



A. Foundations

Part A lays the foundations for the empirical study. Chapter I motivates the research problem, develops the research questions, outlines the research design, and introduces the study's central concept. Chapter II reviews the theoretical perspectives on digital infrastructures and their evolution. It brings these perspectives together in the structural problem that guides the empirical analysis: how a federated digital ecosystem remains operable while its structures continue to accumulate. Part B examines this problem in the case of the Netzwerk Universitätsmedizin (NUM).

I. Introduction

This chapter introduces the study and explains why its central problem matters. It begins with the observation that a federated health data ecosystem continued to add structures while remaining operable (I.1). It then develops the research gap and the three research questions (I.2), outlines the structure of the thesis (I.3), and explains the research design and positioning (I.4). The chapter concludes by presenting the anticipated contributions and introducing the study's central concept, Digital Plasticity (I.5).

I.1 Motivation

“It is not what we do not know that gets us into trouble. It is what we know for sure that just ain't so.” — attributed to Mark Twain

A line commonly attributed to Mark Twain captures the problem well: trouble often begins less with ignorance than with certainty that later proves false. When the pandemic reached German university medicine in the spring of 2020, one conviction appeared self-evident: the main obstacle to faster clinical learning was that data were scattered across institutions. If data silos could be opened and made interoperable, knowledge would follow.

This belief was plausible. It was also incomplete. Beneath it lay a broader promise associated with data ecosystems: that data, once linked across organizational boundaries, could be reused far beyond the settings that produced them (Priego & Wareham, 2024; de Reuver et al., 2024; Günther et al., 2022). Such ecosystems are more than technical repositories; they are distributed sociotechnical systems in which data, standards, governance arrangements, and accountability relations must be coordinated for reuse to become possible at all (Guggenberger et al., 2025).

The more difficult problem was not aggregation alone. It was translation. Clinical research does not treat data mobility as equivalent to evidentiary validity: the capacity of data to support credible clinical claims. It asks whether observations are comparable across

contexts, whether categories remain stable, and whether findings can travel legitimately between institutions (Bowker & Star, 1999; Leonelli, 2015). Data interoperability promises movement. Clinical research demands control. Interoperability favors fluid exchange and the recombination of digital resources; clinical research depends on stable data, auditable processes, and conclusions that can be justified. The pandemic did not create this tension. It merely made it impossible to ignore.

What came under strain, therefore, was not simply a fragmented data landscape. Rather, it was a more basic assumption: that the technical possibility of connecting data could substitute for the organizational and institutional work of producing clinically credible evidence — the relational activity through which data acquire meaning and validity across contexts (Alaimo & Kallinikos, 2024; Kallinikos & Tempini, 2014). It could not. And precisely because it could not, the effort to overcome fragmentation generated a further problem: the need to build shared research capacity without dissolving the local responsibilities, standards of evidence, and governance constraints on which clinical research depends.

At a high level, this resonates with a familiar Information Systems tension between control and change (Tilson et al., 2010; Hanseth & Rodon Modol, 2021). But in the setting of clinical research infrastructures, the opposition sharpens. What stands on the side of control is not merely governance authority, but evidentiary discipline: the institutional requirement that data produce warranted claims, not merely detected signals. What stands on the side of change is not innovation in general, but interoperability-driven fluidity, reuse, and generative expansion (Yoo et al., 2010). The result is a demanding contradiction between the drive toward movement and the requirement of stability.

The *Netzwerk Universitätsmedizin* (NUM), established in April 2020, emerged inside this contradiction (Heyder et al., 2023; Netzwerk Universitätsmedizin, n.d.-a, n.d.-b). It was founded as part of Germany's crisis response to coordinate clinical COVID-19 research across university medicine. Its urgency was obvious. Answers were needed faster than evidence could ordinarily be produced. Relevant observations existed, but they existed in distributed form: embedded in local systems, differently coded, and unevenly available for reuse.

The key shift was not only technical; it concerned institutions and the production of valid clinical knowledge. What had been built as a promise for future research suddenly faced an immediate test: not whether data could be connected in principle, but whether those connections could support credible clinical knowledge under urgent conditions. The promise became an accountability test, and interoperability alone proved insufficient to meet it.

