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DEPARTMENT: INTERNET OF THINGS, PEOPLE, AND PROCESSES

Human-Based Distributed Intelligence in Computing Continuum Systems

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Distributed computing continuum systems (DCCSs) are integrated systems that combine cloud, edge, and Internet of Things devices to deliver scalable and low-latency computing resources across diverse applications and environments. Composed of a heterogeneous mix of computational units, storage systems, and communication networks, DCCSs facilitate real-time data processing and analysis by distributing tasks dynamically based on resource availability and demand. The complex structure of DCCSs reflect the intricate organization of the human body, where different systems work together to maintain overall functionality. This article draws parallels between the human body's intelligence mechanisms and the operational strategies needed for DCCSs. We especially explore several human body analogies or principles that can be incorporated into DCCSs to mitigate interpretable and noninterpretable challenges while enhancing overall performance.

Distributed computing continuum systems (DCCSs) are an emerging computing paradigm that integrates cloud, edge, mobile edge, the Internet of Things, and other computing environments into a unified system.[1,2] In DCCSs, computing tasks are dynamically distributed across geographically dispersed nodes, thus effectively reducing latency by processing data closer to their source. This uses resource hierarchy upon demand and thereby enhances overall system efficiency. With DCCSs, tasks are allocated to the most appropriate computing nodes when needed, resulting in improved performance and resilience. This capability meets the growing demand for complex, data-intensive, real-time data processing, big data analysis, and emerging generative artificial intelligence (AI) applications. DCCSs can be used in a wide variety of fields,[3] including smart cities, health care, autonomous vehicles, and industrial automation, where multiple objectives are required, including low latency, efficient resource utilization, high accuracy, and energy efficiency. DCCSs improve operational efficiency by ensuring the optimal use of computing resources and reducing the need for centralized data processing and storage.

Recently, DCCSs have also integrated smart devices with embedded intelligence,[4] allowing them to autonomously perform simple sensing and control tasks, thereby reducing the need for manual intervention. However, intelligence is needed not only within individual devices but across the entire system. In particular, DCCSs require intelligent and efficient mechanisms to ensure reliable integration, optimal performance, and robust management of complex operations. AI and machine learning (ML) are increasingly utilized in DCCSs for advanced control strategies, enabling predictive

1089-7801 © 2025 IEEE
Digital Object Identifier 10.1109/MIC.2024.3460908
Date of current version 30 June 2025.

maintenance, orchestration, elasticity (e.g., autoscaling), efficient resource utilization, latency minimization, and optimization of processes through real-time data analysis.[5] For instance, in Zhang et al.,[6] multilevel edge management and control modes form hierarchical structures to manage varying levels of control across the system, ranging from local controllers to central supervisory systems. Extended with causality, DCCSs can be easier understood and managed, allowing deeper insights into system dynamics and interactions through analysis of their behavior and impact.[7]

Traditional AI and ML techniques have limitations, particularly in DCCSs; one major issue is that they require vast amounts of input and training data, which can be impractical in resource-constrained environments. These approaches are also computationally intensive, requiring significant processing power and energy, which can be costly and inefficient. In some cases, the benefits of deploying traditional AI/ML solutions can outweigh their costs. However, adversarial attacks can undermine systems' security and reliability, especially faulty training models or mismatched input for training.[8] Moreover, it is difficult to verify real-time accuracy, which complicates their deployment in dynamic and critical applications.

In general, AI/ML approaches rely on historical data to generate or suggest outcomes or solve issues. However, addressing noninterpretable future challenges or needs can be difficult when they are based solely on past information. DCCSs require efficient solutions that anticipate and adapt to future demands, enabling full autonomy and adaptability; however, current AI/ML strategies are not sufficient for that. Alternatively, the human ecosystem serves as a prime example of an intelligent living system. Recent studies have highlighted how the human body efficiently adapts and adjusts to changing environmental conditions through its complex and well-coordinated internal systems.[9] Similarly, the intricate structure of the human body closely resembles DCCS architectures, suggesting that insights from biological systems could inspire more effective and adaptive solutions for managing and optimizing DCCSs.[10] This approach ensures that systems remain effective and relevant as they evolve and face future challenges. With this motivation, we present this article with the following contributions:

- We draw parallels between the complex mechanisms within the human body and DCCSs.
- We explore and study various intelligent mechanisms of the human body that could be effectively incorporated into DCCSs to enhance their adaptability and efficiency.

