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Managing the unintended consequences of radical sustainability innovations: The case of catastrophic failure of leaded gasoline industry

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ABSTRACT

Radical sustainability innovations (RSIs) often run the risk of producing unintended consequences, which can sometimes be of catastrophic nature. Literature offers some innovation management methods (IMMs) for preventing unintended consequences, but these methods remain untested at the boundary condition of failure, i.e., catastrophic failure. This gap leaves blind spots in our understanding of the application of IMMs, especially in cases of catastrophic failure of RSIs. Our objective is to apply select radical sustainability innovation management methods (RSIMMs) to a case where RSI failed catastrophically, in order to: (i) identify shortcomings of these methods at boundary condition; and (ii) understand how these methods can prevent catastrophic failures. We chose representative RSIMMs through systematic literature search. We applied these methods to the case of leaded gasoline, which qualifies the definition of RSI but produced disastrous consequences. We used process analysis technique to explicate discovery, commercialization, institutionalization, and abandonment of leaded gasoline between 1910s and 2000s. Results suggest that disputed science can be leveraged for purely economic gains, and '*show me the data*' and '*my science is right*' mentality can set managers/scientists on pathways leading to failure. We propose a preliminary model for integrating RSIMMs to promote reflective thinking by rendering multiple layers of protection against likelihood of catastrophic failure. Our work has implications for understanding the role of stakeholders in RSIs, rethinking temporal dimension of innovation performance, policy literature on sustainability, and speed of innovation theory. Managers can use these results to improve 'new product development' process by reconsidering the temporal dimension in life-cycle assessments.

"More informative, often, than success stories are stories about failure—especially the failures of once successful enterprises to adapt to new circumstances"

- Oliver E. Williamson (1999).

1. Introduction

In today's world, organizations aspire to innovate for sustainable development (hereinafter sustainability) (Nidumolu et al., 2009; Silvestre and Ţîrcă, 2019). The goal is to create shared value for all stakeholders (Freeman, 1984; Freudenreich et al., 2020; Schaltegger et al., 2019)—value that can be appropriated in tandem with the carrying capacity of our planet (Hart, 1995; Porter and Kramer, 2019; Voegtlin et al., 2022; Whiteman et al., 2013). However, innovation, by definition, is "*the introduction of new things*" (Oxford Dictionary), and the element of newness may hold some unpleasant surprises (McKelvey and Saemundsson, 2021; Merton, 1936). A way to factor the unanticipated surprises is to model the behavior of '*new thing*' (Nohria and Taneja, 2021). However, anticipation of interaction between *something new* and countless economic, political, and societal variables is seemingly a squandering task (de Zwart, 2015). Nevertheless, more often than not, such an activity, if carried out systematically (Bansal et al., 2021), but with some degree of flexibility (Yu et al., 2021), can produce deliberate guidelines for developing and commercializing the '*new thing*' without the risk of running into unpleasant surprises (Owen et al., 2013). In the following passages we present some examples to further illustrate these points.

Coca-Cola and Pepsico have historically been criticized for their contribution to climate change, especially in the form of single-use

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plastic waste (PET bottles) (Socio, 2021). To address this issue, Coca-Cola, in 2009, launched its first PlantBottle® that was made from 30% plant-based materials and 70% virgin plastic (Gunther, 2009). 'Making plastic from plants' was marketed as 'game changer.' Pepsico followed suit and launched its prototype of 100% plant-based plastic bottle next year (Pepsico, 2010). However, the science of plant-based plastics was deeply ignored in the backdrop of this heavyweight competition. The cola giants overlooked the chemistry of plant-based plastics, i.e., thermodynamic properties of plant-based and virgin plastic were exactly the same (Westervelt, 2011). Although raw materials of plant-based plastic bottles were renewable, chemical characteristics of both plant-based and virgin plastic were identical. The plant-based plastic bottles were not biodegradable and posed as much harm as conventional plastic bottles (Laylin, 2011).

In a similar instance, following '*skip the straw, save a turtle*' movement, Starbucks decided to be more responsible by replacing plastic straws with innovative straw-less lids throughout North American stores (Caron, 2018). However, the American coffeehouse giant fell short to recognize that the new straw-less plastic lids weighed slightly more than the plastic straws, technically increasing the plastic waste generated per serving (Mahdawi, 2018). Likewise, McDonald's decision to replace plastic straws with paper straws in UK and Ireland seemed incautious because the new paper straws were relatively thicker, making them nonrecyclable (Picheta, 2019).

