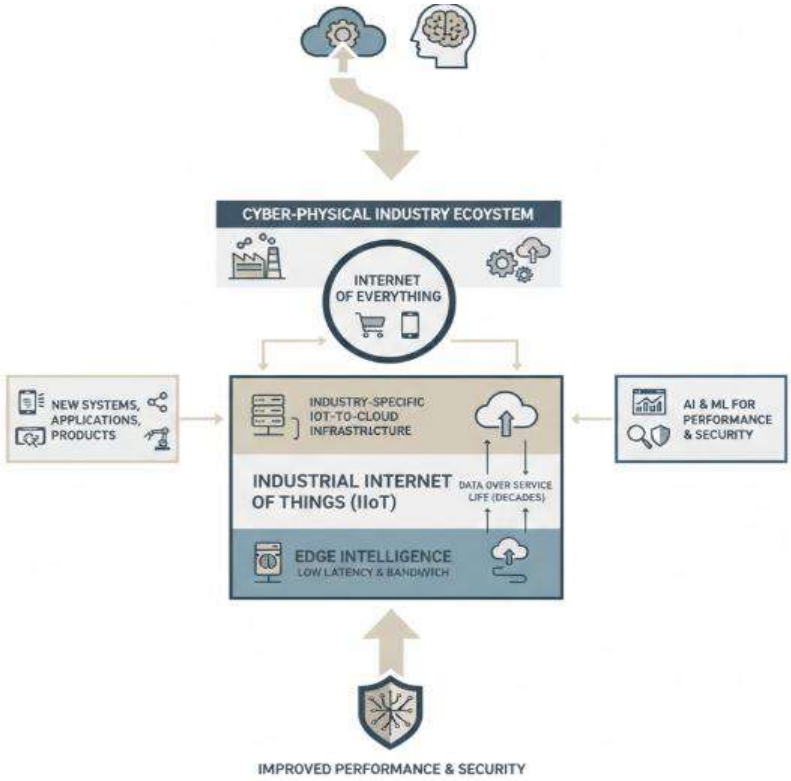

Fig 2.2: The Industrial System-of-Systems: Integrating Edge Intelligence and IIoT-to-Cloud Infrastructure for Long-Lifecycle Cyber-Physical Ecosystems

decades. Edge Intelligence extends the concept of Cloud Computing into the Edge. The Edge refers to Cloud Computing infrastructures that are located geographically close to the data sources or sinks, aiming to reduce latency and bandwidth use in data transmission while enabling faster response of applications. Edge Intelligent Computing integrates Edge Computing with Artificial Intelligence.

2.3.2. Cyber-Physical Systems and Digital Twins

Understanding the fundamental components of Industry 4.0, its research domains, and key technology areas is crucial. Cyber-physical systems (CPS) are an essential building block of Industry 4.0. These systems integrate physical processes, computing, networking, and physical devices through specialized software. They bridge the physical and digital worlds by monitoring physical processes, making decisions based on context and knowledge, and controlling physical activities. Digital twins further extend the CPS concept by integrating the physical and virtual gauges of an enterprise's operation through simulation.

The digital twin technology allows organizations to integrate data to create a real-time digital replica of assets and processes. By integrating engineering knowledge with data from operations and services, organizations can inform real-time operational decisions and enhance predictive capabilities through analytics. Transforming data into information enables optimal decision-making, thereby increasing agility, transforming existing business models into new revenue streams, and enabling faster product realization.

2.4. Integration Patterns and Design Principles

Integration requires the cooperation of the individual components and their interplay, which is controlled by a central co-ordination mechanism. The emerging diverse and large-scale integrated systems pose new challenges in the architectural design of these systems. Compared to the traditional well-defined and small-scale integrated systems, heterogeneity in computers, sensors, communication networks, protocols, and algorithms makes it difficult to achieve effective co-operation in a seamless way.

A messaging framework based on publish/subscribe mechanisms is introduced to support distributed event-driven integration for data-centric integrated systems. A service-oriented architectural model based on web services provides an integration platform for component-based and communication-centric integration. Microservices are also practical when implementing these patterns to meet the requirements for cloud computing systems and embedded systems, respectively. Since replaying events may still be preferred for certain applications, mechanisms are also explored for addressing this need with event-driven architectures.

2.4.1. Event-Driven Architectures and Messaging

The event-based architectural style has proven valuable in modern information systems that require distributed and decoupled components, built around a publish-subscribe paradigm. This principle can also apply to a broader range of components, including physical assets and human users in an enterprise environment. An event-driven architecture often combines event-centric design and operational management with a message queue that acts as a dedicated data distribution and consumption layer for any type and size of data. In this context, the message queue can operate using Lightweight Publish Subscribe or as a Message-Oriented Middleware, depending on the amount and frequency of data being exchanged.

