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Problematic Persistence of Innovation: Breakdowns and Sociotechnical Maintenance of the World's Most Enduring Herbicide Technology

Abstract

Innovation research tends to focus on emerging technologies, overlooking the processes that enable some mature technologies to remain in use longer than others. Existing explanations for why some technologies persist tend to emphasize either firm-level choices within a market-based selection environment, or institutionalized barriers to sociotechnical transitions. Neither perspective carefully considers how breakdowns in sociotechnical systems can initiate maintenance processes, repairing both material malfunctions and strained sociopolitical relationships. We draw on STS theories of maintenance to offer new insights into the longevity of technologies, particularly those that prove repeatedly problematic, illustrated in our focal case study of Monsanto's glyphosate herbicide. By conceptualizing maintenance as a mode of value creation and capture, we extend existing theories of technological persistence. We identify three mechanisms underpinning strategic maintenance processes and theorize on the temporal aspects of how those mechanisms operate across sociotechnical levels. Furthermore, we highlight the unequal distribution of agency for repair work, raising ethical and political questions about the social value of maintaining problematic technologies.

Keywords

Breakdowns; persistence; technological lifecycles; sociotechnical systems; agricultural biotechnology; multi-level perspective

1. Introduction

Temporality in technological lifecycles has become an increasingly important area of research in innovation studies. Uncertainty pervades the timing of technological adoption and diffusion (Kapoor and Klueter, 2020; Rotolo et al., 2015). Most innovations follow a familiar “S-curve,” taking off quickly before leveling off in a mature phase, yet others can take years or even decades to diffuse beyond early adopters (Adner and Kapoor, 2016a; Furr and Snow, 2024; Geroski, 2000). Whether adopted quickly or slowly, not all technologies obsolesce at the same rate. For technologies such as the UPC bar code or copper telephone lines, significant “bends” in the S-curve occurred when innovations in the wider ecosystem extended the original technology's lifecycle (Adner and Kapoor, 2016b). Nonetheless, existing research on technological change often assumes that once a technology has diffused, an improved competing technology will emerge, demand substitution will take place, and firms committed to the old technology will fail (Foster, 1986; Klepper, 1996). Nokia and Polaroid are among the firms upheld as cautionary exemplars of the strategic costs of failing

to adapt to market-driven technological transformations (Tripsas and Gavetti, 2000; Vuori and Tushman, 2024).

It has been demonstrated, however, that some firms can successfully maintain or reinvigorate old technologies even in the face of competing innovations (Edgerton, 2008; Li, 2024). Innovation researchers have made important strides in understanding how old technologies can be preserved in response to changing market demands. Firms can forestall demand substitution, for instance, via exploitation of existing knowledge to incrementally improve performance, as when BMW updated its diesel engines to compete with emerging hybrid electric motors (Adner and Snow, 2010). Indeed, diesel technology has recently been explored as an example of “maintenance work” that has prevented competing technologies from emerging over multiple decades (Sardo and Pfotenhauer, 2025). Firms might also find new markets for old technologies: such has been the case for analog synthesizers (Nelson et al., 2023), Swiss watches (Raffaelli, 2019), and vinyl records (Wiedner et al., 2024). Technological systems may exhibit patterns of path dependence and technological “lock-in,” erecting high entry barriers for innovators seeking to challenge incumbent firms (Marin et al., 2023; Markard and Truffer, 2006).

Whether emphasizing firm responses to market conditions or structural factors that stall innovations, most work on mature systems assumes that old technology still *works*. Left largely unexplored are situations in which an old technology persists even though it repeatedly fails in terms of technical functionality or perceived value to society. Our objective in this study is to provide new insights into the mature stages of innovation. By exploring the history of glyphosate, a technology that has persisted in use for more than five decades despite constant internal and external problems, we build on calls for more attention to the later stages of technological lifecycles in a field predominantly focused on

technological emergence and diffusion (Bento et al., 2025; Georghiou et al., 1986; Markard, 2020).

We draw from science and technology studies (STS) to conceptualize technological longevity as an outcome driven by processes of maintenance that are both social and technical and not always driven by market pressures (Howe et al., 2016). Integrating STS insights helps address calls for more expansive understandings of innovation processes that are not rooted primarily in economic theory (Soete, 2019). Core to the STS perspective on maintenance is recognition that technologies are subject to *breakdowns*: parts wear out, electrical grids fail, and previously prized computers become obsolete as user expectations change. Breakdowns, as conceptualized by Graham and Thrift (2007), occur when sociotechnical systems are perceived as needing repair—whether in physical or social terms. Within the organizational context, breakdowns have generally been conceptualized as cognitive failures, e.g., breakdowns of communication or sensemaking (Kaplan and Orlikowski, 2013; Lok and De Rond, 2013). Conversely, in STS and innovation studies, breakdowns are also material, and can generate new knowledge rather than limit its progress. Because they are perceived as threats to technical functionality and organizational survival, breakdowns are moments when things “go wrong,” yet they can trigger organizational learning and adaptation. Beyond artifacts and organizations, STS theory understands breakdowns in the form of ruptured interorganizational relationships and sociopolitical challenges. In this conceptualization, repair work not only entails fixes for artifacts and physical infrastructures but also aims to restore societal relationships. Accordingly, we view technological maintenance as a process that, beyond preserving existing value, creates new value for society (D’Ippolito and Rüling, 2020; Russell and Vinsel, 2018; Steinert, 2024; Vinck, 2019).

Innovation research has demonstrated how organizations can continue to generate technological value over time via well-studied processes including incremental innovation and resource exploitation (Andriopoulos and Lewis, 2009; March, 1991). We build on these firm-level insights by drawing on the STS conceptualization of technology as embedded in sociotechnical systems (Geels, 2004; Jarrahi and Sawyer, 2019). The STS-derived multi-level perspective (MLP) sheds light on how institutional and sociopolitical factors beyond the nexus of firms and markets can obstruct technological transitions (Geels et al., 2016). Less commonly explored in STS (in contrast to innovation studies) is how individual firms might develop capabilities for repairing broken artifacts, failing systems, ruptured social relationships, or collapsed expectations for a technology's value.

To demonstrate how STS and innovation studies can be integrated to understand technological maintenance as a multi-level sociotechnical process, we present a longitudinal case study of Monsanto's glyphosate herbicide technology (Roundup). Since its discovery as a powerful agrochemical in 1970, glyphosate has proven an exceptionally enduring yet troubled technology. Competing herbicides have averaged lifecycles of just a few years. Glyphosate, however, persists as a core component of industrial agriculture, sprayed in greater volumes than any other agrochemical in history, despite repeated technical and social breakdowns. In an intriguing irony, a chemical touted for rapid physical degradation has persisted in use for decades; Roundup's technology has outlived the firm that commercialized it.

A core contribution of our study is to expand and complement existing research in innovation studies on technological longevity, exploring maintenance processes within, as well as beyond, the firm-market nexus. We reveal three specific mechanisms underpinning maintenance processes, all emerging as responses to breakdowns at multiple sociotechnical levels. Through *controlling specialized knowledge*, *servicing the sociotechnical system*, and

leveraging institutional power, Monsanto preserved the value of a technology that repeatedly failed to meet the expectations of key stakeholders. Exploring these mechanisms sheds light on how other organizations might pursue sociotechnical maintenance processes beyond the boundaries of the lead firm.

Our second core contribution is to define and discuss how these mechanisms are conditioned by the temporality of the repair action. The temporal dimensions of maintenance, we contend, go beyond the S-curve's objective measurement of the length of time a technology remains in use before obsolescing. Temporality factors into maintenance processes in two further ways: first, in terms of subjective understandings of the past and the future, and second, in more indeterminate periodicities of activity that we call "rhythms" of repair. We demonstrate that technological longevity can result from both planned and reactive firm-level maintenance of a sociotechnical system in response to subjectively perceived breakdowns, with differing rhythms characterizing the continuity or discontinuity of repair work.

With these contributions, we build on innovation research that demonstrates how organizations can strategically extend technological diffusion by shaping the broader ecosystem surrounding a technology (Adner, 2017). We also draw on the multi-level perspective in STS research to move beyond market-based selection and interfirm competition, emphasizing how institutional regimes structure the temporality of technological change (Geels, 2010; Geels and Schot, 2007). In doing so, we highlight the heterogeneous distribution of agency within a sociotechnical system undergoing repair, raising ethical questions for management practice and innovation policy in maintaining mature technological systems (Lloveras et al., 2025).

