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Chapter 5: Orchestrating Intelligent Agents and Automated Workflows

5.1. Introduction

As automatic speech recognition, computer vision, and automatic language translation become commodity cloud services, the web is transforming into an intelligent service-oriented application platform. Beyond available cloud services, competing enterprises are investing in the creation of knowledge databases that permit automated internet agents to become intelligent knowledge worker partners. These trends suggest the emergence of complex interconnected agent-based workflows that would decompose a high-level goal into parallel subtasks, continuously evaluate progress, orchestrate the subtasks, and identify and remediate bottlenecks or problems.

For such agent-wide orchestration to occur, the agent community must have a common language for describing service and capability offerings, an understanding of the types of workflow combinations that can occur, and a clear view of the orchestration dynamics. Orchestration refers to the design and maintenance of coordination mechanisms. Choreography refers to automated work that can be assembled from services published by other agents. The construction develops definitions and taxonomies for intelligent agents, automated workflows, and the underlying concepts that would enable the intelligent orchestration of parallel, decomposed agent work.

5.1.1. Overview of Key Concepts and Objectives

Orchestrating intelligent agents and automated workflows—representing the entire range of physical, information, or knowledge-based automation technologies—encompasses two highly interdependent areas. Orchestration refers to the coordination of activities across a diverse set of autonomous intelligent agents that operate as a cohesive system of systems. Automated workflows represent the coordination of automated tasks, activities, or processes across information-systems-interfaced applications.

Orchestration incorporates concepts from both the slew of scientific domains covered by the term intelligent agents and the automated workflows field straddling the discipline of information systems and adjacent fields such as software engineering, business process management, and enterprise architecture. Intelligent agents are defined and categorized; their architectural templates described; and assembly principles provided. The narrative focuses particularly on agent-wide orchestration or how the entire set of agents are coordinated through a shared mental model. Command, control, and communication—including the most advanced applications of digital education and chat—are the change tools to maintain this shared situational awareness so that workflow factories effectively operate automatically end to end.

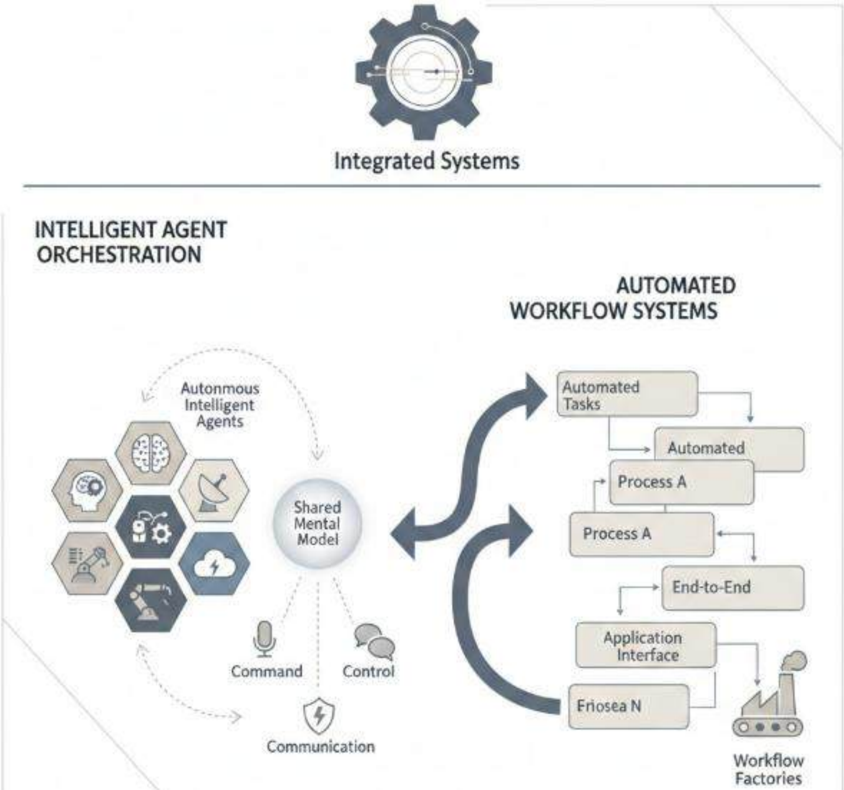

Fig 5.1: Architectural Foundations of Agentic Orchestration: Synchronizing Shared Mental Models with End-to-End Automated Workflow Systems