Event streams and clouds naturally handle incremental changes, making them suitable for applications based on Digital Twin technologies. Such applications are inherently

event-driven, where a change in the physical process triggers the appropriate actions on its Digital Twin resident in the Cyber-Physical System's Cloud. Event sources also include the satellites within an emerging Space-Based Internet-of-Things infrastructure. Here the events signal periodic updates of the monitored area, weather conditions, and the operational status of each satellite, created by connections made possible by a Space-Based Communication infrastructure. In fact, Cyber-Physical Systems with Digital Twins and platforms supporting Space-Based Internet-of-Things are reference areas for the emerging Industrial Internet-of-Things, as wide-area services utilize sensors to detect physical phenomena at a given point in time and space.

2.4.2. Service-Oriented and Microservices Approaches

As organizations adopt information systems based on the Internet of Things, the service-oriented architecture pattern is well suited to facilitate integrated system designs. Some enterprise use cases for these systems have shown that decoupling an integrated system into multiple services allows for the parallel development of systems within a given use case. Service management tools help to establish the necessary integration, scaling, and resilience of the system, yet risks of service sprawl must be actively managed.

In some functional areas of an enterprise, the use of microservices architecture may further improve the flexibility and agility of service development and operation. Microservices decompose a service into multiple self-contained units whose implementations can evolve independently. The individual microservices of an integrated system may communicate through a service mesh, supporting additional capabilities such as observability and security on a per-service basis. Microservices technology can also facilitate incremental evolution toward an integrated systems architecture, as the development, deployment, and operation of microservices may be independently managed according to their cycles.

2.5. Security, Privacy, and Reliability in Integrated Systems

Integrated systems must securely manage digital assets while maintaining privacy and reliability, particularly for sensitive data such as business secrets or personal information. System complexity further complicates the establishment of trust in security mechanisms. Well-defined identity, access, and auditability capabilities govern digital asset usage. Resilience, fault tolerance, and disaster recovery ensure continued operation following failures caused by malicious attacks or accidental malfunctions.

Identity, Access, and Auditability: Integrated systems incorporate device, software, and user identification in closed environments as part of an identity and access management

solution. Device and software identification, typically combined with two-factor authentication, facilitate trusted messaging, asset usage, and service composition. Users are identified at entry points via two-factor authentication, tracked via association with active session management software. All monitored digital asset usage, such as messages sent, databases referenced, files accessed, and assets consumed, is recorded. In open environments, such as the Internet, the same principles underpin a solution based on digital certificates and public keys with hierarchical or peer-to-peer structure. Auditability is ensured by data recording and algorithms for detecting malicious behaviors, misuse, abuse, or improper use of digital assets.

Fig 2.3: Securing the Digital Commons: A Unified Framework for Identity, Access, and Forensic Auditability in Hybrid Integrated Systems

2.5.1. Identity, Access, and Auditability

Security for integrated systems must address confidentiality, integrity, and availability metrics that are supported by resilient and robust implementations. Recent trends in cloud computing and cyber-physical systems increase the requirements for security hit

the cloud. In a cloud environment, security services are often configured, accessible via user friendly management consoles, and in general cheap to use and life-cycle. Cloud computing is instantiating a new model where security services become available, supporting intrusions detection, identity management provisioning, monitoring, secure data provisioning, key provisioning to name some of them. Security-as-a-Service delivers solutions directly from a cloud provider eliminates the complexity of deployment, configuration, and management of security services, but normalisation in the cloud computing industry is still on the way and Service Level Agreement still require a high level of attention since deduplication represents a high risk of a lack of proximity for the data. Consequently, security requirements tend to be suppressed by infrastructures managers focusing mainly on availability and not on confidentiality and integrity.

Security has to be applied as a pattern in the design phase and not as patching library in the implementation phase with clearly defined roles and responsibilities for access management both at human and program level for security auditability. Security is required to be modular in order to use the most suitable library/service for a particular requirement and access to sensitive data and resources needs to be carefully handled and controlled. In an IoT-based infrastructure the area of identity management and access management becomes critical given the number of devices that need access to sensitive data and resources and the number of services that can be compromised and used to access sensitive data.

2.5.2. Resilience, Fault Tolerance, and Disaster Recovery

While many Integrated Systems for modern industries have stringent counterparts, such as a zero Downtime requirement in External Systems, it is reasonable, and even economically viable, to set resilience, overall reliability, and maintenance costs on an acceptable value rather than a target value of 100%. Cost/benefit analyses can be elaborated with industrial use cases. Nevertheless, Business Continuity must be a top priority of any organization supported by an Integrated System, due to the huge dependence of the operation enterprise on these Systems. To achieve this, Disaster Recovery and Business Continuity Plans aligned with Business Continuity Plans must be defined, implemented, updated, and tested regularly. As Integrated Systems are composed of multiple Subsystems, each Subsystem normally has Internal Systems whose function is to manage fault detection and management, and put in recovery, unless they are out of the resilience targets, the services of the monitored Internal System. A useful approach is based on layered management of Internal Systems, Machine Learning and Business Data Analysis, treating each Internal System's component and service as a subject for Failure-Cause Prediction and, as consequence, redefinition of the Resilience

Cost/Benefit Model. Further approaches to Fault Tolerance, such as Partial Redundancy or Multi-Organization collaborations, can also be evaluated.