2. Literature review

Within innovation studies, there are two primary sets of explanations as to why some technologies persist longer than others. The first, explored in Section 2.1, focuses on firm-level choices and capabilities within a market-based selection environment. Section 2.2 considers how sociotechnical systems can become resistant to transformation on multiple levels. Neither the firm-level nor the multi-level perspective in innovation studies, however, fully considers how *breakdowns* shape the trajectory of technological persistence. In Section 2.3, we explore how STS theories of maintenance offer new possibilities for explaining the longevity of technologies.

2.1 Firms, Markets, and Technological Persistence

Organizational longevity is often linked to a firm's capabilities, specifically to striking a balance between exploring new knowledge and exploiting an existing technological portfolio (Lavie et al., 2010; Raisch et al., 2009; Roper and Hewitt-Dundas, 2008; Salge, 2012). Firms with a diverse knowledge base may be particularly effective at exploitation (Quintana-García and Benavides-Velasco, 2008). Successful exploitation can thus be understood as one means of preserving a technology's value in the marketplace over long periods of time, often via “demand-led” incremental innovation (Freeman, 1996).

Innovation scholars further point to the appropriability regime to account for technological longevity. In some industries patent enforcement and litigation are routinely used by firms to prevent rivals from developing substitute technologies (Cohen et al., 2000; Rudy and Black, 2018). Patents can produce knowledge spillovers, however, so firms may need to develop multiple appropriability mechanisms, such as “locking in” expert tacit knowledge or deploying trademarks to extend the lifecycle (Nasirov, 2020; Wang and Zheng, 2022).

Complementary assets—including marketing, service, and distribution capabilities—can further extend a technology's lifecycle (Teece, 1986). When firms lack essential

complementary assets, they may collaborate with competitors or suppliers, although doing so heightens the difficulty of protecting specialized knowledge while sustaining trust beyond the lead firm's boundaries (Kretschmer et al., 2022; Oxley and Sampson, 2004; Toh and Agrwal, 2023). Firms may be able to extend the lifecycle of an old technology by collaboratively developing complementary assets within a wider ecosystem, as occurred in the 1990s semiconductor lithography industry (Adner and Kapoor, 2016b).

Exploitation, appropriability regimes, and complementary assets offer substantial explanatory power for why some firms prevent the displacement of particular technologies. Yet this strand of innovation theory rests on assumptions of market-driven decision-making, with firms investing in modes of preserving technological value in response to perceived user demand (Adner and Snow, 2010; Furr and Snow, 2024; Li, 2024). A narrow focus on market-centered selection environments, however, obscures how uncertainty about future market conditions shapes the temporality of innovation. The long-term value of a maintained technology is unclear at any given point in time (Gans and Ryall, 2017; Garud and Nayyar, 1994; Nelson et al., 2023). Patent preemption, for example, can help defend the value of a technological resource, but requires costly investments under highly uncertain expectations of future value appropriability (Ceccagnoli, 2009; Grimpe and Hussinger, 2014; Ziedonis, 2004). Markets evolve over time, including those for specialized complementary assets (Moreira et al., 2023).

A second shortcoming of market-based explanations for technological longevity is their limited attention to non-market factors. Beyond the lead firm, strategic value maintenance unfolds within a broader sociopolitical environment (Oliver and Holzinger, 2008; Sun et al., 2012). Corporate political activity to defend the institutional status quo can enable long-term value maintenance for specific resources; Toyota, for instance, shaped emissions regulations in ways that preserved the long-term value of its hybrid engine

technology (Wesseling et al., 2015). Furthermore, not all efforts to create or preserve technological value are motivated by market factors. For “outlaw” innovators or open source developers, the value of a technology may stem from curiosity rather than financial rewards (Flowers, 2008).

2.2. Sociotechnical Transitions and the Multi-Level Perspective

Recognizing the limitations of market-centered factors in the explanation of technological trajectories, innovation scholars have increasingly turned to non-market factors (Hoppmann et al., 2013; Lavie et al., 2010, 2013; Mansell, 2021). A key concern in understanding technological persistence is why some transitions—such as those to low-carbon transport or energy infrastructures—are stalled or blocked by asymmetrical power relations (Freeman, 1991; Jarrahi and Sawyer, 2019; Nelson and Nelson, 2002). Conceptualizing technology as embedded within sociotechnical systems requires attention to choices, ideas, and institutions that exist beyond firms and markets (Glynn, 2002; Green et al., 1999; Soete, 2019).

These insights from STS help explain why some sociotechnical systems remain highly stable while others experience dynamic change (Svensson and Nikoleris, 2018). Geels’s influential work in the MLP moves beyond artifacts, firms, and markets to theorize that sociotechnical “regimes” are the locus of stability, where the set of rules laid down by institutions and social norms reinforce existing structures and expectations (Geels, 2002, 2004, 2010; Geels and Schot, 2007). Regimes in this perspective exhibit technological lock-in and path dependence, enabling powerful incumbents to prevent the emergence of new technologies (Geels et al., 2016; Zolfagharian et al., 2019). A study of the diffusion of genetically engineered (GE) soybeans in 1990s Argentina, for instance, explains lock-in as the result of cognitive mechanisms that prevented alternative technologies from being conceived as novel (Marin et al., 2023).

Transformative technologies, in the MLP, emerge within “niches” where actors change the rules of the game. “Niches” remain outside the stable “regime,” however, until developments in what Geels (2007) calls the “landscape” enable such rule-breaking. Landscapes, in the MLP, are slow to change, and include such elements as cultural values, political ideologies, and demographics (Fuenfschilling and Truffer, 2014). This multi-level understanding usefully emphasizes the agency of organizations and institutions beyond the market (Markard and Truffer, 2006; Nuñez-Jimenez et al., 2022; Smith et al., 2010).

In the MLP’s account of technological stability and change, however, there is limited room for firm-level agency, except within “niches” where innovative activity is assumed to target radical change. Both regimes and landscapes are conceptualized as inherently slow to change, with little explanation for why the dynamics within any given regime shift when they do (Svensson and Nikoleris, 2018). A core critique of the MLP is its insufficient attention to power asymmetries (Smith et al, 2010). Sociotechnical regimes are portrayed as inherently stable, rumbling on semi-autonomously until a “reconfiguration” dismantles their locking mechanisms (Edmondson et al., 2019). By redirecting attention away from firm-level actions, the MLP risks overlooking why certain organizations have more power than others to prevent sociotechnical transitions. To address this limitation, we draw on additional STS insights on breakdowns and maintenance to explain technological persistence over time.

2.3 Breakdowns and Maintenance in Sociotechnical Systems

STS scholars call for attention to the significance of maintenance in the innovation process, particularly the “invisible” and often underpaid work required to keep technologies functioning (Denis and Pontille, 2015; Shapin, 1989). We have rich theories of how value is created or captured by the introduction of new knowledge, artifacts, or practices, yet the value of maintenance often goes unnoticed until “technologies become inoperable” (Graham and Thrift, 2007: p. 2). Inoperability, when as a breakdown by relevant actors, can prompt

organizational adaptation and learning, producing new forms of value creation from an existing but reconfigured technology (Denis et al., 2016). This view of breakdowns as generative of change challenges the MLP's assumption of sociotechnical regime stability. Perhaps counter-intuitively, technologies that experience operational problems may prove as persistent as those embedded within highly stable sociotechnical regimes.

Innovation scholars have not ignored breakdowns. Kapoor and Klueter (2020) provide insights into what they term “setbacks,” or discontinuities in the diffusion of new technologies. Different organizations respond differently to “setbacks,” although in Kapoor and Klueter's conceptualization, the most likely response to a problematic emerging technology is resource withdrawal, as organizations move on to other less troublesome technological options. Yet as Geels and Raven (2006) illustrate in a study of Dutch biogas plants, repeated technical breakdowns can produce sociotechnical reconfiguration. Faced with persistent problems including blocked pumps, ineffective digesters, and corroding pipelines, biogas promoters responded not by withdrawing their resources but by reconfiguring the sociotechnical system via “repair work” (p. 380). Some of this repair was technical, but much was cognitive, as biogas promoters repeatedly shifted the sociopolitical expectations of biogas technology (Geels and Raven, 2006).