Under ordinary conditions, interoperability is often imagined as a long-term infrastructure benefit: an investment intended to expand future options, improve exchange, and make future knowledge production possible — built, as Ribes and Finholt (2009) put it, for users and uses not yet in existence. In the pandemic, however, that was no longer enough: what had been tolerated as a long-range promise was suddenly forced to justify itself under immediate pressure to deliver evidence. The underlying tension became explicit. Systems optimized for movement are not automatically optimized for evidence production. The ability to circulate data does not by itself solve the problems of comparability, traceability, and legitimate interpretation. In medicine, signals require validation before they become evidence.

This is why NUM matters analytically. It did not emerge because Germany lacked prior data infrastructure altogether. It emerged because existing infrastructural advances were not sufficient to solve the crisis-specific problem of coordinating clinically credible evidence production under conditions of urgency. The issue was not simply the absence of technical capacity. It was the absence of a coordination layer capable of mobilizing distributed capacities toward a common evidentiary purpose.

NUM became important precisely because it made this shift visible in a single empirical setting. It was asked to make distributed data more fluid without undermining the control requirements of evidentiary work. In other words, it had to support change without sacrificing the forms of stability on which clinical credibility depends.

NUM did not enter a vacuum. It entered an already evolving infrastructural landscape shaped by the Medical Informatics Initiative (MII). The MII had established data integration centers, developed a modular core data set based on shared standards, and created a broad consent framework for the secondary use of patient data in research (Medical Informatics Initiative, n.d.-a, n.d.-b, n.d.-c). NUM-DIZ explicitly built on these prior structures (Netzwerk Universitätsmedizin, n.d.-c). But what NUM inherited was not a finished platform waiting to be activated. It inherited an installed base: local governance arrangements, partially harmonized implementations, routines of negotiation, technical shortcuts, institutional memory, and practical knowledge of what federated coordination could and could not force (Hanseth & Lyytinen, 2010).

This matters because crisis-driven expansion rarely arrives on clean ground. Every new coordination layer attaches itself to prior decisions and prior compromises. NUM was therefore not a greenfield design project. It was an emergency overlay on a landscape that was already heterogeneous before the crisis began. That landscape provided capacity, but it also shifted constraints. It made rapid activation possible while limiting how far and how quickly the resulting arrangements could later be reorganized, simplified, or selectively consolidated.

The relationship between MII and NUM is therefore analytically precise. MII was necessary, but not sufficient. It created the infrastructural foundation on which crisis coordination could build, but it did not by itself resolve the problem that the pandemic made urgent: how distributed hospitals, data practices, and evidentiary responsibilities could be mobilized into a nationally coordinated research capacity without dissolving local control. NUM emerged not in spite of MII, but because the existence of that foundation did not eliminate the need for a new coordination and prioritization layer.

Here the central tension of the case becomes sharper. Interoperability infrastructures tend to reward addition: more interfaces, more modules, more possibilities for reuse (Yoo et al., 2010; Hanseth & Rodon Modol, 2021). Clinical research, by contrast, often rewards discipline: stable categories, carefully bounded protocols, clear responsibility, and defensible restrictions on what counts as evidence and who may legitimately speak for it. Interoperability logic is generative and expansive, thriving on fluidity. Clinical research logic is selective, filtering carefully and depending on control.

NUM had to operate under both logics at once.

That is why the system could add more easily than it could subtract. New structures could be justified quickly in the name of urgency, coordination, and public value. Existing arrangements were far harder to remove, consolidate, or overrule. They were locally embedded and professionally defended. The consequence was not straightforward integration, but cumulative layering: new capacities were added on top of old ones, provisional workarounds became routine, and crisis coordination sedimented into lasting structural density (Hanseth & Lyytinen, 2010; Henfridsson & Bygstad, 2013; Rodon Modol & Eaton, 2021).

NUM was therefore not simply a success story of activated interoperability. It was a case of rapid infrastructural accumulation in which evidentiary control and digital generativity had to coexist without becoming fully aligned.

This is the configuration from which the puzzle of this monograph emerges. A federated clinical research infrastructure, created under acute pressure to mobilize data across institutional boundaries, entered the field with a dual promise. It was supposed to increase fluidity: more exchange, more reuse, more collective learning. At the same time, it was supposed to support a form of clinical knowledge production that depends on control: comparability, accountability, and defensible interpretation. These promises are not identical. They can reinforce one another, but they also pull against one another in systematic ways.