Integrated Systems are being made resilient all over the world to control the final level of part of the Systems that are completing a process and being that make that part slow. A high rate of repeated Finished Processes at this slowed part of the system is detected with the support of Machine Learning and a business rule. An ideal Solution would be to stop that external system and dedicate that part of the Integrated System to that external system. However, pausing an external factory's production and allocate resources dedicated to it are highly complex and costly decisions (transfer of raw material, money transfer, allocation of man power not required, redefinition of security aspects). The faster approach being used is detect real slowness on part of the Integrated System followed by a tolerance limitation on the response time of the Integrated System before being penalized and allowed for a set support at that external system."

2.6. Governance, Standards, and Compliance

Integrated systems call for governance structures, compliance with quality and safety standards, and adherence with international standards. Industry standards, created through the collaboration of governments, manufacturers, and operators, address vital aspects of business-to-business and business-to-consumer transactions, product quality, operation safety, manufacturing processes, electromagnetic compatibility, chain-of-custody, and Because integrated systems are susceptible to security breaches, privacy violations and service failures, ensuring identity and access management, providing audit authenticity, addressing resilience and fault tolerance, and enabling disaster recovery are respected compliance elements. The secure-by-design principle calls for embedding preventive, reactive, and detective security mechanisms from the design stage. Products, services, and processes must also respond to their clients' demands for secure lifecycle management and digital sustainability. These objectives are answered by DevSecOps, a collaborative development and operation approach that integrates the traditional "DevOps" model with explicitly-defined automated capabilities to enable security and privacy protection.

Compliance with the standards of industry foundations associated with primary international organizations promotes interoperability across a variety of different technical domains. Common definitions, classification categories, and terminology enable industry foundations to develop interoperability standards and guideline documents that accelerate technology adoption and business realization. Supply-chain and lifecycle management standard organizations govern the development administration and adoption of standards for the management of supply chains and the secure integrated lifecycle of products and systems, including services. International

government bodies are responsible for communications, electromagnetic compatibility, and information technology security.

2.6.1. Industry Standards and Interoperability Protocols

A side effect and requirement of interoperability in Integrated Systems is the availability of suitable standards. Different industries and institutions participate in establishing formal and informal consistency requirements and implementations for devices, platforms, architectures, processes, and protocols. These comprise industry standards such as the ISA-88 model of batch control operations, which is implemented in systems of the process industries, the IEEE 802.1 Time-Sensitive Networking standards that make Ethernet suitable for the transport of audio and video, and the DNP3 standard for the monitoring and control of Electric Power Systems.

The availability of appropriate semantic standards that allow the mutually understanding of devices developed by different competing companies is crucial for the adoption of IIoT in electric power systems. In this area, devices developed by different companies do not understand each other despite the relatively small number of different control functions that syste.ms need to accomplish. For example, a relay produced by one manufacturer cannot be commanded by a relay made by a competing manufacturer to open a circuit in a line at another location. Proper semantic standards could also provide for the integration of legacy devices. Other examples are the definitions of the syntax and semantics of data messages in the case of the OPA communication protocol. One of the simplest examples is represented by the KHR0S radio protocol for the control of simple radios in a poorly concrete-definition-of-operating-point-environment. Emergency brakes commonly provided in a vehicle using public transport.

2.6.2. Lifecycle Management and DevSecOps

Software lifecycle governance requires strong support for automated provisioning in combination with Identity & Access Management (IAM) – ideally based on Industry Standard Protocols (ISP) – up to DevSecOps capabilities for integrated verification across the entire lifecycle. In this context, DevSecOps integrates security into the DevOps integration process by applying policies and tools to mitigate security risks in the pipelines so that security is integrated into the code instead of being fixed after the fact. The principle of “Shift Left” is used to highlight the fact that security detection is integrated earlier into the software engineering and testing processes through Infrastructure as Code (IaC) security scanning; template scanning and monitoring to help ensure that runtime environments are compliant with security posture; use of Declarative Secure Baselines to validate security at the start of the pipeline and automating security

testing during the testing phase. DevSecOps promotes a security culture across all participants within the workflow – both in development and operations – through education, assurance of security best practices being simply achievable within the integrated DevOps environment, integrating security education within the development lifecycle and secure toolchain management to facilitate DevSecOps adoption.