Such work highlights the need to interrogate breakdowns more fully. The STS approach to breakdowns suggests that certain organizations may be able to develop capabilities to maintain highly problematic sociotechnical systems. Sardo and Pfotenhauer (2025) demonstrate that diesel automobiles have remained in widespread use for more than a century, despite constant challenges including critiques of diesel engines' problems with air pollution, fuel inefficiency, greenhouse gas emissions, and—in the case of “Dieselgate”—outright scandal. The persistence of diesel engines, in this reading, required incessant maintenance of an inherently fragile sociotechnical regime, repair work which Sardo and

Pfotenhauer (2025: p. 2) argue occurs primarily in the realm of “sociotechnical imaginaries.” These insights highlight the significance of macro-level, non-market maintenance work in sociotechnical systems. Yet attributing causal force to conceptually slippery “imaginaries” reveals the need to further develop and clarify what is meant by technological “problems,” “setbacks,” or in the terminology we find most useful, *breakdowns*.

Building on Graham and Thrift (2007), we define breakdowns as moments of rupture within a sociotechnical system, when one or more elements of a technology that are expected to produce value for stakeholders fail to do so. The materiality of technological systems is significant in this regard. In common parlance, breakdowns are generally perceived as physical failures—a punctured tire, a blown fuse, a collapsed bridge. Recent STS work builds on this quotidian understanding of breakdowns, insisting that hardware embodies social values; thus, even prosaic acts of physical repair are elements of ongoing processes of value maintenance (Steinert, 2024). A non-functioning technology does not produce value. The Therac-25 radiation therapy device developed by Atomic Energy of Canada Limited (AECL), for instance, experienced multiple disastrous breakdowns in the early 1980s when both software and hardware problems led to at least six lethal or near-lethal radiation overdoses. AECL devoted substantial effort and resources to developing new knowledge capabilities to repair the technical failures (Leveson, 1995).

A technology’s failure to deliver value can however occur at multiple sociotechnical levels, requiring consideration of breakdowns as more than physical damage or software bugs. Some breakdowns in sociotechnical systems occur in firms and markets, as with the collapse of sensemaking capabilities at Nokia when faced with platform-based competition from Apple (Vuori and Tushman, 2024). The Nokia example encapsulates what Graham and Thrift (2007) consider the phenomenological aspect of breakdowns, for the “problem” of Nokia’s exploitation of its industry-leading hardware capabilities only became “visible”

when senior managers were surprised by the rapidity of consumers' changing value expectations. This highlights STS's view of maintenance, which posits that as sociotechnical systems grow in scale and complexity, the cost of not repairing breakdowns increases (Cuevas-Garcia et al., 2023; Vinck, 2019; Vinsel, 2017).

Interorganizational relationships with multiple stakeholders may be required to maintain a system's functionality. Therac-25's disasters, for instance, exposed a wider set of failings in the medical devices industry, spurring development of a preventative software design standard, IEC 62304 (Dahlke and Ginsberg, 2021). Interorganizational relationships can be affected by unequal access to the knowledge or other resources needed to initiate or sustain repairs, however (Crooks, 2019; Howe et al., 2016). Research on users of technology demonstrates that maintenance knowledge can either be tightly controlled by firms ("black-boxed") or more readily shared with end users (Gonzales, 2016; Gonzales et al., 2016; Kline and Pinch, 1996).

Breakdowns and maintenance processes can occur at levels beyond artifacts, organizations, markets, or interorganizational relationships, extending into the external environment of political institutions and ideologies. Regulatory policies and the broader economic and political context shape the maintenance choices that organizations can make (Godin and Vinck, 2017; Tidd, 2001). Henke and Simes (2020) offer the example of weapons development in the wake of an international ban on nuclear testing in 1996. Deprived of the ability to physically demonstrate the power of the U.S. atomic arsenal, weapons designers, military leaders, and politicians reconceived how to maintain the status quo, increasingly directing resources toward sustaining pro-nuclear ideologies. Yet repair work is not always post-hoc. Processes of maintenance at the regime level may routinely involve continuous, anticipatory responses to possible future breakdowns aimed at preventing them (Pinjala et al., 2006). Such pre-hoc maintenance, for instance, motivates firm- and industry-level

investments in safety and environmental regulatory compliance (Russell and Vinsel, 2018). Organizations that do not proactively develop effective maintenance processes, e.g. for complex software or architectural structures, may be forced to reactively expend resources when responding to breakdowns (Kaufmann-Buhler, 2022; Levrat et al., 2008).

A core insight of the STS approach to breakdowns is that maintenance can create new value from a sociotechnical system, rather than simply fix an old problem. This may seem counterintuitive. Strategic and operations management literature, for instance, portrays technological maintenance not as a value creation opportunity, but as a cost that firms should minimize (Bowman and Ambrosini, 2007; Cooke, 2003; Murthy et al., 2002; Tsang et al., 1999; Wang, 2002). From an STS perspective, however, recognizing the generative impact that breakdowns can have for organizations is essential, as breakdowns produce visibility of otherwise unnoticed challenges (Graham and Thrift, 2007; Howe et al., 2016). When technological failures become spectacles, they can generate creative, forward-thinking aspects of maintenance that contribute to technological innovation, thereby creating long-term value for organizations and society (Cuevas-Garcia et al., 2023; Russell and Vinsel, 2018). The case of Therac-25, for instance, is still widely studied by software engineers as a learning opportunity to produce technology of higher social value (Dahlke and Ginsberg, 2021). Multi-level approaches to innovation that include such processes of “re-invention” and “maintenance” can produce transformative social innovations (Pel et al., 2020: p. 10).

But even as STS draws attention to the value-generating potential of maintenance, research also insists that capabilities for maintenance are not evenly distributed in a sociotechnical system: stakeholders, including competing firms and technology users, may not have equal access to the resources required to maintain a technology (Gonzales, 2016; Raffaelli, 2019). Indeed, if some organizations can develop more successful maintenance processes than others, there is a potential “dark side” to consider. Incumbents may exploit

maintenance to prevent socially beneficial change in sociotechnical regimes (Henke and Sims, 2020; Pel et al., 2020). Although repair of old technologies is lauded by advocates of circular economy as a means for reducing manufacturing waste and energy usage, maintenance processes can also enable a single firm to control the lifecycle of a complex technological ecosystem (Lloveras et al., 2025).

In summary, innovation research currently offers useful market-focused explanations for why some technologies last longer than others. STS concepts of breakdowns and maintenance complement such perspectives, offering opportunities to comprehensively explore how organizations maintain mature but problematic technologies as a means of creating value over a long time. We explore these issues by asking: How could Monsanto maintain its glyphosate technology as a valuable resource for so long?

3. Research design

3.1 Methods and Data

Initial research suggested to us that the persistence of glyphosate was an extraordinary phenomenon. Monsanto's competitive position depended on glyphosate from the 1970s to its acquisition by Bayer in 2018. As detailed by Elmore (2021) and summarized in **Table 1**, Roundup effectively transformed Monsanto from a mid-sized manufacturer into a global agrochemical powerhouse. Global adoption of glyphosate rose 12-fold from 1995 to 2014, impacting 30 percent of the world's cultivated farmland. Roundup has been widely used for five decades; no other pesticide has been sprayed so much, on so many acres, in agricultural history (Benbrook, 2016; Elmore, 2018, 2019). The lifecycles of other herbicidal technologies, by contrast, have averaged only three years (Duke, 2012, 2018).

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Early in our literature review, we identified the need to consider multiple interconnected sociotechnical levels, or domains of activity (Geels, 2002, 2004; Geels and Schot, 2007). Our

levels of analysis are not intended as hard-wired ontological entities; rather, they constitute analytical frames that we mobilize to identify the relevant “set of actors” within which value propositions and capture mechanisms are enacted (Adner, 2017). At the micro-level are technological artifacts, which as STS theory has demonstrated are both products and producers of sociotechnical change (Allen and Hecht, 2001). The meso-level sociotechnical system, as explored in the MLP, encompasses the capabilities and activities of the lead firm, along with interorganizational relationships with buyers, suppliers, and competitors in an environment characterized by market transactions and interconnected technical systems (Geels et al., 2016). Finally at the macro-level are institutional aspects of the nonmarket environment including political activities and external stakeholders’ responses to technological change (Henke and Sims, 2020; Sardo and Pfotenhauer, 2025). As noted in the literature review, STS theory has convincingly demonstrated that these domains of sociotechnical activity are inherently interwoven; however, for analytical purposes. it remains useful to keep them distinct, given the uneven distribution of power.