These examples are only a few of many cases where well-intentioned innovations caused more damage than the original actions (Islam, 2020). While these innovations did not fail catastrophically, there are many cases in the past where well-intentioned innovations produced disastrous fallouts, causing irreversible damage to the planet (Nawaz et al., 2019; van den Hove et al., 2012). Given that sustainability innovations are gaining increasing importance in organizational literature and practice (Ambos and Tatarinov, 2022; Domínguez-Escrig et al., 2018), it seems the right time to ask: whether and how unintended consequences of sustainability innovations assessed before launching them in the market (Voegtlin et al., 2022)? Our interest is to explore and solve unaddressed puzzles in conventional wisdom related to this question. In this pursuit, we exclusively focus on sustainability-related radical product innovations.

To begin with, it is important to define 'sustainability innovation' (Meuer et al., 2020) and create a distinction between sustainability and green/eco innovations (Bansal, 2009; Geradts and Bocken, 2018). Inspired by the work of several accomplished scholars, we define sustainability innovation as creation of a *new thing* (such as product, process, or service) which adequately captures opportunities of long-term shared value creation (for business and society) by means of reconceiving products and markets in tandem with the carrying capacity of our planet (in terms of finite natural resources and waste absorption limits) (Bacq and Aguilera, 2022; Bansal and Song, 2017; Bansal, 2009; George et al., 2021; Mayer, 2020; Porter and Kramer, 2019; Spence and Rushing, 2009; Thompson and MacMillan, 2010). Parallel to this, eco/green innovations are defined as "*innovations which reduce the environmental impact of production and consumption activities*" (Kiefer et al., 2017, p. 1494). An innovation as simple as replacing plastic straws with paper straws can be eco/green innovation because its purpose is to reduce the environmental impact of product (Kiefer et al., 2019). In some cases, eco/green innovations come with a premium price tag (Orsato, 2009), which disputes the shared value creation perspective of sustainability innovation. It is, however, possible that domain of sustainability and eco/green innovation overlap in some cases (Bansal, 2009; Lee, 2021). For example, General Electric's (GE) Ecomagination program creates shared value by redefining products and markets, and it reduces environmental impacts throughout GE's value chain (Clark, 2017). Thus, sustainability innovations may generally qualify as eco/-green innovations, but the likelihood of eco/green innovations being classified as sustainability innovations is relatively less (Bansal, 2009; Lee, 2021; Meuer et al., 2020).

The idea of sustainability innovation is radical and disruptive (Bansal, 2019), and it shows excellent promise to address global challenges that pose time-bound existential threats to the planet (Kennedy et al., 2017; Longoni and Cagliano, 2018; Voegtlin et al., 2022). Adoption of radical innovation, however, is often troublesome because of institutional (societal, cultural, and political) and technical (viability of newness) barriers (Sandberg and Aarikka-Stenroos, 2014). Societal acceptance of radical innovation is slower than incremental innovation, but once radical innovations get adopted, it becomes extremely difficult to deinstitutionalize them (Nohria and Taneja, 2021). The stakes of innovators, entrepreneurs, investors, customers, and consumers get so high over time that discontinuation becomes out of question. Since adoption of radical innovation is path-dependent, its discontinuation is also nonlinear. Then the question is: what can be done if an institutionalized RSI starts producing more damage than good because of its unintended consequences?