HUMAN BODY ANALOGY WITH DCCSs

The human body is an intricate and highly sophisticated system, composed of cells organized into tissues (approximately 37.2 trillion cells, each specialized for different functions), and organ systems that work in harmony to sustain life. There are several systems in the body that are deeply interconnected, including the skeletal, muscular, nervous, cardiovascular, and respiratory systems. All of these systems depend on one another to function properly. Similarly, DCCSs mirror this complexity and interconnectedness, as shown in Figure 1. We have classified the human body's anatomy into two main categories, infrastructure systems and regulatory systems, which are further discussed in the next sections in relation to DCCSs.

Infrastructure Systems

The human body infrastructure system contains three parts: the skeletal, cardiovascular, and nervous systems. These systems are vital for maintaining the structure of the body, efficiently moving resources, and coordinating functions across various parts. These systems are closely parallel to key elements within DCCSs, such as devices, communication or coordination, data transmission or flow, and learning or knowledge extraction capabilities. Next we illustrate how biological principles can inform and enhance our understanding of complex computing systems.

In the human body, the skeletal system provides a network of bones and joints that facilitate movement while protecting vital organs. Similarly, a DCCS's structural framework is analogous to its physical infrastructure, which includes devices such as servers, routers, and data centers. Just as the skeleton supports the body, this physical infrastructure supports various computing tasks so that the system functions effectively. The cardiovascular system circulates blood, delivering oxygen and nutrients to cells while removing waste, ensuring that every body part receives the resources it needs. In DCCSs, it is data that move through networks and communication channels, thus ensuring that computational resources and information are efficiently distributed across nodes. Hence, data can be seen as the system's "blood." Next, the cardiovascular system's role in maintaining steady blood flow parallels how DCCSs manage energy supply, dataflow, and bandwidth to maintain optimal performance and prevent bottlenecks. Finally, the nervous system transmits signals, processes information, and coordinates actions, enabling the body to respond quickly to stimuli and adapt to new situations. Similarly, in

DCCSs, communication networks and learning capabilities facilitate rapid information exchange between distributed nodes, ensuring task coordination and timely responses.

Medical research shows that neurons are not confined to the brain, they are present in various organs throughout the body, each serving specialized functions: the brain, with its approximately 86 billion neurons, serves as the central hub for processing information and decision making. The spinal cord, which contains roughly 13.5 million neurons, functions as a crucial communication pathway between the brain and the rest of the body. The enteric nervous system, often referred to as the *second brain*, manages the digestive system with approximately 500 million neurons, overseeing gastrointestinal processes independently. The heart contains roughly 40,000 neurons that regulate its rhythm and function, ensuring efficient cardiac operations. The eyes have approximately 100 million neurons in their retinas, which process visual information.[11] Additionally, the skin is equipped with millions of sensory neurons that detect touch, pressure, temperature, and pain, allowing the body to respond to environmental stimuli. This complex distribution of neurons across various organs highlights the body's sophisticated system for managing diverse and essential functions.

Neurons are crucial for both physiological functions and cognitive processes. They enable the brain to acquire, process, and store information and adapt responses based on experience—an aspect that is also central to learning in AI and ML. The widespread distribution of neurons across different organs is an instance of distributed intelligence, similar to how DCCSs operate. Edge and fog devices can perform localized computations, like the heart and gut, while the cloud handles more extensive computations. For instance, DCCSs can directly compute visual data analytics at intelligent edge devices, hence mimicking the high amount of neurons integrated into the system's "eyes." Just as the human body's various parts collaborate to manage complex tasks efficiently, organs with specialized neurons work together to form an integrated and responsive system. This parallel suggests that DCCSs can emulate the decentralized processing and coordination seen in the human body, enhancing its efficiency, intelligence, and autonomy.