And yet the system did not simply break under that tension.

It thickened. It accumulated interfaces, governance arrangements, and infrastructural layers. It became denser, more path-dependent, and more institutionally entangled. Still,

it remained operable. The outcome was neither equilibrium, collapse, nor classical lock-in. It was continued operability under patterned accumulation. That NUM became more complex is, under the conditions described here, unsurprising. What makes its continued operability puzzling is the asymmetry beneath it: the ecosystem kept functioning, adapting, and producing coordinated capacity even where selective reduction was harder to authorize than further expansion.

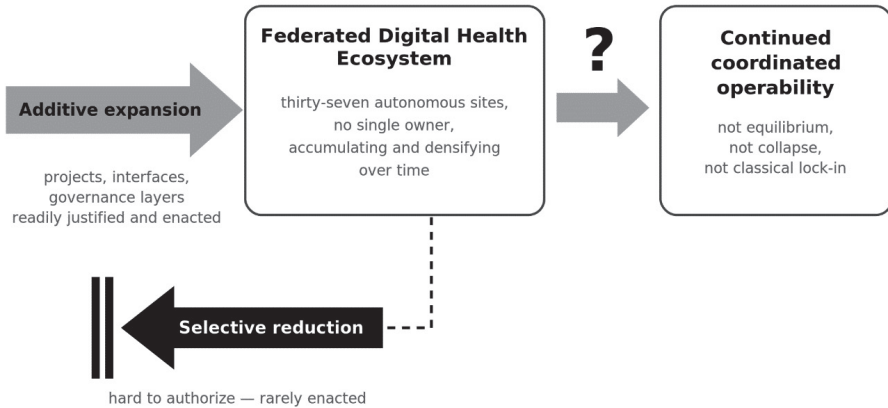
But this puzzle has a second dimension. Why did a new national coordination layer become necessary despite prior infrastructural investments? And how could the resulting tensions repeatedly be absorbed without breaking the system? The empirical material suggests that the answer does not lie in technical integration alone, nor in formal governance design alone. What becomes visible instead is a recurrent pattern of negotiated boundary settlement through which local responsibilities, data access claims, evidentiary standards, and coordination obligations were repeatedly reworked without being definitively centralized or dissolved.

This repeated settlement did not remove the contradiction but made the system workable. The puzzle of the monograph is therefore not only one of persistence under complexity, but of how distributed tensions are converted into a form of adaptive coherence without architectural closure.

The explanation pursued in this monograph, however, does not remain at the level of these observable settlements themselves. Boundary settlement describes the observable coordination practices, but it does not yet explain why they recur. The analytical task is therefore to identify the mechanism configuration that generates these practices and sustains adaptive coherence.

The phenomenon to be explained is plain: a federated infrastructure keeps coordinating, adapting, and producing capacity even as layers accumulate, arrangements become entrenched, and selective reduction grows harder to activate than further expansion. That asymmetry — operability sustained while reduction lags expansion — is the puzzle. Figure 1 states this puzzle in compact form; resolving it is the task of Part B.

Figure 1: The Empirical Puzzle



Note. Author's illustration. The figure states the puzzle that motivates this monograph. In the ecosystem studied here, adding structures — projects, interfaces, governance arrangements — remained institutionally easier to justify and enact than selectively reducing what had already accumulated. Under such an asymmetry, plausible trajectories would be fragmentation or rigidity. What the case shows instead is continued coordinated operability under patterned accumulation. How this is possible is the question Part B sets out to answer.

I.2 Research Gap and Research Questions

The puzzle has a theoretical counterpart.

Information Systems research has developed a sophisticated understanding of how digital infrastructures evolve, scale, and endure. Generativity research shows how innovation arises in layered modular architectures and how digital recombination expands the range of possibilities (Yoo et al., 2010; Henfridsson & Bygstad, 2013). Installed base theory explains how prior commitments enable and constrain development through inheritance, irreversibility, and path dependence (Hanseth & Lyytinen, 2010). Path constitution research demonstrates how trajectories stabilize through reinforcement and self-reinforcing commitments (Sydow et al., 2009; Singh et al., 2015). Complex adaptive systems theory explains how patterned order emerges from distributed interaction without centralized control (Benbya et al., 2020). At a higher level, IS research has shown that digital infrastructures repeatedly confront paradoxes of change and control (Tilson et al.,

2010), while architecture and governance coevolve through tensions between stability and change (Hanseth & Rodon Modol, 2021). More recently, work on generative entrenchment has sharpened our understanding of how adaptive capacity becomes unevenly distributed across layers as certain components become increasingly relied upon by others (Rodon Modol & Eaton, 2021).