Exploring technological maintenance longitudinally as a multi-level sociotechnical process requires a rich dataset. We examined an extensive range of historical records covering the period from the 1970s to the 2010s, seeking to uncover the dynamics of processes that occurred over decades. The dataset includes forty-three archival documents of varying lengths—ranging from short internal memos to lengthy strategic reports—gathered from the Monsanto Company archives held at Washington University. We also systematically searched U.S. government records for relevant reports, court documents, and congressional testimony. In addition, three oral history interviews (held at the Science History Institute) with Monsanto scientists provided insights into organizational culture and processes. The trade journal *Pesticide Chemical News* (later *Pesticide and Toxic Chemical News*) provided month-by-month reports on how glyphosate technology was perceived by

key stakeholders. We gathered Monsanto press releases spanning 2003-2018, downloaded from a website subsequently deactivated in 2019. During our analysis, we identified additional scientific literature on glyphosate, revealing important insights that contradicted statements by Monsanto managers. Altogether, these 319 documents provide evidence of the actions and views of multiple stakeholders—managers, researchers, customers, competitors, regulators, and concerned citizens—regarding glyphosate technology.

3.2 Data Analysis

Having collected data along a loose timeline, we proceeded to data analysis, systematically developing 152 first-order codes grounded in the empirical data using NVivo software (Eisenhardt, 1989). We repeatedly re-examined our initial codes, seeking coherent patterns across the dataset. We specifically focused on processes of reconfiguration—series of events and decisions unfolding over time during which existing configurations of technological artifacts and systems, organizational resources and capabilities, and stakeholder relationships were dynamically transformed to preserve or capture value in the face of perceived technological breakdowns (Gehman et al., 2017; Langley et al., 2013). Linking our iterative reading of the dataset to the literature review, patterns emerged from our reading and re-reading of the coded data (see Appendix A). We began collating our first-order codes into three broad maintenance processes—*rebuilding the technological system*, *repairing the sociotechnical system*, and *collaborative patching of the regime*—which we explore in detail in the Findings section.

Next, we constructed visual maps of the granular elements underpinning each maintenance process. This step revealed interconnected flows of events over time (Langley, 1999; Miozzo and DiVito, 2016). We looked for discrete events and specific causal relationships and outcomes, while also examining how interconnections changed over time. In searching for breakdowns across sociotechnical levels, we considered whether they might

generate value-creating repairs (Pel et al., 2020; Vinck, 2019). To evaluate the distribution of agency throughout the sociotechnical system, we differentiated between actions taken by Monsanto managers and actions taken by external stakeholders. We noticed a patterned relationship between actors and levels, with internal actors focusing on artifacts, organizations acting at the level of the sociotechnical system, and broader institutions dominating in the sociopolitical environment. To understand the consequences of these actions over time, we developed a visual vocabulary using standard symbolic conventions (Langley and Ravasi, 2019): triangles for breakdowns; ovals for consequences; boxes for actions taken by Monsanto managers; rounded boxes for actions taken by actors outside the firm. We then sketched visual maps to depict sequences of events and outcomes for each maintenance process, linked together with arrows representing causal relationships. We used these diagrams to iteratively explore how maintenance processes occurred at multiple sociotechnical levels, with particular attention to responses to perceived breakdowns. This visualization highlighted distinct temporalities of maintenance, with some activities occurring before a breakdown became widely visible and others occurring post-hoc. Visualization also revealed contrasting rhythms of activity, with some repairs occurring on a continuous basis while others happened more sporadically. Given the granular complexity of the resulting maps, we present the findings of our analysis in narrative form in the next section and further discuss them in Table 2 (full versions of the maps can be viewed in Appendix B).

4. An understanding of the unfolding maintenance processes

4.1 Rebuilding the technological system (1970-1990)

John Franz discovered the extraordinary herbicidal properties of glyphosate in 1970. Franz's work at Monsanto was enabled by the firm's commitment toward systematic discovery of patentable chemicals, including procedures emphasizing process engineering for cost-efficient manufacturing. Monsanto's agrochemical successes in the 1960s included alachlor

(Lasso), which despite market-leading sales in the 1970s was increasingly losing effectiveness. Franz's work on herbicides began in the 1960s under plant physiologist Philip C. Hamm, who had become convinced that a phosphonic acid technology could be developed to replace Lasso, well before alachlor's problems became widely evident. Finding an effective herbicidal application of phosphonic acids, however, required a continuous screening process that Franz nearly abandoned after repeated failures. Glyphosate, commercialized as Roundup in 1974, proved Hamm's foresight to be correct, as its functionality as a multipurpose herbicide was unprecedented. It was easy to apply and did not persist long in the soil after application, allowing farmers to plant crops quickly after weeding. Monsanto bolstered glyphosate's value proposition through the 1980s, developing new Roundup formulations to meet consumer demands (e.g., the ability to spray after rainfall). U.S. farmers increasingly adopted glyphosate in the 1980s and early 1990s to enable no-till agriculture—a soil conservation technique explicitly encouraged by Monsanto's marketing team. Ironically, in the early stages of Roundup's commercialization, its propensity to literally break down quickly was a key selling point.

Monsanto's vision for an “endless number of applications” for Roundup (Monsanto Company 1989) encapsulates the early stages of the Roundup technological system. A series of interlocking decisions and outcomes at the micro- and meso-levels of the glyphosate sociotechnical system enabled Monsanto to offer a powerful herbicide to loyal agricultural users at low cost. Regulatory actions at the macro-level supported this initial strategy. EPA approval of glyphosate as a low-toxicity, non-persistent, multipurpose broadleaf herbicide, paired with patents on both chemical and engineering knowledge, simultaneously ensured customer loyalty and erected high barriers to entry for firms with competing herbicides.

A significant breakdown occurred in 1991 when the initial patent on glyphosate as an herbicide expired, prompting a “key question” in Monsanto's 1992 shareholder report: “How

long can we extend the growth of Roundup herbicide for?” Even before competitors flooded the market with generic glyphosate, Monsanto executives began orchestrating a reconfiguration of the company’s capabilities and organizational identity: outsized investments in biotechnology research in the 1980s and a wave of mergers and acquisitions in the 1990s shifted the firm from proprietary agrochemicals towards a knowledge-based system, capturing value via licensing intellectual property (IP). The result of this long-term, continuous rebuilding of the technological system for Roundup led to the 1996 commercial release of Roundup Ready (RR) soybeans, which bundled Monsanto’s branded glyphosate together with seeds carrying patented IP. The RR system dramatically increased efficiency of soybean production, enabling farmers to apply glyphosate *after* planting seeds, killing post-emergent weeds but not the soybeans. Within a few years, Monsanto commercialized RR seeds for canola, maize, and cotton. A farmer recalled the transformative impacts of RR soybeans two decades after introduction: “it took away the need to walk the beans every summer, saving two weeks... [RR] made a tremendous difference for farmers” (U.S. DoJ and U.S.D.A., 2010: 152). Although farmers had access to generic glyphosate after 1991, only Monsanto sold RR seeds, and its existing supply arrangements and product stewardship cultivated customer trust in Roundup’s quality and effectiveness.

Rebuilding Roundup from a self-contained chemical technology to a biotech-based seed-chemical bundle emerged as a pre-hoc response to anticipated future breakdowns in the Roundup sociotechnical system, both in terms of operational functionality as had been the case with Lasso, and in anticipated losses of IP protection. Monsanto required farmers who purchased RR seeds to contractually agree to purchase new seeds seasonally via a technology use agreement. Farmers who replanted or resold seeds faced lawsuits. One farmer protested that Monsanto’s patent rights extended only to the point of purchase, not to the farmer’s fields where a seed could self-replicate. In *Bowman v. Monsanto* (2013), however, Monsanto

successfully counterargued that its patents prevented reproducing its seed technology, effectively extending the firm's control over IP throughout the entire sociotechnical system rather than simply the artifacts (Olson, 2012). This was a different approach than normally pursued in preemptive patenting strategies (Ziedonis, 2004). In *Bowman*, Monsanto sought to not only preempt competitors from piggybacking on RR technology, but also assert control over the ownership rights of *users* of the technology.