5.2. Foundations of Intelligent Agents

1—Definitions and Taxonomies

Intelligent agents are generally defined as hardware or software entities that can perceive their environment and act autonomously to pursue goals. The perception-action cycle is universally accepted as the defining characteristic and is the core model of intelligent control, but many perspectives on intelligent agency exist. Russell and Norvig's AI textbook divides intelligent agents into four classes—simple reflex, model-based reflex, goal-based, and utility-based—according to their degree of sophistication. Other categorizations describe agents as reactive, deliberative, or hybrid. Yet other taxonomies employ the distinction of data-driven versus goal-directed, or emphasize rationality, learning, and communication. A comprehensive taxonomy of agents recognizes the influence of collaboration and competition, individual versus collective rationality, mental structure, learning capability, and timing on the design of intelligent systems. These and other perspectives transcend the distinction between artificial and natural agents; for example, human agents share a common design with a word-processing system, and how a set of agents should behave in a work environment is independent of whether the agents are human or machine.

2—Architectural Patterns

Intelligent agent design is guided by architectural patterns that capture the essential operation and structure of intelligent agents. Two observed patterns recur in the design of different agent classes. The subsumption architecture captures the stepwise construction of a system as a layered composition of simple reflex agents, giving rise to complex behaviors voted by multiple reflexes. The BDI architecture provides an abstract sensor-actuator model including a poor mental state—declarative beliefs plus procedural desires and intentions—operated by a set of three generic mental processes: how to select a desire for intention, how to select an action intention, and how to execute an action intention.

5.2.1. Definitions and Taxonomies

Intelligent agents are widely discussed in the literature, yet no clear consensus exists regarding their definition or classification. This is not surprising, given the diverse communities that have taken an interest in the topic and the perspectives that see intelligent agents as a means to a goal, rather than a thing in itself. Within distributed AI research, substantial effort has been devoted to an architectural perspective on agents; however, these contributions represent the work of primarily one sub-community. An alternative taxonomy, based on the agent’s objectives, is more widely used, but many different interpretations are adopted. Until there is broad agreement on a proper definition and classification, the term will remain too vague to be useful.

Intelligent agents (henceforth referred to simply as agents) can therefore be defined as entities that perceive and act autonomously within an environment. Agents can also be seen as problem solvers that use perception to gather information about their environment and action to change their environment. Over time, they build a model of their environment, called a mental model, that stores relevant information about how it works. The terms "agent" and "agent-based system" will not be exclusively reserved for structured systems containing multiple agents working towards a common goal. A single-agent system will still be considered an agent-based system, because the term is used more generally to classify a set of architectures or frameworks for implementing systems and their characteristics.

5.2.2. Architectural Patterns

Architectures in any domain define the participating entities, their interrelations, and groupings, and thereby the types of collective and inter-related activities that can be accomplished. All the entities in an agent-wide architecture take roles in a plan, structured as needed by the task, and participate in its execution acting cooperatively, complementary to each other. All possible workflows are analysed and know-how is coded (preferably automatically or semi-automatically) in the form of development process meta-models that define the possible roles (the corresponding skills the agents must have) and how these roles are recursively grouped.