Literature offers several practicable methods, models, systems, and processes (hereinafter collectively referred as 'methods' or alternatively 'RSIMM,' standing for radical sustainability innovation management method) that help managers deal with the unintended consequences of RSIs (Domínguez-Escrig et al., 2018; Hansen et al., 2009; Kennedy et al., 2017; Schot and Geels, 2008). We conducted a comprehensive literature review (discussed in the next section) to identify RSIMMs and to understand the unresolved puzzles related to them. After carefully reviewing 332 articles, we found that while RSIMMs are intended to produce sustainable outcomes, no attempts have been made in the past to apply and test these methods at the boundary condition of failure, i.e., catastrophic failure. A catastrophic failure is a "*vicious spiral of socio-technical pathologies, rarely with one precursor or single cause but often an accumulation of failures in organizational learning, planning, and agility processes*" (McMillan and Overall, 2017, p. 283). Such failures are categorically different from simple and complex failures. The temporal, structural, and organizational antecedents of catastrophic failures make them intractable, disastrous and irreversible (Chai et al., 2021; McMillan and Overall, 2017). Management scholars have stressed on the importance of studying catastrophic failures to be able to predict such failures in future (Williamson, 1999). Vaughan's (1990) work on NASA's space shuttle *Challenger's* tragedy, Maguire and Hardy's (2009) account on *decline of DDT*, and Chai and colleagues' (2021) recent study of *Virgin Galactic Test Flight Crash* attest that attention to catastrophic failures can be truly instructive in planning future innovations.

Our goal in this study is to understand how RSIMMs can prevent catastrophic failure of RSIs. As noted, dynamics of catastrophic failure are different from simple and complex failures (McMillan and Overall, 2017). It involves complete and irreversible breakdown of the system. We aim to uncover whether/how we can predict if an RSI is heading towards a catastrophic failure, and if so, how can we prevent, or minimize the impact of, such failure? Our thorough review of existing literature (discussed later) reveals that researchers are unaware how RSIMMs generate 'early warning signs' of catastrophic failure of sustainability innovations. We also do not know how the sequence of events leading to a catastrophe can be predicted using RSIMMs. And if catastrophic risks are detected, how societal and political actors attend to the need to make amends in focal innovation. If unattended, these gaps may lead to permanent blind spots in our understanding of the application of RISMMs, especially in case of catastrophic failures, and we would run the risk of repeating same mistakes that led to the catastrophic failure in the first place. Conversely, we can use 'failure' as a 'learning opportunity' and leverage valuable insights to identify operational and technical constraints of RISMMs, specifically for catastrophic failures (Cannon and Edmondson, 2005; McGrath, 2011). Learning from past failures can enable us to better inform and update RSIMMs in the face of risk of failure in future. In absence of such an account, we fear our knowledge of RSIMMs, and subsequent application of these methods, will remain limited.

This article is divided into six sections. After introduction, we review literature pertaining to RSIMMs. Third section provides an account on research method. Results and findings are discussed in fourth section, followed by discussion, contributions, implications, and limitations in the fifth section. The last section concludes this study.

2. Literature review

We used Web of Science to systematically search for literature related to RSIMMs. We conducted search using following search string: [radical AND sustain* AND innovation]. We refined search results by applying filters. We included only original articles published in Management, Business, Environmental Science, and Environmental Studies literature in English language. We did not define a publication period to identify as many relevant articles as possible. Our search returned 332 articles. We first reviewed all titles and abstracts and shortlisted studies which aligned with the scope of this work. For example, we excluded articles that were context driven since results of such studies are usually limited to countries (e.g., Fernández et al., 2021) or business (e.g., Chadha, 2011). Since our focus was product innovation, we also excluded studies related to business model innovation (e.g., Baldassarre et al., 2017). Finally, we excluded conceptual papers due to a lack of empirical grounding (e.g., Gaziulusoy and Brezet, 2015).

In the second step, we reviewed full text of shortlisted articles to identify IMMs that are intended to eliminate or minimize the unintended consequences of RSIs. Six RSIMMs were identified as a result of this review (Table 1). There were a few other candidates with potential to be included in this list (e.g., Hall and Martin, 2005), but these methods seemed underdeveloped, which is why we did not include them in this work. From Table 1, we selected three methods for this study: sustainability-oriented innovation (SOI), strategic niche management (SNM), and dynamic capabilities (DCs). This approach is justified because these three methods are representative of all six methods (Table 1), an approach also used by Meuer et al. (2020). Since experimentation, learning, and participation of stakeholders are part of SNM and DCs, we did not include Bounded socio-technical experiment, Leaders' stewardship behavior, and Backcasting methods because these are driven by the same mechanisms.