The RR system consequently produced a set of interlocking and self-reinforcing consequences. Users and suppliers of RR became locked-in to the technology; competitors lacked incentives to invest in R&D for alternative herbicides; and a noncompetitive market for herbicidal biotechnology spurred antitrust investigations and reputational losses. A potentially major breakdown in the rebuilding process occurred in 2004, when Monsanto withdrew applications for regulatory approval of a new RR wheat variety in multiple countries, halting a continuous development process that had been ongoing since 1998. U.S. and Canadian wheat growers rejected RR wheat, fearing the loss of overseas markets where consumers opposed GMOs. Monsanto managers responded to this exceptional breakdown by realigning its strategy with growers' interests, dropping RR wheat development to enable continued sales of proprietary glyphosate in a key market. This response helped forestall further potential relationship breakdowns; for example, in 2010 the U.S. National Association of Wheat Growers joined Monsanto in fighting organic producers seeking to ban RR alfalfa. Similar efforts to cultivate backing from agribusiness organizations included a 2009 commitment to provide technical support for first-generation RR soybean seeds for more than a decade after its key patent expired in 2014.

Despite buy-in from big commercial farmers, the reputational damage of Monsanto's approach to rebuilding the technological system was severe, as environmentalists and smallholder farmers attacked "Monsatan" from the late 1990s onward. Post-hoc criticisms of

Monsanto's bundling of RR seeds and chemicals tend to assume a planned, exploitative intent (Dupraz, 2012). Yet our evidence demonstrates a more emergent, pre-hoc turn to rebuilding, contingent upon multiple external and interorganizational events and decisions in the face of anticipated breakdowns. Rebuilding was initially rooted in Monsanto's focus on maintaining the value of the technological artifact of glyphosate as a chemical herbicide with "endless applications." The rebuilt RR technological system emerged out of iterative and continuous responses to breakdowns, increasingly moving from the micro-level of the sociotechnical system up to the meso- and macro-levels. In the early phases of maintaining Roundup's value offer and value capture mechanisms, Monsanto managers built on existing capabilities in chemistry, engineering, manufacturing, and marketing. Responding to post-hoc threats to the sociotechnical system, however, Monsanto managers increasingly took actions at more meso- and macro-levels to protect and defend not only the value of RR, but also the organizational identity of a firm producing its core revenue through licensing access to a knowledge-based technological system.

4.2 Repairing the sociotechnical system (1970-2000)

The second process of value maintenance revealed by our data was driven by three breakdowns: the first occurring at the level of the technological artifact (surfactants in Roundup), the second at the infrastructural level (glyphosate resistance), and the third in the external environment (health and ecological concerns).

Although glyphosate is the all-important "active" ingredient, Roundup also includes significant proportions of "inert" surfactants. Inert ingredients are subject to less regulatory scrutiny than active ingredients. Monsanto and the EPA assured early users of Roundup in the 1980s of glyphosate's low toxicity. Some scientists, however, began reporting disturbing toxicity levels for aquatic animals exposed to Roundup formulations containing surfactants such as MON0818 (Folmar et al., 1979; Sawada et al., 1988; Servizi et al., 1987; Wan et al.,

1989). Despite publication of this knowledge, Roundup's toxicity did not produce widespread concern in the 1980s as Monsanto-supported scientists concluded that "under normal usage" the affected aquatic environments would dilute the toxins (Mitchell et al., 1987). Such a formal publication by a Monsanto employee was relatively rare, given the firm's controls on its scientists' ability to publish research involving proprietary chemical knowledge (Franz, 1994). Controlling knowledge of potential harms to animal (including human) health fit a longer pattern. In 1979, Monsanto successfully sued to prevent the EPA from releasing data on Roundup's health effects (House Committee on Agriculture, 1985). Monsanto scientists may have had more pre-hoc awareness of toxicity problems during this period than other key stakeholders, including users, regulators, and shareholders. A 2018 legal case revealed evidence of Monsanto managers actively silencing a scientist (James Parry) whose Monsanto-contracted research in 1999 discovered substantial potential human health effects from exposure to glyphosate (Elmore, 2021; House Committee on Science, Space, and Technology, 2018).

Because scientists knew of the potential harms of surfactants, by the early 1990s significant technological repairs were underway, as Monsanto repeatedly reformulated Roundup products with lower levels of certain surfactants. Rather than advertising the lower toxicity, however, Monsanto touted the new formulations as better suited to no-till soil conservation practices (Monsanto Company, 1995). The RR system furthermore incorporated stewardship agreements restricting external scientific research on glyphosate's potential environmental harms. Controlling knowledge of potential toxicity proved effective; external scientists only began to publish more widely on the human and animal health impacts of Roundup's "inert" ingredients at century's turn (Mann and Bidwell, 1999; Mesnage et al., 2019).

Glyphosate-resistant (GR) “superweeds” (first discovered in 1997, and a consequence of the exponential increase in global glyphosate usage) generated a far more publicly visible breakdown (Bétrisey et al., 2022). Additionally, evidence of glyphosate’s link to crop-damaging fusarium mycotoxins drove up costs for users as the herbicide’s functionality declined. In contrast to surfactants, our evidence for pre-hoc awareness of these breakdowns is limited. Monsanto’s response to these problems was, however, continuous and substantial, as the firm developed complementary technological artifacts and innovative services to repair the system. Incorporating additional herbicides, such as dicamba, into the second-generation RR system provided a potent weapon against GR weeds and was marketed as a means of increasing crop yields and flexibility of application. Added complexity, however, triggered the need for risk-management support. Dicamba’s high toxicity, tendency to “drift” across property lines, and duration of soil persistence compared unfavorably to glyphosate. With Monsanto scientists aware of the risks of dicamba, the firm invested significant resources into maintaining trust-based relationships with customers and regulators. Sales forces were trained in providing customers with knowledge about GR, and a new Crop Protection Division was created to assure stakeholders that the commercial benefits of Roundup’s continuance outweighed environmental costs (Monsanto Company, 2006). Monsanto launched online risk assessment tools and funded university research into users’ management practices for confronting GR (Monsanto Company, 2005). The firm also conducted research and recruited managers to support users in continuing to plant RR seeds, including with the digital RR PLUS technology released in 2012 (Monsanto Company, 2012).

Repairing the sociotechnical system of RR in the face of toxicity and glyphosate resistance led to a continual increase of RR usage through the 2010s. One consequence of rising public knowledge of RR’s breakdowns was a need for Monsanto to exchange knowledge more openly: with customers, external scientists, and—as the next section

reveals—with competitors. Maintaining the value of the RR system for core users, however, increasingly exposed Monsanto to further breakdowns originating in the external environment (Chataway et al., 2004). Anti-GMO protests and litigation led critics to label the firm “Monsatan,” while mounting evidence of toxicity led the International Agency for Research on Cancer to declare glyphosate a “likely carcinogen.” Monsanto’s post-hoc, sporadic efforts to repair reputational damage included publicizing research from US and European regulators downplaying glyphosate’s carcinogenic risks (Monsanto, 2016). Critics, however, dismissed Monsanto’s efforts as a “disinformation” campaign (House Committee on Science, Space, and Technology, 2018).

4.3 Collaborative patching of the regime (2010-2018)

The third value maintenance process revealed in our analysis was driven initially by the sheer scale of resources needed to transform a chemical firm like Monsanto into a biotechnology innovator. Pioneering ag-biotech firms of the 1980s such as Calgene challenged firms reliant on mass production of proprietary agrochemicals. Monsanto strategists such as CEO Richard Mahoney recognized early in the move toward ag-biotech that no single firm could afford the knowledge to deliver every seed trait that farmers desired: Monsanto would specialize in weed control for instance, while others targeted drought or insect tolerance (Monsanto Company 1994). By the mid-1990s, Monsanto and agrochemical competitors including BASF, Bayer, Dow, and DuPont had segmented the market to limit direct competition (Copping, 2018; Howard, 2015). Providing a “complete menu” of genetically modified seeds required continuous collaborations with other agribusinesses, such as a 1996 cross-licensing arrangement with seed firm DeKalb (Kilman and Fritsch, 1996). Cross-licensing seed, chemical, and biotech knowledge thus became a core element of crop protection technologies for the following decades, establishing collaborative knowledge exchange as an industry-

wide strategy to enable “stacking” of proprietary genetic traits from multiple firms into seeds branded and sold by individual firms.