A sensible distinction for agent-wide orchestration is based on the breadth of coordination required. Activities involving only a small number of agents can be handled by simple message passing; with appropriate shared resources, repositories, and document management systems, agents can leverage knowledge and data developed elsewhere. At the next level of breadth, workflows guided by orchestration meta-models can be enacted (elementary workflows). These structure how agents perform their tasks, mostly independently but with a manager acting as high-level coordinator via successive degrees of reaction to problems. Agent-based systems supporting the execution of application workflows that are themselves agent workflows belong in this grouping; they can be built out of agent-based workflow management systems plus any system that supports multi-agent environments. Finally, systems where the actual task consists in devising a plan or an agent-wide plan fall into the category of deliberative multi-agent systems.

5.3. Automated Workflows: Concepts and Context

Automated workflows have been the subject of years of academic research, and they occupy a prominent role in industry and commerce. Industry leaders have developed and deployed workflow management systems that provide software implementations of the key engineering concepts underlying workflows. These systems enable companies to increase work deliverables, reduce costs, and improve quality by automating many repetitive or predictable tasks that would otherwise be done by people. Yet, these industry offerings do not provide the full functionality desired by process engineers. They allow the precise specification of the sequence of structured tasks, including data dependencies, that must be followed, but they do not encompasses aspects such as providing a range of alternative implementations, deciding which implementation to execute at any given time—or whether to execute the process at all—monitoring the execution, intervening in the execution, or continuously improving the definition of the task.

Real-world processes must be seen as implementations of higher-level processes that specify desired outcomes rather than preordained sequences of actions to be followed. The design and execution of these higher-level processes is often referred to as orchestration, while the engineering of the lower-level processes as choreography, emphasizing that it is the participants that determine how best to achieve the desired outcome. The orchestration–choreography distinction is not an exclusive one because many processes that are considered inner-loop processes also need to be orchestrated, but it serves to clarify the concepts. Indeed, even the expression work-flow should be seen in its wider sense. Although the term has been widely adopted within the business community to denote a system that supports the automation of a very restricted form of human work, in engineering terms it denotes any repeatable enterprise work process that can be executed largely without human intervention.

5.3.1. Workflow Models and Meta-Processes

The term workflow has different meanings in various contexts. The Computer Science field understands a workflow as an abstraction in distributed computing that models a computation consisting of tasks that can run in parallel, by describing control and data dependencies between tasks. These abstract models allow users to reason about and compute metrics such as memory footprint and time complexity of the distributed computation without having to know the details of the implementation of the tasks. However, a workflow could be defined as a sequence of business processes, or a series of related activities that produce a product or service. Hence a workflow can be viewed as a meta-process. From this perspective, even a single event can be regarded as a workflow; in such cases, workflow execution will require the orchestration of processes and service participants. Workflows, in fact, tend to rely on services provided by lower-level processes or services certified as complying with the expected quality of service.

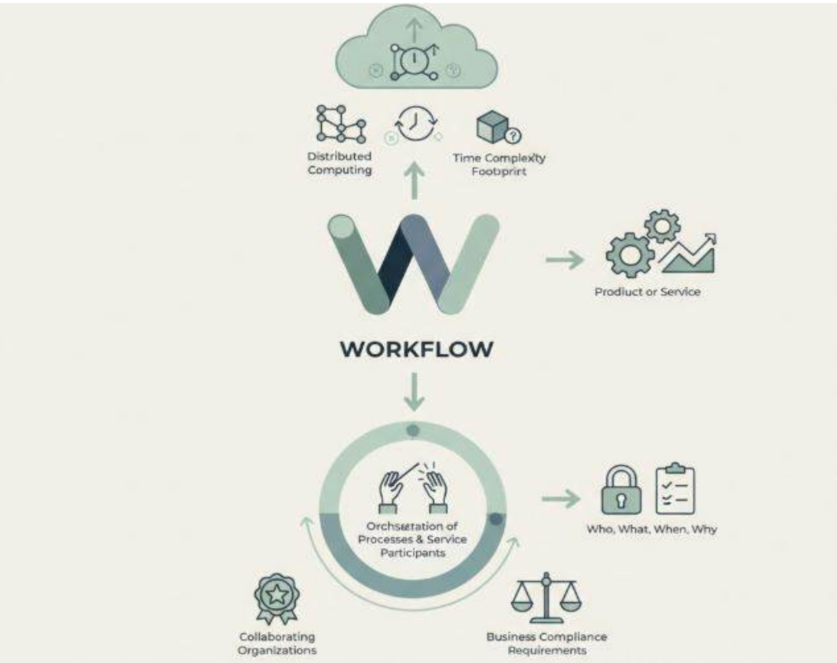
Distributed Computing
Time Complexty Footbprirt
Prodluct or Service
WORKFLOW
Orchsætation of Processes & Service Participants
Who, What, When, Why
Collaborating Organizations
Business Compliance Requirements