Regulatory Systems

The human body's regulatory system contains two parts: the lymphatic and endocrine systems; together, they regulate the body's internal environment, preserving balance and coordinating responses to internal and external changes. The lymphatic system is essential for maintaining fluid balance and protecting against infection. It includes lymph nodes, vascular system vessels, and lymphoid organs like the spleen

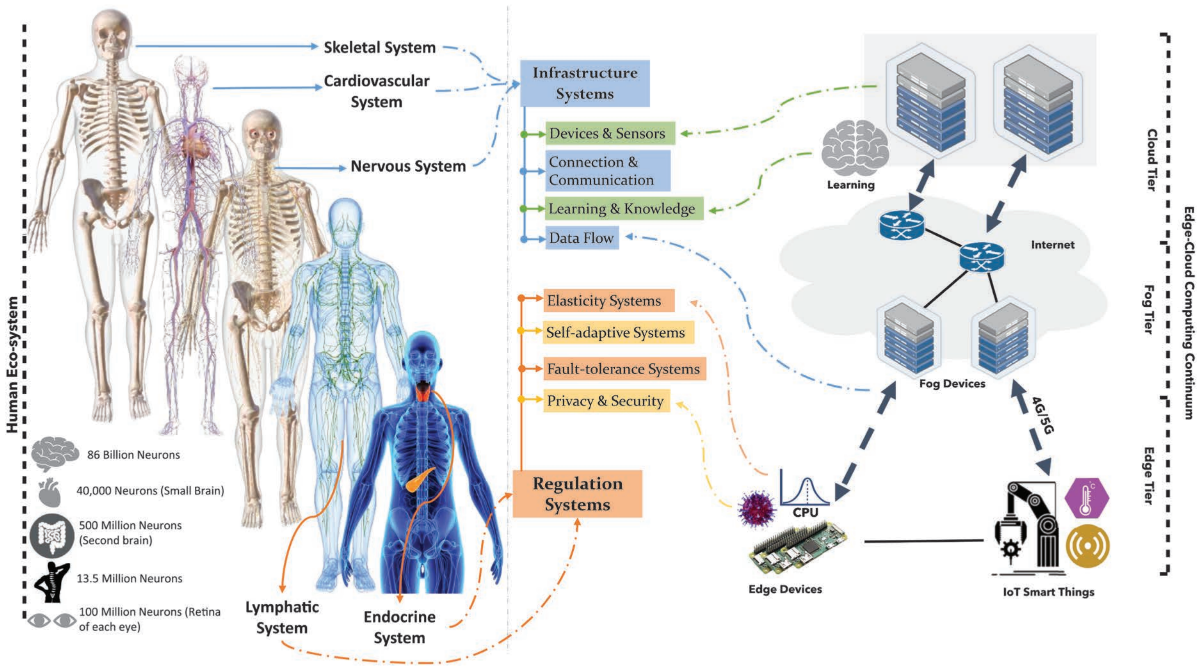

FIGURE 1. Parallels between the human body and DCCSs. IoT: Internet of Things.

and tonsils, which collect excess tissue fluid, filter out pathogens, and support the immune system by transporting lymphocytes. The endocrine system, on the other hand, regulates various physiological processes through hormone secretion. For this, glands release hormones into the bloodstream to control growth, metabolism, mood, and reproduction, thus maintaining overall bodily balance and homeostasis.

Similarly, DCCSs incorporate elastic features to dynamically allocate resources based on demand, e.g., during peak usage times. Thus, it is possible to scale up a service according to external requirements. To adapt to changes and recover from disruptions, DCCSs can also ensure fault tolerance through redundancy and recovery protocols, thus mirroring abilities such as the immune system's response to infection. Similar to the lymphatic system, DCCSs regulate data transfer to ensure efficient communication and security. The endocrine system's role in hormonal signaling parallels distributed control mechanisms in DCCSs, where various components and nodes use protocols and algorithms to coordinate tasks, optimize performance, and adapt to changing conditions.

HUMANLIKE INTELLIGENCE IN DCCSs

The previous section demonstrated that the human body exemplifies distributed intelligence throughout its intricate and interconnected systems, each of which is essential for maintaining overall function and adaptability. In this section, we examine how DCCSs can benefit from incorporating humanlike systems. Specifically, we examine how concepts such as feedback loops and adaptability, self-healing capabilities, efficient communication and coordination, and advanced decision-making processes can significantly enhance DCCS functionality. Figure 2 summarizes which intelligent mechanisms of the human body can be replicated as operational strategies in a DCCS. We assume a healthy human body for the following analogies.