Collaboration, however, produced sporadic cycles of trust and mistrust with multiple stakeholders connected to the RR system. The value of collaboration was clear at the point of introducing an innovative technology into the system, but waned as the technology diffused more fully. Opening RR’s black box exposed Monsanto to potential loss of control over the technology’s long-term value prospects. Independent seed dealers, essential partners due to their distribution and marketing capacity, were able to license Monsanto’s RR technology for inclusion in their own proprietary seeds. Monsanto’s Vice President for Industry Affairs explained in 2010 that such agreements reflected the importance of “hav[ing] a lot of people at the table” for preserving RR’s value proposition (U.S. DoJ and U.S.D.A., 2010). Dealers licensing RR technology complained, however, of Monsanto’s black-boxing of valuable technical knowledge and refusal to provide access to “manufacturing and distribution assets and channels” (Pullen Seeds, 2006: 12). Monsanto penalized dealers selling generic glyphosate after a key patent expired in 1991, restricting access to RR technologies. Meanwhile, surfactant problems with generic glyphosate emerged in the 2010s, leading users to redouble their trust in the Roundup brand and its higher-quality formulations, and thus from a marketing perspective validating Monsanto’s restrictive relationships with seed dealers.

Breakdowns in the mature technology forced a return to collaboration, however. The technological breakdown of glyphosate resistance, along with awareness of a key patent expiration for the first generation of RR seeds, spurred Monsanto to develop further collaborative relationships. Competitors piggybacked on the RR system, such as in 2006 when Dow and FMC jointly produced a premixed herbicide targeting GR weeds. Monsanto responded by collaborating with competitors to extend the RR system with “stacked” genetic

traits, such as a 2008 agreement for Monsanto and Syngenta to “cross-enable each other” and halt patent infringement lawsuits (Monsanto Company, 2008). Monsanto monitored firms’ use of RR technology aggressively, however, never hesitating to litigate perceived transgressions of contractual boundaries (Monsanto Company, 2010). Limiting full access to its proprietary knowledge produced deep mistrust, notably in protracted legal battles with DuPont over efforts to stack RR with its Optimum GAT seed trait (Dupraz, 2012). Such litigation is just one example of the challenges posed by “patent thickets,” in which firms laid competing claims to proprietary technologies, resolving the contest either through lawsuits, cooperative licensing, or mergers and acquisitions (Howard, 2015). As research on patenting and co-opetition in pharmaceuticals has demonstrated, cooperative relaxation of patent fencing can produce mutually beneficial outcomes for firms with complementary assets, but like the classic prisoner’s dilemma of game theory requires a willingness to trust an untrustworthy competitor (Pitelis et al., 2018). In Monsanto and DuPont’s case, cycles of mistrust and trust overlapped temporally; even as they battled over stacked traits in GAT seeds, the two firms were simultaneously sharing technical data and proprietary knowledge to foster other collaborative innovations (U.S. DoJ and U.S. DoA, 2010: 181).

An irony emerged from these tensions of collaboration: the RR system maintained its value (albeit problematically) even after the firm that initiated its sociotechnical system disappeared. In the 2010s, Bayer strategy chief Werner Baumann initiated a takeover bid to expand Bayer’s small pesticide business by synergizing with Monsanto’s seed, biotech, and digital crop protection technologies. Bayer’s formal bid for acquisition was announced in 2016; the deal closed in June 2018. Within weeks, Bayer lost a lawsuit centered on Roundup’s carcinogenic effects, followed by additional lawsuits from residential users of glyphosate costing Bayer hundreds of millions of dollars in damages (Sherman, 2019). Bayer dropped the Monsanto name, and in 2021 announced plans to discontinue selling Roundup to

residential customers. At the same time, Roundup Ready remains the most widely used crop protection technology in the world among *agricultural* users, suggesting that farmers' trust in glyphosate remains steadfast (Maggi et al., 2020).

5. Discussion

This paper explores how an organization can maintain a technology's functionality over time despite operational breakdowns and challenges to the system's viability. We engage with ongoing debates in innovation studies to illustrate how technological maintenance can generate both value and knowledge from mature technologies. By delving into the capabilities that an organization develops to preserve a technology undergoing breakdowns, this research complements existing innovation literature by shedding light on maintenance as an integrative pathway for value creation and capture.

The process of maintaining value is inherently conditioned by the uncertainty of when, and at what scale, a technology might break down, highlighting the need to carefully consider the temporal dynamics and levels at which maintenance unfolds. Drawing on STS theories of sociotechnical systems and maintenance allows us to extend economics-rooted perspectives in innovation studies that emphasize exploitation, appropriability regimes, and complementary assets as means for preserving a technology's value. Attention to maintenance as a distinct firm-level capability developed in response to breakdowns, furthermore, extends the MLP by addressing the agency of organizational actors, whose access to resources for repair is unevenly distributed.

Our analysis revealed that multiple maintenance processes underpinned the extraordinary persistence of glyphosate. As **Table 2** (second and third columns) indicates, we observe variation in the nature of the breakdowns and the degree of agency involved in repair, including organizations and institutions beyond the market for glyphosate (Smith et al., 2010). "Rebuilding" maintenance processes occurred across all levels of the

sociotechnical system. Temporally, repair actions were rhythmically ‘continuous’ in this process, regardless of whether the organization anticipated them or not. One exception arose when a major breakdown occurred (i.e., when users perceived a loss of technological value). Most of the repair work in the rebuilding process focused on deploying tangible resources to improve technical functionality, a common tactic used by incumbents seeking to upgrade old technologies to stave off competitive substitutes (Adner and Snow, 2010; Nelson et al., 2023). More novel insights emerged when examining the process of “repairing”: while breakdowns occurred across all levels of the sociotechnical system, both pre-hoc and post-hoc repair actions targeted the level of the sociotechnical system or above on a continuous basis. This suggests that maintenance processes can create value for the focal organization even when repair occurs beyond its own boundaries. Finally, the “patching” process – empirically less frequent in our dataset – entailed repair work exclusively at the level of the sociotechnical system. In other words, no actor within the focal firm could enact this form of repair, underscoring the role of agents outside the focal organization’s boundaries.

--- INSERT TABLE 2 ABOUT HERE ---

In what follows, we shed light on the mechanisms that enabled Monsanto to undertake specific repair activities in response to breakdowns (i.e., a closer discussion of columns “Temporality and rhythm of repair action” and “Mechanism”) and, subsequently, proceed with the theoretical discussion of our case study evidence.

5.1 Mechanisms for maintaining technical and social value

Processes are context-specific: how one agribusiness firm maintained its technology may bear only passing resemblance to another firm’s maintenance processes. Yet processes can be understood as combinations of more fundamental mechanisms, i.e., as “events that change relations among specified sets of elements in identical or closely similar ways over a variety of situations” (Tilly and Goodin, 2006). As outlined in Table 2, our analysis reveals three

such mechanisms within and across each of the maintenance processes detailed in our findings.

Mechanism (a): Controlling specialized knowledge. The ambiguous nature of ownership and control of intangible resources conditions their strategic value, particularly when such resources cross organizational boundaries (Hamilton and D'Ippolito, 2022; Lavie, 2006).

Monsanto invested considerable time and effort to protect the value associated with proprietary knowledge. Patents protected manufacturing processes and chemical compounds (Mahoney and Pandian, 1992; Teece, 1986); however, more subtle mechanisms of control were being devised to hinder access to specialized knowledge (e.g., unpublished methodologies, which scientists could not discuss outside the firm's laboratories) or assert control over technological knowledge (e.g., black-boxing technical knowledge with distribution partners, and deploying TUAs to limit external scientific research on RR).