Fig 5.2: Workflows as Meta-Processes: A Multi-Dimensional Framework for Distributed Orchestration, Business Compliance, and Lawful Verification

The distinction between process and service appears especially relevant with respect to the events of a lawful business. In this case, legitimate participants in the processes need to fulfil usually implicit constraints to ensure that observed transactions are lawful and cannot be falsified. Those participants who are not executing the processes must rely on services provided by those executing the processes. Different organizations must collaborate to support such services, and, as a result, no single party can arrange for everything. Business compliance requirements are a prime example of such constraints. Therefore, workflows express constraints on how specific events must be realized in order to allow the verification of issues such as who did what when and why when an event occurs.

5.3.2. Orchestration vs. Choreography

The varieties of linguistic or architectural patterns in the execution of workflows can be classified and their use modelled independently. It is commonplace to distinguish between orchestration and choreography. In the orchestration metaphor, there are usually workflows or processes at work. These assign a composer—known either as the orchestrator or conductor—and a score. The roles specified in the score undertake instrumental activities, usually referring to detecting and executing their implementations as partners, in addition to ensuring that they are dynamic and harmonious. In the simplest case, one of the partners is the orchestrator itself. In choreography, by contrast, there is no separate composer and the partners coordinate their actions with one another without an overseeing or controlling agent. Hence the term for the preferred architectural design in workflow execution: Peer-to-Peer Choreography. Workflows thus become copies of the same orchestral routine, each executing the work plan independently and sending notifications on progress to the others.

This distinction is important. Although workflows and processes can sometimes be used interchangeably, a network of partners engaged in a common undertaking is often called a process in order to break away from the strict implications of a workflow. In Parts III and IV, the context of use for both patterns—the concerns and issues that govern when to use which for agent-wide orchestration of activity—is distilled into three design principles: 1. process-centred agent communities; 2. enhanced mental models for decision-making; and 3. high levels of automation.

5.4. Agent-Wide Orchestration: Design Principles

An intelligent agent-wide, executing agent orchestration is concerned with processes or mechanisms for coordinating groups of agents to harmonize their actions and interactions towards a shared goal, fulfilling the orchestration role of directing the entire multi-agent system. This requires specifying not only how to coordinate planning and executing actions that usefully relate to each other but also how to describe expected surface-level states during execution and how to determine safe ways of achieving them. It leads to a number of principles applicable to other orchestration types.

Coordination mechanisms are typically task-specific. Coordination might be provided as higher-level services. Mental models of other agents express beliefs and beliefs about beliefs of others, permitting high-level prediction of other agents' decisions, alternative state trajectories, and assessment of the coherence of models without practical execution. An agent-wide shared mental model can act as a decision-support system. At the other extreme, no shared model might be used for the common physical surface-level state and safety constraints.

5.4.1. Coordination Mechanisms

Shared mental models, established through a coordination mechanism that enables local decision-making at different levels, constitute a key element of agent-wide orchestration. The introduction of controlled coordination offers agents a limited view that supports high-level tasks in a global perspective while facilitating the execution of local operations. The coordination patterns enable an agent to temporarily delegate decision-making authority to a sub-agent, partially releasing local control without abandoning the awareness of objects and processes that must be kept synchronized.