2.1. Sustainability-oriented innovation (SOI)

Although there is a profusion of working definitions of SOI (Adams et al., 2016; Cillo et al., 2019), we will expand Bos-Brouwers's (2009, p. 419) and Hansen and Große-Dunker's (2013, p. 2407-8) definitions as these are well-suited for this work. According to these authors, SOI pertains to '*commercial introduction of a new or improved product which serve the specific purpose of creating and realizing social and environmental value, in addition to economic returns, based on a superior comparative performance over the prior version's physical life cycle.*' Although formal discussion on SOI began with work of Wagner and Llerena (2008) and Paech (2007), it was Hansen et al. (2009) who proposed a three-dimensional SOI framework for the first time. These three dimensions include: *target dimension*, *product life cycle dimension*, and *need dimension*. Target dimension refers to the effect of innovation on the triple bottom line (TBL), i.e., economic growth, environmental protection, and social development. Life cycle dimension accounts for value creation over complete life cycle of innovation. And need dimension indicates three levels of need fulfillment, including: (i) *technical level* (new physical products); (ii) *usage pattern level* (solutions instead of products); and (iii) *cultural level* (create or change needs). Hansen et al. (2009) proposed that the three dimensions form three axes of SOI cube which reduces uncertainties associated with the development of RSIs over complete life cycle.

Hansen and Große-Dunker (2013) later revisited SOI cube to propose a more functional two-dimensional framework. According to the authors, since cultural dimension is embedded in the type of innovation (product, process, or organizational), only *target dimension* and *life cycle dimension* are sufficient for ensuring directional consistency of RSIs (Geradts and Bocken, 2018).

2.2. Strategic niche management (SNM)

Literature on the transition of technological regimes dates back to 1970s (Rosenberg, 1976) but its application in context of sustainability is recent. The first scholars to argue for SNM's utility for RSIs were Kemp et al. (1998). The authors stressed on eliminating unintended

Table 1
RSIMMs identified through systematic literature search.

RSIMMs	Objective	Underlying Mechanism	Shortcomings	References
Sustainability-oriented innovation	Building competitive advantage through radical sustainability innovation	- product design and development - value chain integration in design process	- linear process, leaves less room for subjectivity and improvisation - hard to reframe the problem once innovation process begins	(Kennedy et al., 2017; Luqmani et al., 2017)
Leaders' stewardship behavior	Organizations should be responsible for the consequences of their actions	- organizational learning capability	- dependence on human agency (bounded rationality) - consequences of change in leadership are unaccounted	(Domínguez-Escrig et al., 2018; Domínguez-Escrig and Mallén-Broch, 2021)
Strategic niche management	Provide protected spaces to nurture radical innovations beyond the point of 'unintended consequences'	- systematic mapping - establishing networks -experiment and learn - participation of stakeholders	- requires a lot of time and investment - approval-based process - path dependent method, posing threat of irreversible changes	(Caniëls and Romijn, 2008; Slayton and Spinardi, 2016; Turnheim and Geels, 2019; Witkamp et al., 2011)
Dynamic capabilities	Develop, integrate, and (re)organize resources and competences to embed sustainability principles in innovation process	- internal and external orientation -resources-based view - behavioral and cognitive learning	- fully sensing environmental changes is inconceivable - risk of cognitive blind spots - frequent reorganization of resources can challenge strategic coherence	(Dangelico et al., 2017; Kiefer et al., 2019)
Bounded socio-technical experiment	Innovative approaches for solving societal problems	- experiment and learn - participation of stakeholders	- static treatment of societal problems - seemingly a team building exercise only	Brown and Vergragt (2008)
Backcasting	Backtrack desired outcome to avoid uncertainty	- participation of stakeholders	- temporal uncertainty is unaccounted (tunnel vision) - lack of room for improvisation	Zimmermann et al. (2012)

consequences of RSIs by creating protected spaces where new and promising technologies can be tested and collaboratively nurtured in a controlled environment, minimizing the likelihood of negative unintended impacts on the society. The divers of SNM include (Kemp et al., 1998; Raven et al., 2010):

- *Articulating expectations* – attracting actors with similar expectations and using their expectations as a pathway to obtain tangible results.
- *Building social networks* – interacting with stakeholders, even if they do not share expectations, but can affect propagation of innovation.
- *Reflexive adjustment* – aligning with user preferences, regulations, social values, and willingness to society to change.