Monsanto's capacity for maintaining control over an entire knowledge domain discouraged other organizations from identifying an alternative. Consider by comparison the stalled emergence of electric-battery vehicles (BEVs). Despite significant governmental and entrepreneurial investment in BEVs as a green alternative to internal combustion in the 1990s, dominant automakers resisted R&D that could have hastened a technological transition (Cowan and Hultén, 1996). Control over specialized knowledge enables lead organizations to build high entry barriers, for instance through boundary spanning inventions (Whalen, 2018), foreclosing investments in new knowledge production that could allow organizations to escape technological lock-in.

The extent to which controlling knowledge produces organizational value is contested in the innovation literature. There is evidence that knowledge protection through secrecy is crucial for firms subject to legal requirements to disclose information (Sofka et al., 2018). Conversely, some research questions the effectiveness of secrecy mechanisms, as they may

trigger litigation processes that can cause knowledge spillovers (Awate and Makhija, 2022). Knowledge protection can, however, help organizations maintain the status quo. Lane's (2019) study of the Potteries explores how one industrial district maintained its technological viability for an exceptionally long time, through socially embedded restrictions on sharing valuable technical knowledge. Similarly, we show how Monsanto proactively collaborated with competitors to gain access to restorative technologies and control their developmental direction. As a mechanism for value maintenance, then, control over specialized knowledge requires continuous, fine-grained calibration across multiple levels to match changes in market and nonmarket environments.

Mechanism (b): Servicing the sociotechnical system. In recent years, many stalwart agribusinesses—from John Deere to Syngenta—have reframed their strategies around service platforms, in line with broader trends in manufacturing and financial industries (Shakhovskoy et al., 2021). In Monsanto's case the shift to a service logic emerged out of technological maintenance efforts that were driven not by a clear plan for capturing value from services themselves, but by glyphosate's imbrication in the existing sociotechnical regime of industrial agriculture. The market for Roundup emerged within a "selection environment" of limited options (Glynn, 2002; van den Ende and Kemp, 1999). A crucial factor in this process for Monsanto was the significance of cultivating trust with key consumers—namely, North American large-scale commercial farmers. In what one historian calls the "industrial ideal" (Fitzgerald, 2003), American commercial farmers faced institutional compulsion to adopt large-scale production and specialized technology over the course of the twentieth century. Monsanto's Roundup enjoyed immediate success after commercialization because its value proposition fit neatly into this industrial ideal. As our dataset reveals, customer expectations for increased production efficiency—particularly on large-scale farms where Roundup's

general-purpose effectiveness enabled tight control over mechanized farming—were instrumental in fostering trust-based relationships between users and the lead firm.

Similar examples of extending the lifecycle of a product via cultivation of trust include Singer’s service-oriented approach to globalizing sewing machines (Godley, 2013), or Sony’s decades-long fine-tuning of the Walkman (Sanderson and Uzumeri, 1995). In these cases, maximizing consumer trust in a complex consumer technology reduced the risks of firm investments in maintenance. Providing additional service was not merely tacked onto the existing value proposition, but became an integral component of the overall technological system. This suggests that maintaining a technology for long-term use requires not only that the core technology continues to function as expected, but also that its users continue to believe in its prolonged functionality (Sardo and Pfotenhauer, 2025).

Mechanism (c): Leveraging institutional power. A firm’s ability to generate economic value can come at a sociopolitical cost—both to the lead firm (as with reputational losses) and to society (as with harm to human and ecological health). CSR arose in the late 20th century as a means for organizations to manage this tension (Crilly et al., 2016; Rome, 2021). Monsanto was an early adopter, establishing a CSR committee in 1981. Our findings indicated, however, that CSR constituted only one element within a broader maintenance strategy. Alongside formal CSR initiatives, Monsanto actively sought to *maintain* the political environment of industrial agriculture through a mix of proactive and reactive non-CSR tactics (Oliver and Holzinger, 2008), aiming at reinforcing the existing sociopolitical status quo rather than fundamentally altering it (Abdurakhmonov et al., 2023).

Previous research has addressed the synergies between CSR and corporate political activity. Responding to stakeholder concerns in a coherent fashion requires organizations to be aware of both aspects of nonmarket strategies (den Hond et al., 2014; Mellahi et al., 2015). The Monsanto case furthers this literature by evidencing how nonmarket strategies for

leveraging institutional power can be a means to engage with the wider sociopolitical regime and strategically maintain market-based competitive advantage.

One leveraging act we observed was Monsanto's efforts to coordinate and control external stakeholders' access to valuable knowledge. On the one hand, the firm invested in long-term relationship-building with some of its competitors, seeking, for instance, to incorporate competitors' technical knowledge into the RR platform (Peloza and Falkenberg, 2009), demonstrating its capacity to integrate external actors and knowledge-based resources within a wider ecosystem (de Vasconcelos Gomes et al., 2022). On the other hand, through bolstering existing IP rights regimes, Monsanto pursued multiple legal contests against both users and competing firms to stall the emergence of alternative systems, which proved critical for RR's continuance. Government support—in the form of court decisions and limited regulatory intervention—upheld the status quo (Sun et al., 2012). Noteworthy is the central role played by political institutions, particularly in the United States, in supporting and steering the industrial ideal in agribusiness, which is sustained through a strong bureaucracy and a longstanding politico-corporate “revolving door” that abets regulatory capture (Hiatt and Park, 2012; Sheingate, 2001). Through leveraging institutional power, Monsanto could collaborate selectively or withhold collaboration from other agrochemical firms. Extant literature on collaborations highlights how leading firms often work with competitors at the initial stages of development and diffusion (Lopez-Vega et al., 2016). Building on work that demonstrates how organizations can work with competitors even in later stages of the technological lifecycle (Adner and Kapoor, 2016b), we contend that effective governance can support ecosystem management not only when entering a new technological domain (Adner, 2017), but also throughout mature phases of innovation, when organizations must continuously balance between navigating interorganizational tensions (Wareham et al., 2014) and controlling access to the ecosystem (Zhang et al., 2020).

5.2 Theoretical implications: The role of sociotechnical maintenance in sustaining mature innovations

Our case study highlights how maintenance constitutes a generative response to breakdowns in sociotechnical systems, and not solely a response to market signals. Occurring across multiple sociotechnical levels, technological maintenance is best conceptualized as a mode of value creation and capture that complements extant understanding of how value is created by (and within the boundaries of) the firm, such as organizational renewal, incremental innovation, or resource exploitation.

Our research draws attention to overlapping, iterative, and self-reinforcing processes of maintenance. Breakdowns can be generative, pushing organizational responses in new directions rather than simply presenting “setbacks” (Howe et al., 2016; Kapoor and Klueter, 2020). As illustrated in Table 2 and discussed in the previous section, the identified maintenance processes are underpinned by specific mechanisms that operate across multiple sociotechnical levels. To examine the temporal aspects of maintenance more closely, we plotted the identified breakdowns in a matrix (see **Figure 1**), locating repair mechanisms along two analytically distinct axes: (i) whether repair occurred pre-hoc or post-hoc and (ii) whether repair was actioned through continuous or discontinuous rhythms. Because these dimensions are categorical rather than continuous, the precise positioning within each quadrant is not intended to convey additional analytical meaning.

--- INSERT FIGURE 1 ABOUT HERE ---

First, we observed no instances of discontinuous response to anticipated breakdowns (i.e., empty bottom-left quadrant). Breakdowns that were perceived in advance led the organization to allocate resources to repair actions continuously, irrespective of the level of the breakdown (artifact, sociotechnical system, or regime). This further validates the

importance of conceptualizing maintenance as a continuous process rather than a discrete intervention. Second, the matrix reveals that each mechanism clusters primarily within a specific quadrant. Controlling specialized knowledge appeared most effective when continuous repair actions were developed to address anticipated breakdowns (bottom-right). Because expert knowledge is sticky and context-specific (Pisano, 1996), organizational responses to breakdowns affecting key sources of value creation (e.g., user perception or operational functionality of a technological artifact) targeted the timely retention of unique expertise, for instance through post-patent support or the formalization of technological agreements (Szulanski et al., 2016). Because the observed maintenance processes span all three levels of the sociotechnical system, this research highlights how social and material dimensions of technology constitutively co-construct one another over time (Orlikowski, 2010). In doing so, it connects with parallel conversations in organization studies, which argue that a regime perspective on technology-driven phenomena can shed light on how new practices of coordination, decision making, and control emerge from the possibilities inherent to technological change as illustrated by algorithmic technologies in platforms such as Uber (Faraj and Pachidi, 2021). Extending this insight, our application of STS maintenance theory reveals how breakdowns in mature technologies can also generate novel capabilities (Vuori and Tushman, 2024).