Feedback Loops and Adaptability

In the human body, feedback loops play a crucial role in regulating processes such as cell growth, division, self-repair, and responses to environmental changes. These loops are essential for maintaining homeostasis through long-range extracellular feedback between cells. Feedback loops involve a process in which a system's output influences its own activity, either by amplifying it (positive feedback) or reducing it (negative feedback).[12] A negative feedback loop is a control mechanism in which the output of a system counteracts the initial stimulus, helping the system to maintain stability and equilibrium. For example, when blood sugar levels rise after eating, the pancreas releases insulin, which helps cells absorb glucose and lower blood sugar levels. As blood sugar drops to normal levels, insulin secretion decreases. If blood sugar levels fall too low, the pancreas releases glucagon to raise it back up, maintaining balanced blood sugar levels. On the other hand, a positive feedback loop is a process in

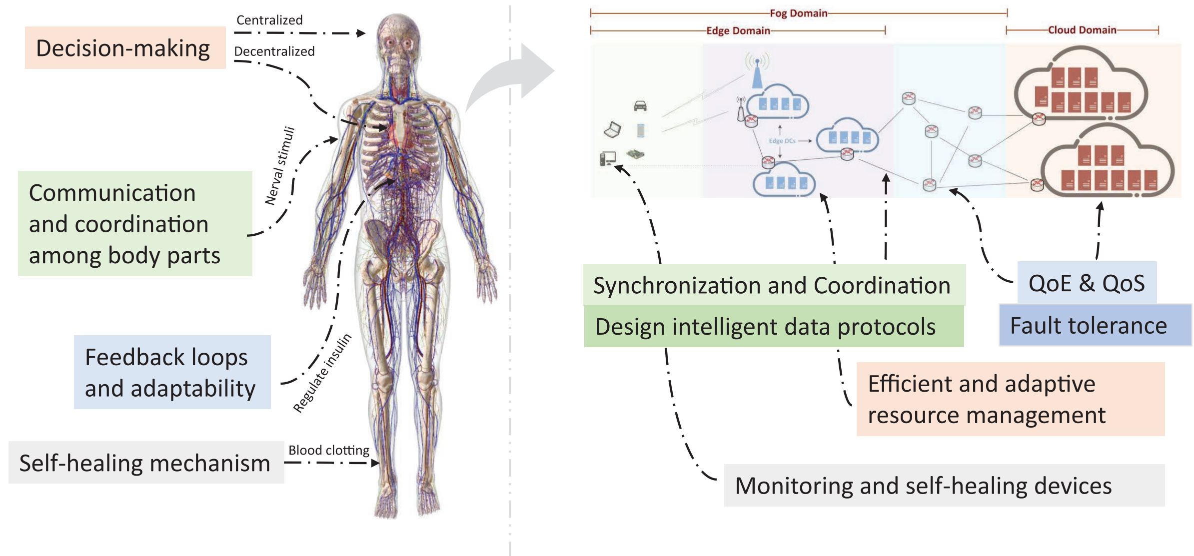

FIGURE 2. Human body's intelligent mechanisms and the operational strategies need for DCCSs. QoE: quality of experience; QoS: quality of service.

which the output of a system amplifies the initial stimulus, pushing the system farther in the same direction. Unlike negative feedback, positive feedback loops often lead to rapid changes and are typically involved in processes that require quick decisions. Blood clotting is a well-known positive feedback loop. When a blood vessel is injured, platelets stick to the site and release chemicals that attract more platelets. As more platelets accumulate, they release even more chemicals, rapidly amplifying the clotting process until the wound is sealed.

To enhance adaptability, resilience, and quality of service (QoS), bioinspired feedback loops can be introduced to DCCSs: negative feedback loops help DCCSs maintain the system's overall stability and adhere to service-level objectives (SLOs) by balancing resource allocation.[13,14] For example, when computational resources such as bandwidth, CPU, or memory meet critical SLO thresholds, the system can automatically scale down certain processes or offload tasks to prevent overload and minimize potential damage. This proactive adjustment helps ensure that performance remains within SLO parameters. Similarly, positive feedback loops are crucial for rapidly scaling resources in response to sudden spikes in demand, thereby supporting the SLOs related to performance and latency. For instance, when a surge in data processing is detected, positive feedback mechanisms can trigger swift allocation of additional computing resources, such as autoscaling virtual machines or distributing tasks across edge devices. Implementing these feedback control strategies in a DCCS allows for coping with unforeseen fluctuations, such as occasional network breakdowns,[15] a sudden rise in resource demand, or on-demand privacy enforcement on streaming data.[16] Thus, in case of failures, dynamic adjustments and resilience mechanisms enhance quality of experience and QoS.