An alternative idea relies on a global physical model and monitoring capabilities over the whole environment. Global monitoring empowers an agent to observe and communicate high-level state changes, leaving the implementation of low-level operations to other agents. Similarly, the global model augments global agent capabilities by providing indirect citation of knowledge, such as road objects, resource availability, or unwanted states like flooding or fires, with local agents transforming these triggers into queries to their own local models. These different collection mechanisms work in harmony to evolve a shared mental model, exploited at a higher logical level in individual reasoning processes.

5.4.2. Decision-Making with Shared Mental Models

Data about agents' capabilities and status also enables a richer synchronization of agent activity by informing agents' decision making. Such shared mental models specifically enable mutual reasoning about potential sequences of actions, making the goals of orchestration—and indeed of many other forms of coordination—implicit rather than explicit. Indeed, when agents are aware of each other's goals, they can perform actions that are consistent with each other's objectives without having to be explicitly instructed to work together.

Approaches to automatic sharing of planning or execution goals among agents and to inference over shared goal knowledge about the environment also create possibilities for synchronized actions without orchestration. Nevertheless, while agents working toward a common goal may seem similar to an implicit orchestra, the richness of their individual plans can still create confusion if the actions are not temporally coordinated in some way. Even when a group of agents shares a common goal, mental-model-sharing mechanisms can be applied to remove the need for explicit coordination. Temporal coordination of such agents can also been advanced with ideas of common temporal goals in mind.

5.5. Technologies Enabling Intelligent Orchestration

Reliable agent wide orchestration requires well-defined coordination mechanisms and decision-making based on shared mental models. Information, which enables concerted yet automated efforts, must be communicated in a language understood by all communicating agents. Communication languages built on the Knowledge Query and Manipulation Language facilitate cooperation across heterogeneous agent teams. Core functionalities such as task and activity state tracking, and user intervention monitoring, can be constructed using a Composite Application Design Pattern. Middleware capable of supporting agent internal knowledge bases, providing a Shared Mental Model within agent teams, and acting as an operational planner with reasoning capabilities, is also invaluable. Systems using the Distributed Multi-Agent Planning life-cycle models and frameworks are especially suited to fulfilling these requisites.

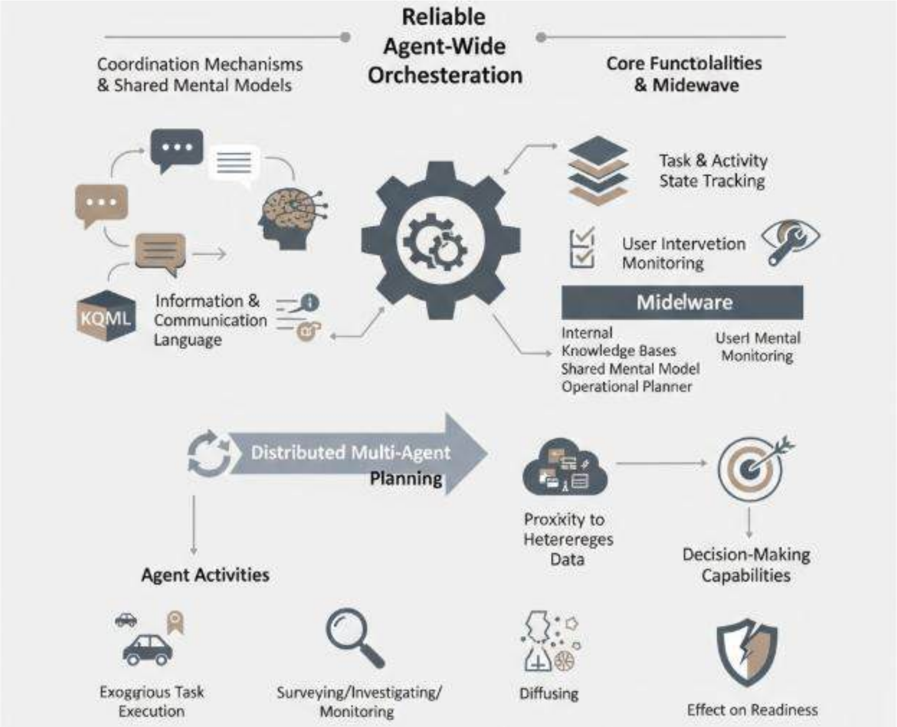
Reliable Agent-Wide Orchesteration
Coordination Mechanisms & Shared Mental Models
Core Functolalities & Midewave
KQML
Information & Communication Language
Task & Activity State Tracking
User Intervetion Monitoring
Midelware
Internal Knowledge Bases Shared Mental Model Operational Planner
Userl Mental Monitoring
Distributed Multi-Agent Planning
Proxkity to Heterereges Data
Decision-Making Capabilities
Agent Activities
Exoggrious Task Execution
Surveying/Investigating/ Monitoring
Diffusing
Effect on Readiness