Second, we found that when unanticipated breakdowns were occurring at the level of the sociotechnical system (e.g., decreasing operational functionality or the emergence of competitors that challenged the decisions of the focal organization), maintenance efforts were redirected away from rebuilding the system and focused instead on either repairing it or patching the higher-level regime. Through servicing the sociotechnical system, the search for new knowledge is actively steered rather than left to serendipity (Rambert et al., 2017). The history of how a compound “incidentally created” what eventually became modafinil

(Scholte and Yaqub, 2025: p.1) evidences the importance of institutional mechanisms (e.g., drug scheduling or labelling) in sustaining the success of the drug. We extend this body of work by shedding light on the temporal dynamics of these interventions: repair actions aimed at overseeing strategic phases of the value chain (e.g., quality control) or specific knowledge domains underpinning the technology (e.g., herbicidal GMO) were required on a continuous basis when breakdowns at the system or regime level occurred.

Finally, in the top-left quadrant of the matrix, we observe how the unpredictability of breakdowns at the level of the system or above encouraged the organization to leverage institutional power to maintain system functionality (Hardy and Maguire, 2010). This mechanism was the least frequently deployed, reflecting the challenges posed by unanticipated breakdowns occurring well outside established boundaries of the sociotechnical system. At the level of institutional regimes and the sociopolitical landscape, the conditions for dealing with breakdowns appeared to depend heavily on heterogenous power structures (Ballesteros and Magelssen, 2021; Henke and Sims, 2020; Howe et al., 2016). In some contexts, close collaboration across organizational and institutional boundaries could enable effective responses even to high-level ruptures in the sociotechnical regime and landscape. This was the case with the medical software designers who instituted an industry-wide standard for developing and testing safer devices after Therac-25's failures (Dahlke and Ginsberg, 2021), or of semiconductor lithography developers to collaboratively extend the life of their technological ecosystem (Adner and Kapoor, 2016b), or of Dutch biogas promoters who reconceived the social value of their systems in the face of setbacks (Geels and Raven, 2006). In our study, however, the unanticipated nature of sociopolitical breakdowns generated a range of fragmented and loosely coordinated responses, including forms of coopetition within the industry and a series of disinformation campaigns. As with the persistence of diesel engines, the work of defending the sociotechnical status quo for an

increasingly problematic technology may require ethically questionable forms of repair work, potentially generating short-term economic value while simultaneously risking longer-term reputational damage to lead firms (Sardo and Pfotenhauer, 2025).

In summary, our first main contribution to innovation studies consists in widening the understanding of technological persistence. We identify specific mechanisms underlying processes of technological maintenance: *controlling specialized knowledge*, *servicing the sociotechnical system*, and *leveraging institutional power*. The STS lens enables the integration of firm- and market-level responses to breakdowns alongside wider sociotechnical processes, revealing how organizational capabilities can be developed to maintain the value of a problematic technology over time. The first and third mechanisms encourage scholars to consider maintenance as a proactive multi-level capability for sustaining sociotechnical systems, alongside more structural factors such as technological lock-in and path dependence. The second mechanism links to recent research in innovation studies exploring how relations between technology users and producers are being transformed by the development of platforms and ecosystems (Bhargava, 2022; Gawer, 2014). Breakdowns in the operational functionality of technology, as perceived by users, call for repair activities at the level of the technological artifacts or services that complement the core technology, thereby constituting a process of servicing the sociotechnical system (Cenamor and Frishammar, 2021; Gonzales et al., 2016). Maintaining a sociotechnical system, as we further emphasize, may require significant leveraging of institutional power in the nonmarket environment.

Our second contribution to innovation studies lies in explicating how temporality shapes capabilities for technological maintenance. We draw on STS research to differentiate between pre-hoc and post-hoc responses to perceived and unanticipated breakdowns, highlighting how planning for technological durability can become a self-fulfilling prophecy.

This stands in contrast with the more fully studied process of “planned obsolescence,” whereby firms intentionally build breakage into their business models to generate revenues from technological failures (Slade, 2006). In the case of Roundup, the passage of time entailed increasing complexity and global expansion of the technological system, which generated ever-more visible functional breakdowns, requiring Monsanto to engage with wider organizational and institutional contexts to develop capabilities for system repair and service. Importantly, the response to breakdowns increasingly moved away from the initial focus on exploiting existing resources for incremental innovation, pushing repair work into higher-level domains. The radical business model innovation of bundling glyphosate with Roundup Ready seed-IP emerged not as a response to a competitive technology, but as a means of embedding the original Roundup technology into a higher infrastructural level in which new forms of value could be created and captured without departing from existing markets. These efforts to reduce competitive pressures resemble other industries, such as semiconductors (Lim et al., 2010) or pharmaceuticals (Slinn, 2008), in which firms have used regulatory mechanisms and patent preemption to preserve market share. Yet, unlike semiconductors and pharmaceuticals—where organizations faced with patent expiration typically pivoted to new innovations—glyphosate technology persisted well after key patents expired. The persistence was enabled, in part, by an increasing willingness at Monsanto to selectively exchange knowledge with competitors, similarly to how Abbott maintained the value of its Humira monoclonal antibody technologies through licensing agreements with competitors such as Genzyme (Moreira et al., 2020).

6. Conclusion

Our research conceptualizes how maintenance can enable an organization to preserve and actively defend the value of a technological resource despite repeated breakdowns. These maintenance processes could potentially benefit contemporary organizations seeking to

lengthen technology lifecycles to promote more sustainable resource use. Such thinking animates, for instance, the “right to repair” movement, in which users demand the ability to fix their own devices without fear of contract infringement lawsuits or loss of warranty protection. The movement pointedly addresses the issue of agency in technological maintenance. In setting boundaries for *who* can do repair work, an organization such as Apple, John Deere, or Nikon creates asymmetrical power relationships (Perzanowski, 2022). Recent works on maintenance from STS scholars have increasingly drawn attention to this dark side, noting how large-scale infrastructure maintenance projects, for instance, can reinforce state authority and corporate power while undermining the ability of underrepresented groups or disfranchised stakeholders to direct maintenance activities in ways that might benefit society more broadly (Barnes 2017; Lloveras et al., 2025). This critical element within maintenance studies thus offers a useful corrective to research on unethical strategies, which tends to highlight unethical behavior as a means of entering a competitive market rather than as mechanism for sustaining an uncompetitive market (Ostler, 2025).

Our work builds on these insights, demonstrating how sociotechnical maintenance can generate self-reinforcing mechanisms at multiple scales. Extending this cautionary lens on technological persistence can further enrich innovation studies, as researchers seek to reconceptualize how sociotechnical transitions to more sustainable futures are both enabled and restrained (Bento et al., 2025; Nuñez-Jimenez et al., 2022; Sardo and Pfotenhauer, 2025). Furthermore, our work has implications for both managerial practice and innovation policy, for while we illustrate how managers can develop organizational capabilities to preserve the value of existing technologies, we also underline the need for policymakers to consider interventions that ensure that the value created by those technologies is delivered in ways that are socially equitable and environmentally sustainable (Pel et al., 2020).

There are limitations to our research. Our focus on Monsanto's Roundup represents an exceptional case that, whilst creating an explicit connection between breakdowns, technological repair and value capture and creation across multiple sociotechnical levels, highlights a need for further research into more "ordinary" forms of technological maintenance. Future research could address this by incorporating fine-grained process studies based on archival or ethnographic data, examining how organizations in other industry contexts have managed technological maintenance over long periods of time. Likewise, another area of maintenance worthy of further investigation is situations, such as open-source software development, in which a central organization does not strategically coordinate maintenance activities. Our research, however, is intended to open such research avenues, encouraging work on the strategic nature of maintenance, rather than precluding the existence of multiple modes through which maintenance capabilities may be developed.

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