Scientific publications on the evolutionary nature of the Integrated System architecture support the proactive preparation for the complete transformation of an existing environment into a digital transformation flow based on a services system with no boundaries between private and commercial services. As organizations adopt and shift towards software-defined data centers and data fabrics the relevant abstract architecture model should characterize all logical high-level operating activities within the complete integrated system from the data source and control systems, through the IT enterprise and base services, as well as the relevant integration support. Consequently, the adaptation of the Logical 3-8 Architecture to incorporate DevSecOps as a complete set-up and policy for recruiting, provisioning, operating and maintaining any IT enterprise cloud service application is achievable while ensuring that all new core integrated system cloud enterprise are under Infra as Code (IaaC) management.

2.7. Conclusion

Today's computational systems increasingly utilize a wide variety of cooperating devices and services on massively distributed computing infrastructures connected

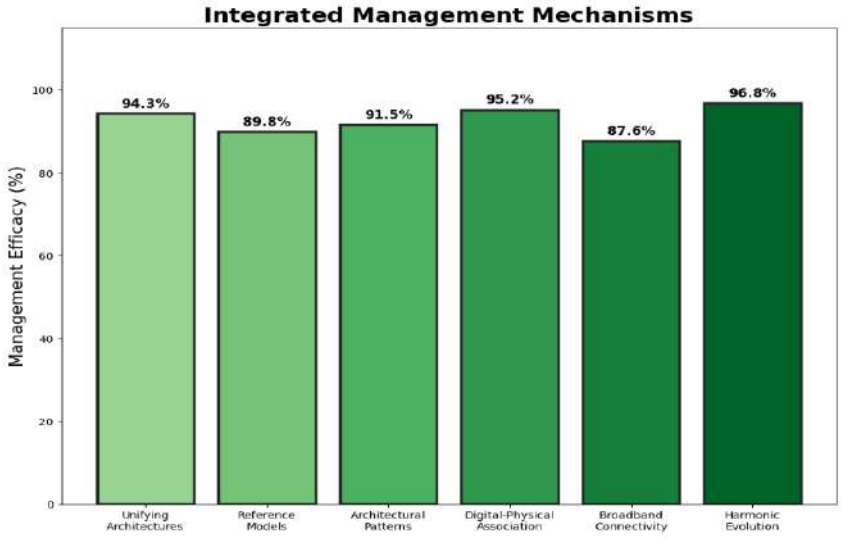

Fig 2.4: Integrated Management Mechanisms

through high-speed broadband networks. New solutions are required to efficiently manage systems composed of innovative components enabled by the collaborative association of both digital and physical worlds. Integrated Systems provide such a management mechanism through unifying architectures, reference models, and appropriate architectural patterns, thus systematically handling the full complexity of digitally transformed modern industries while presenting a harmonic evolution of related themes without unnecessary overlap.

Future research should investigate advanced templates specific to Integration Patterns for Real-Time Embedded Systems, Cyber-Physical Systems, and interactions between the Internet of Things and Cloud Computing paradigms, whose convergence constitutes the Intelligent Edge. Interest should also grow in the dynamic evolution of Security, Privacy, and reliability dimensions, as well as in life-cycle management concerns associated with Governance, Development, Compliance, and Operation.

2.7.1. Final Reflections and Future Directions

Over the last decades, SOA has emerged as a prominent architectural pattern in information technology, with the goal of enabling the integration of heterogeneous systems through coordination and collaboration. While these services are traditionally developed and responsible for supporting internal applications, in SOC they are exposed to third parties for consumption, either from users or other applications. Furthermore, the Internet has fostered new forms of business cooperation among independent actors, all connected through service interfaces. The widespread deployment of devices capable of sensing, acting upon, and affecting the environment has also accelerated the demand for services that support indirect interactions among those devices. Such evolution has generated a paradigm called Web Services that enables Internet-scale discovery and invocation of services.

In parallel, there is a profound transformation under way in industrial systems with respect to the way they are designed, operated, and used. Real-world systems and their digital counterparts are becoming more closely networked and more integrated through the convergence of IT and OT technologies. Thin film technology and nanostructures with modularity and multi-functionality characteristics will lead to the demand of a permanent close relationship between “activity” and “information” providers. Device networks, sensor webs, and agent-oriented systems will create environments for sharing data and services among all nodes. The growing energy demand, mainly in urban areas, combining weather-related data will demand not only a focus on energy generation, but also a continuous analysis and intelligent prediction of energy distribution.

To complement the above-mentioned SOC architecture foundations, two recently matured concepts are contributing to modernize the way of understanding industrial systems: cyber–physical systems (CPS) and the digital twin concept. CPS can be defined as systems that integrate computation, networking, and physical processes, emphasizing the close coupling between these components and their preeminent Internet connection features. The digital twin concept rides on top of the CPS concept as it involves all phases of the product lifecycle.

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