Fig 5.3: Distributed Multi-Agent Planning and Orchestration: Leveraging Shared Mental Models and Data Lake Proximity for Complex Mission Readiness

Proximity of intelligent agents to heterogeneously sourced data offered by data lakes can significantly enhance their decision-making capabilities. The widely accepted and in-depth studied concept of exogenous task execution certainly requires specific vehicles and navigational support, whilst other activities undertaken by intelligent agents such as surveying, investigating, monitoring, surveilling, and diffusing (harbouring complex and fragile structures) certainly have an effect on readiness. Diffusing is perhaps the most complex of the activities, requiring the military to dedicate political, and diplomatic resources to a now disintegrating concept of deterrence operations that once held sway.

5.5.1. Middleware and Integration Frameworks

Various intelligent wildcard orchestration solutions incorporate concepts and principles from Enterprise System Integration and Middleware. In particular, the design and usage of intelligent wildcard orchestrators can greatly benefit from the class of middleware known as Enterprise Service Buses (ESBs) or Service-Oriented Middleware. This middleware layer allows different systems or applications to communicate with one another and is often designed for improved manageability and system reconfiguration, so that the communication layer behaviour can be easily altered without requiring code changes for the participating systems.

ESBs can also bridge heterogeneous environments. However, unlike traditional point-to-point communication schemes, when services are assembled dynamically into virtual service compositions, there is an inherent need for more advanced orchestration features such as dynamic service discovery and selection, service invocation monitoring and correlation, service composition validation, and exemplary process execution features such as transient data persistence. More advanced implementation schemes can also enable the dynamic development and deployment of orchestrated services directly on the ESB environment.

For intelligent wildcard orchestration to be a viable solution at large, distributed, and heterogeneous command and control application domains, especially domains that need to dynamically assemble cooperation services either due to the dynamically varying S/I/T or due to the complexity and resource intensiveness of the task, further research is needed.

5.5.2. AI Planning and Reasoning Systems

AI planning and reasoning capabilities can enhance intelligent orchestration in three main contexts. In heterogeneous groups, planners can compute high-level strategies mapping goals onto objectives of different agents, exploiting social preferences to favor agents completing the easiest or least valuable subgoals. By generating plans for the activities of multiple agents, they can improve coordination by producing efficient schedules. Finally, shared plans, including explicit specifications of the responsibilities of different agents, can facilitate monitoring and help in post-event evaluations.

Meta-process models supporting agent-based workflows typically focus on the control flow rather than optimizing resources. Moreover, temporal aspects are often considered in an informal way. The use of process patterns can help structure and guide the design of complex processes but does not simplify their implementation and execution. Combining high-level process descriptions with ground planning can simplify workflow design based on execution knowledge. Indeed, if the workflow's process model is sufficiently formal and detailed, ground planning can generate a plan tailored to the available resources and supporting preferences. The resulting plan can then guide the coordination of agents participating in the workflow.