Self-Healing Mechanism

Self-healing is the body's natural ability to restore balance and health without external intervention, often utilizing feedback loops to regulate this process. But can self-healing mechanisms be applied to DCCSs? The answer is, to some extent, yes. In our previous work,[17] we explored this concept by drawing parallels with human wound healing to manage and govern participating devices within a computing continuum with low human intervention. These self-healing agents could be employed to address abnormal device activities by drawing from the human wound-healing process; this process was structured into four distinct stages: hemostasis, inflammation, proliferation, and reshaping. Figure 3 provides a high-level overview of this approach, along with four stages and their operations.

Hemostasis, the body's immediate response to injury, parallels the DCCS approach of isolating and mitigating failures. When a disruption occurs in a DCCS, affected services are swiftly isolated, and tasks are

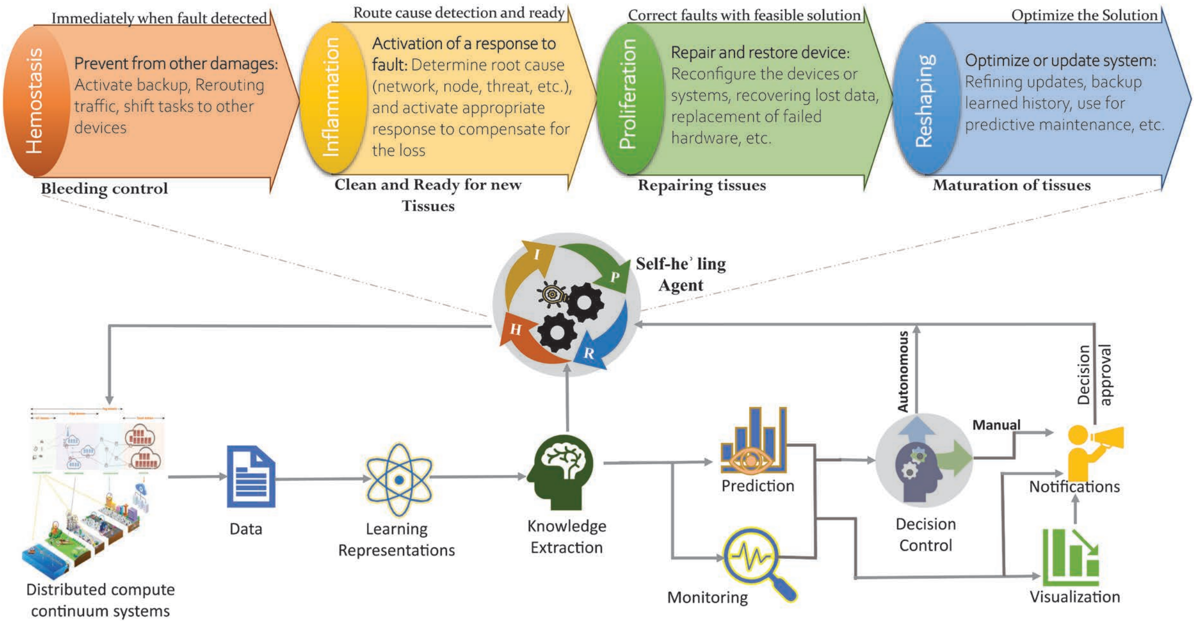

FIGURE 3. Wound self-healing mechanism for monitoring, governance, and predictive fault tolerance in DCCSs.

rerouted to stable computing nodes, minimizing damage and preserving overall system stability. *Inflammation* involves immune cells identifying and containing the problem site in the body. Similarly, in a DCCS, this stage entails diagnosing the root cause, whether it is a network issue, malfunctioning node, or security threat. The system gathers relevant data or learned representations, diagnoses the issue, and activates appropriate response measures, such as zero-touch service provisioning, to contain the disruption. This focused action prevents the problem from escalating and prepares the system for recovery. *Proliferation* in wound healing is characterized by the growth of cartilage tissue to replace damaged cells. In a DCCS, this stage is mirrored by reconfiguring devices or systems, restoring services from backups, redistributing tasks across the network, autonomously recovering lost data, and replacing failed hardware. These measures ensure that the system returns to normal operations quickly, maintaining stability and minimizing downtime. Finally, the *reshaping* phase involves strengthening the new tissue and realigning the structure. In a DCCS, this stage is reflected in postrecovery optimization, in which the system refines updates, backs up learned history, and utilizes these data for predictive maintenance. By analyzing the failure and recovery process, the system implements improvements such as enhancing fault tolerance, updating algorithms, and refining monitoring mechanisms, thus bolstering its resilience against future disruptions.