These are substantial theoretical achievements. Together, they explain a great deal about how digital systems grow, why they become difficult to redesign, and how distributed order remains possible even under structural heterogeneity. In generativity research in particular, such limits are increasingly acknowledged: core contributors now caution against reading generativity as a universal explanation of digital evolution irrespective of institutional and material conditions (Yoo et al., 2024). Recent IS research also questions accounts that explain socio-technological transformation through bounded actors or static interaction models alone (Mousavi Baygi et al., 2021). This concern is also relevant to the present study. Yet the gap at issue here is more specific. It concerns not whether digital infrastructures are in motion, but under what institutional conditions different forms of movement remain activatable.

But these perspectives do not yet explain the specific configuration that NUM makes visible.

This configuration involves more than growth, lock-in, or distributed coordination. It foregrounds a persistent tension between two partially incompatible system logics — a federated instance of the paradox of change and control that IS research has shown to recur in digital infrastructures (Tilson et al., 2010). The generative logic of digital interoperability favors movement: fluid exchange, reuse, modular extension, and generative recombination. The selective logic of clinical operation and research favors control: comparability, provenance, and defensible inference. The generative logic expands possibility and tends toward addition; the selective logic narrows what counts as legitimate and proceeds only where necessity can be demonstrated. Existing theory helps us understand each logic in isolation. It is less precise in explaining how a federated infrastructure remains operable when both must be sustained simultaneously.

That gap becomes sharper under conditions of cumulative layering and dispersed authority. Generativity explains how variation enters a system; path constitution shows how that variation stabilizes into trajectories; complex adaptive systems theory explains how order emerges from local interaction. The account that comes closest is generative entrenchment, which already identifies an asymmetry in adaptive capacity: components that others come to depend upon grow progressively harder to modify (Rodon Modol & Eaton, 2021). But that asymmetry concerns the distribution of adaptive capacity across an infrastructure's evolving core-periphery structure. It explains where change becomes progressively more demanding; it does not explain why selective reduction fails to



become institutionally activatable even where redundancy is recognized and consolidation is widely seen as desirable. What none of these perspectives specifies is the institutional condition behind that failure. They leave open why generative mechanisms remain easier to activate than selective ones; why new interfaces, projects, and coordination layers can be justified more readily than consolidation, retirement, or simplification; and why this asymmetry is not episodic but durable. The result is the condition already named: continued operability under patterned accumulation.

A further limitation concerns the process through which recurring tensions are accommodated while operability is sustained. Existing vocabulary is strong in describing architectures, trajectories, and adaptive order. Work on the distributed tuning of boundary resources comes closest here, showing that coordination across a federation proceeds through the negotiated adjustment of technical and organizational interfaces among actors with divergent interests, rather than through unilateral control (Eaton et al., 2015). What remains unspecified is the system-level question: how such recurrent settlement, accumulating across layers over time, contributes to sustained operability under structural incompleteness. In the NUM case, the material does not merely reveal friction, conflict, or governance difficulty. It reveals repeated acts of negotiated boundary settlement: recurrent episodes in which claims to access, authority, and infrastructural obligation are rendered temporarily compatible without being structurally resolved. Earlier infrastructure research points to a related limitation, showing that infrastructural coordination depends on background arrangements that recede in routine operation and often become visible only through breakdown, inversion, or the practical work of repair (Star & Ruhleder, 1996; Bowker & Star, 1999).

This is the unresolved theoretical problem to which the monograph responds. What remains undertheorized is the mechanism configuration through which a distributed digital ecosystem can absorb change, become structurally denser, and remain coherent even when selective reduction is systematically harder to enact than further expansion. The existing vocabulary of flexibility, resilience, generativity, or adaptation captures parts of this phenomenon, but not its specific architecture. It has no term for a condition in which the capacity for selective reduction persistently lags behind generative expansion, yet coordinated operability endures.

These literatures do not yet name this configuration; they create the explanatory demand for it.