5.6. Governance, Ethics, and Risk Management

Intelligent orchestration of automated intelligent agents and workflows poses numerous governance, ethics, and risk management issues. Dispersed and autonomous nonhuman agents are difficult to supervise and hold accountable. Orchestration must ensure adequate safety, security, and robustness, and satisfy all relevant requirements. Automating decision-making using knowledge representation and reasoning and AI planning opens up additional vulnerabilities.

Carefully designed governance structures—the "rules of the road" for intelligent orchestration—are essential. The responsible use of intelligent nonhuman actors requires adequate oversight to avoid illicit or harmful actions and provide recourse to those harmed. Responsibility, accountability, and compliance with laws, regulations, and standards must be established, as must cybersecurity and privacy protections. Orchestration must also address sources of bias and discrimination and minimize environmental impact.

5.6.1. Accountability and Compliance

Successful orchestration relies upon assurance of accountability: the responsibility for the consequences of a workflow execution (whether successful or not), combined with the ability to trace both the execution of the workflow and the underlying processes that actually created the output. Orchestration requires a clear understanding of which agent is responsible for executing each subtask, and whether this is implied (as would happen in a form of implicit choreography) or explicitly stated in the orchestration model. Workflows (and the actual processes that execute the workflow) should be checked against external regulatory requirements—such as privacy legislation, or industry or cultural practice guidelines—that prescribe what agents must and must not do. Automated systems are as capable of incorporating these regulations as of disobeying them, although a failure to do so may carry serious consequences for human parties. This analysis can also extend to decision trees used for risk analysis during execution of the workflow. Such trees can be enriched with compliance checking using standard process compliance checking techniques.

In the enterprise domain, SAS 70 or its successor SSAE 16 offers a basis for third-party audits. Other industries have similar methods or currently work toward a third-party-checkable scheme. However, in all industries, automated support for information technology general controls speed the auditing process, thus reducing audit expenditure. By using information compiled by the controlling metadata repositories during normal operations, triggers can offer audit cubes to those responsible for checking compliance—much as a data mart is prepared for business intelligence purposes.

5.6.2. Safety, Security, and Robustness

Assuring the safety, security, and robustness of agent-wide orchestration technologies is essential to the development of usable, trustworthy systems. If one agent's actions could have disastrous consequences, then all agents should be aware of the risk and take precautions. For example, they could check to ensure that the coordinating agent is still operational. A security breach in one agent could lead to a breach in others, so an agent that is more trusted and less exposed should assist in monitoring others, by checking authentication keys or reporting unusual activity. System-wide knowledge could facilitate greater resiliency. For example, if one agent suddenly stops answering, candidates for substitution could be inferred by other agents based on the shared mental model. In addition to incorporating such considerations in the design and architecture of an agent-wise orchestration infrastructure, development should produce safe, secure, and robust applications.