Communication and Coordination

The human body's communication and coordination systems are remarkably complex and interconnected, which is comparable to a DCCS's. The human body employs a sophisticated system of communication and coordination between its various parts, primarily through two main systems: the nervous and endocrine systems.[18] These systems work together to maintain homeostasis, respond to environmental stimuli, and regulate bodily functions. The nervous system acts as a rapid communication network, transmitting electrical signals through neurons to coordinate immediate responses, whereas the endocrine system provides slower but more sustainable communication through hormones. Similarly, a DCCS needs robust communication and coordination systems among devices (ranging from edge, fog, and the cloud). A typical computing system focuses on low-latency and ultrareliable communications, similar to a nervous system. If an edge device detects a critical event, such as a security breach, it immediately transmits this information to other nodes in the network, just like when you touch something hot, the nervous system sends pain signals to your brain. However, sometimes it is not necessary to be low latency, but sustainable and reliable communications are necessary. For example, periodic updates or reconfigurations that maintain system stability and efficiency do not necessarily require faster communications.

Furthermore, circadian rhythms in the human body demonstrate an even broader level of coordination. The suprachiasmatic nucleus in the brain communicates with peripheral clocks in organs such as the liver, muscles, and adipose tissue. The metabolic processes are synchronized with the day–night cycle through a variety of signals, including hormones and neural pathways. For example, the liver clock regulates glucose metabolism in response to feeding patterns, while muscle clocks influence insulin sensitivity and glucose uptake. This coordinated timing system allows the body to anticipate and prepare for daily physiological demands, optimizing energy use and metabolic function. DCCSs employ advanced scheduling and load-balancing mechanisms to maintain resource management equilibrium across the network. DCCSs predict and adapt to fluctuations in network traffic and processing demands in a way that is similar to circadian rhythms in the body. For example, during peak traffic hours, the system dynamically allocates resources by distributing tasks across various nodes, leading to efficient load handling. Similar to how the body conserves energy during periods of rest, the system may downscale operations during periods of low traffic.

Decision Making

Decision-making processes in the human body are highly sophisticated and efficient; in particular, they are balanced between centralized and decentralized components.[19] The brain serves as the central command center for decision making; it processes sensory information, coordinates complex behaviors, and initiates responses. Nevertheless, not all decisions are governed by this centralized system; many organs and systems have a degree of decentralized, autonomous decision making. For example, the heart can regulate its rate based on local conditions without relying on the brain, and the digestive system has its own enteric nervous system that functions independently. The spinal cord triggers immediate responses without involving the brain, while the endocrine system facilitates decentralized communication by releasing hormones, allowing for flexible regulation without central coordination. Similarly, the immune system can detect and respond to threats locally, ensuring rapid and targeted action against infections.

DCCSs apply a similar approach to their decision-making process: the cloud manages high-level orchestration and overall system stability, while decentralized nodes and devices perform autonomous decisions based on local data. However, this process needs decision making not only at the source but also during transmission, which is similar to the endocrine system in the human body. The security systems in DCCSs achieve superficial advantages of adapting features and a working model of the immune system.[20]

CONCLUSION

This article explored the parallels between the human body's intelligence mechanisms and the operational strategies required for DCCSs. We aim to address both interpretable and noninterpretable challenges in DCCSs while improving their overall performance by examining human body analogies and principles. Specifically, we investigate how concepts such as feedback loops and adaptability, self-healing mechanisms, decision-making processes, and communication and coordination can be applied to DCCSs based on the human body analogy. Each of these aspects provides valuable insights into creating a more intelligent and responsive DCCS. In the future, we will implement these techniques and our solutions using existing or new toolsets to bring our insights and gains closer to reality.

ACKNOWLEDGMENTS

This work is supported in part by the European Union grant agreements. 101070186 (TEADAL), and Ayuda CNS2023-144359 financiada por MICIU/AEI/10.13039/501100011033 y por la Unión Europea Next GenerationEU/PRTR.

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