This study develops an account of this condition. It does so by identifying the mechanism configuration through which adaptive coherence is sustained under structural incompleteness, cumulative layering, asymmetrical activation thresholds, and recurrent forms of boundary settlement. The monograph pursues that demand through three nested research questions.

RQ1. How does a federated digital infrastructure sustain coordinated operability under cumulative layering when selective reduction is institutionally harder to activate than further expansion?

RQ2. Through what asymmetrical mechanism configuration does this form of adaptive coherence become possible?

RQ3. Under what boundary conditions can this mechanism-based account be analytically generalized to comparable distributed digital ecosystems?

These questions are nested rather than parallel. RQ1 identifies the empirical phenomenon to be explained, RQ2 reconstructs the mechanism configuration that explains it, and RQ3 specifies the boundary conditions under which the resulting account can travel analytically beyond the NUM case. The vocabulary shifts with this nesting: RQ1 names the phenomenon as a federated infrastructure — NUM as object — while RQ3 extends to the broader class of distributed ecosystems. The terminological note in A.I.4 holds these registers apart.

The mechanism-based explanation these questions require is the one this monograph develops under the name Digital Plasticity. At this stage the term marks only the explanation to be built, not a settled construct; its conceptual specification and its differentiation from adjacent concepts are developed in B.V.

I.3 Structure of this Thesis

The monograph is organized in three parts. Within each part, chapters are numbered in Roman numerals; cross-references add the part prefix to identify them unambiguously across parts (for example, B.II).

Part A — Foundations establishes the problem, the research questions, the design logic, and the research background of the study. A.I Introduction develops the empirical puzzle from the NUM case, specifies the research gap and the nested research questions, positions the study as a critical-realist, abductive-retroductive mechanism study, and states the anticipated contribution. It also introduces Digital Plasticity as the conceptual direction of the monograph. A.II Research Background then builds the theoretical funnel. It establishes three ontological characteristics of digital infrastructures — unfinishedness, layering, and sedimentation — and reconstructs the structural problem that follows from them: how large-scale digital ecosystems remain operable under cumulative layering and asymmetrical activation thresholds. It reviews the contributions of digital infrastructure research, complex adaptive systems theory, path constitution, and generativity, while clarifying the explanatory gap that remains.

Part B — The Study reconstructs the empirical case and develops the mechanism-based explanation. It first introduces NUM as a federated clinical research infrastructure within the German health-research space and shows why this space is constitutively federated rather than merely nationally coordinated. It then presents the epistemological grounding in critical realism and the abductive logic of systematic combining. It also explains the multi-stage analytical architecture through which the study moves from observable coordination practices to a mechanism-based explanation. The empirical reconstruction traces the emergence and evolution of NUM across crisis mobilization, consolidation, and accumulation, and shows how coordination was accomplished across micro-, meso-, and macro-level settings. The analysis then moves from empirical reconstruction to explanation. It identifies the asymmetrically activated generative and selective mechanisms through which adaptive coherence is sustained despite cumulative layering, structural incompleteness, and unresolved tensions. The final chapter of Part B conceptually closes the NUM study by specifying Digital Plasticity, anchoring it in the relevant theoretical traditions, and differentiating it from adjacent concepts such as flexibility, agility, generativity, and resilience.

Part C — Contributions and Implications derives the implications, boundary conditions, and concluding argument of the monograph. It develops implications for Information Systems research, federated infrastructure governance, and the design and management of digital ecosystems, including threshold stewardship as a derived governance implication. It then summarizes the monograph's contributions, addresses limitations and boundary conditions, and returns to the opening puzzle: what it means for a system to remain operable not by resolving its contradictions, but by learning to carry them.

I.4 Research Design and Positioning

This section states the study's positioning before the case is presented: the paradigm it works within, the inference it relies on, why NUM is treated as the case, and how the scope and vocabulary of the claims are delimited. The full methodology — research design, data, and analytical stages — is developed in B.II.

The study is positioned within critical realism (Bhaskar, 2008; Sayer, 2000), adopted not as an abstract epistemological commitment but as an operational research logic for reconstructing the generative mechanisms that produce observable patterns in complex sociotechnical systems. Coordination practices in NUM are treated as empirical expressions of deeper mechanisms that cannot be observed directly; explaining the case means recovering those mechanisms rather than merely describing the practices (Wynn & Williams, 2012).