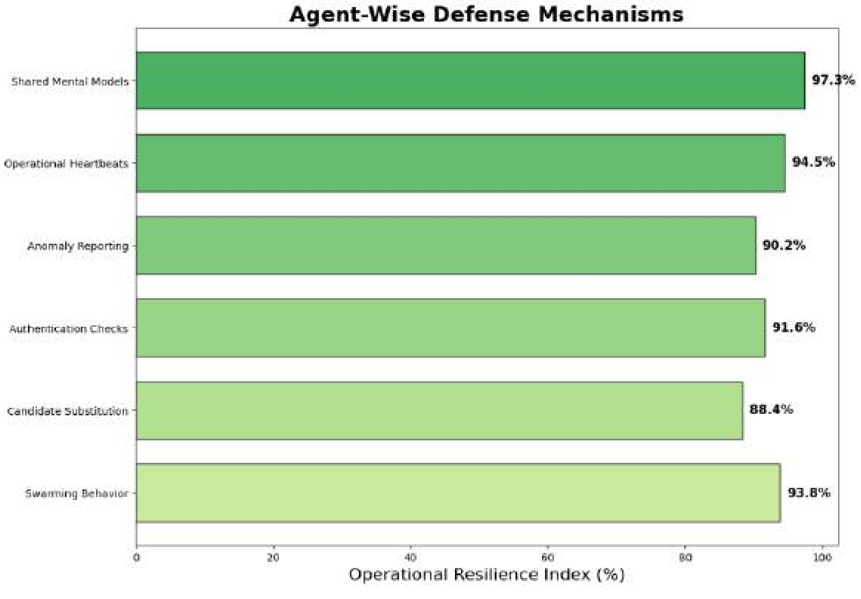

Fig 5.4: Agent-Wise Defense Mechanisms

Safety is the reducing risk of fatalities or injuries. Security prevents unauthorized access or actions, and maintains integrity, availability, and non-repudiation. Robustness is about tolerating errors and unexpected situations. Illustrating the preliminary of these concepts, Andrews et al. (2017, 341) discuss relevant issues for "hormimitating" agents embedded in smart cities systems that behave like social insects and whose collective action addresses certain aspects of smart-city infrastructures. Authors note that practical concerns reduce the feasibility of creating agents that are exactly modeled on these social insects, and suggest that imitating certain aspects, such as swarming behavior, can yield similar results; however, they also point out that in any case it is important to properly account for safety and security.

5.7. Conclusion

From the perspective of technology management, future business systems will orchestrate the action of intelligent agents and automated workflows and will implement agent-wide coordination functions. Agent coordination introduces concepts and techniques from the field of agent-based systems into the domain of automated workflows, planning software systems and process meta-models. Five categories of coordination mechanisms and horizons of coordination are distilled to yield agent-wide design principles. Risk analysis and decision-making based on shared mental models are identified as two particularly demanding mechanisms.

From a technology perspective, the vision of intelligent orchestration reflects an interoperable agent-based framework that facilitates action and supports information processing where, when, and how required. The framework consists of a middleware that manages collaboration, a suite of integration and reasoning mechanisms and an agent client/application that hosts the local services and decisions of each intelligent actor. The technologies reside in the latter and include centre-based orchestration that registers, finds and enables participation and control both in task-related activities and in data sharing, natural language processing to capture and convey knowledge in sharable form, service orchestration to create ad-hoc event-driven workflows and business process modelling that conforms with agent commission requirements. Risk analysis safeguards potential hazards and loss exposure from acting during distressed situations and AI planning supports agents from making their plan decisions.

5.7.1. Final Thoughts and Future Directions

The orchestration of intelligent agents and automated workflows represents a new frontier of digital innovation. Current implementations are not yet genuinely intelligent—rather they are based on information technology scripting, programming and parameterization. Twelve proposed design principles, addressing coordination mechanisms and decision-making with shared mental models, can transform established frameworks and middleware components into environment-agnostic operations capable of adapting based on contextual information. AI planning and reasoning systems provide complementary decision-support capabilities able to ingest shared mental models and outlined parameters during run-time.

To deliver consistently improved services, agents must not only work together, but also learn from previous interactions. This requires the continual capture of contextually relevant information expressed as a shared mental model for a dedicated group of intelligent agents responding to an established business service level agreement. Such a model can enable response options to be progressively shortlisted as specific contexts recur, culminating in fully automated responses to frequently repeating user requests associated with simple outcomes requiring little thought beyond the initial consideration. Successful automation can then be applied where little human judgement is involved, progressively extending the model-based approach through iterative consideration, testing and monitoring. Over time, such developments are expected to create reduced workloads, set formalisable tasks requiring little complex thought, or free up increased time for higher-priority activities.

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