Schot and Geels (2008) extended Kemp and colleagues' argument. They maintained that niche formation not only allows for testing directional consistency of RSIs, but it also enables policymakers to evaluate the readiness level of society in terms of absorbing the focal innovation, and the changes associated with it, thus, making the outcomes more sustainable.

2.3. Dynamic capabilities (DC)

Organizational literature on DCs is well established (Eisenhardt and Martin, 2000; Teece et al., 1997). However, its application in context of RSIs is fairly recent. Dangelico, Pujari, and Pontrandolfo (2017, p. 491) view DCs in context of sustainability as "*the firm's ability to integrate, build and reconfigure competences and resources to embed environmental sustainability into new product development to respond to changes in the market.*" Teece (2007) originally proposed three capacities to operationalize DCs: sensing, seizing, and reconfiguration. Mousavi, Bossink, and van Vliet (2018) applied these capacities in context of sustainability. According to the authors (p. 225):

> "*Sensing refers to the identification and assessment of an opportunity for sustainability. Seizing involves the mobilization of internal and external resources/competencies to address an opportunity and capture value from it. Reconfiguring refers to continued renewal and orchestration of resources to keep the resource base of the company in line with the shifts in the business environment.*"

At micro-level, DCs are "*distinct skills, processes, procedures, organizational structures, decision rules, and disciplines*" (Teece, 2007, p. 1319). Strong DCs allow firms to adapt while simultaneously offering an opportunity to shape the external environment through partnerships (Rothaermel and Hess, 2007). Based on Iles and Martin's (2013) and Mousavi and Bossink's (2017) work, Dangelico et al. (2017) categorized DCs for RSI at three levels:

- *External Resource Integration* – develop links with external actors to deal with the complexity of sustainability issues through the exchange and integration of knowledge and competencies.
- *Internal Resource Integration* – integration of external resources brings more complexity to the internal processes, thus requiring cross-functional integration. Put differently, it is the exchange and integration of knowledge and competencies within the firm.
- *Resource Building and Reconfiguration* – knowledge and competencies are resources to be created within a firm, and if need be, these resources must be reconfigured to adapt. Adaption allows for directional consistency of sustainability innovation.

2.4. Research gap

Although several studies highlight the utility of chosen RSIMMs (Childs and Jin, 2018; Kemp et al., 2000; Mousavi and Bossink, 2017), application of these methods to cases of failure have been generally overlooked. Since these methods are intended to ensure directional consistency of RSIs, it is surprising that none of previous researchers applied these methods to cases where unintended consequences of RSIs led to catastrophic failures. Admittedly, as mentioned by Merton (2013), it is not possible to predict all the variables that can cause failure in the future, but we can most certainly advance our understanding of the robustness and utility of these methods through past failures (Edmondson, 2011).

Literature on learning from failure posits that managers and entrepreneurs have a tendency to forget mistakes if learning from failure does not take place in timely fashion (Amore et al., 2021; Shepherd et al., 2011). However, it does not imply that one should perform a postmortem of failure in order to learn, as each failure involves idiosyncratic events (Edmondson, 2011). Instead of involving in vicarious learning, Maslach and colleagues (2018, p. 255) suggest that "*actors [should] impose their own context as part of the learning [from failure] process*." In context of this paper, it means that RSIMMs should be applied to a catastrophic failure of RSI in order to (Tinsley et al., 2011): (i) identify shortcomings of these methods at boundary condition of failure, i.e., catastrophic failure, and (ii) understand how these methods can prevent catastrophic failures in the future (in the form of early failure indications, fail-safe conditions, socio-political challenges, and role of stakeholders).

In the past, selected RSIMMs have been studied with an inward view, i.e., how can these methods be implemented successfully. For example, Hoogma et al. (2017, p. 183) discussed '*The Rügen Project*' from the perspective of SNM. The project involved experiments on the use of vehicles powered by alternative energy sources. These experiments, conducted in 1992, consisted of testing 100 battery-powered electric vehicles that were manufactured from modified internal combustion engines. The developed niche failed to scale up mainly because of the lack of partnerships to support the venture. Although well-intentioned, instead of accounting for the utility of SNM for sustainability innovations, Hoogma and colleagues focused on the reasons of failure of *The Rügen Project*. To overcome this shortcoming, we embrace an outward view, i.e., how selected RSIMMs can prevent catastrophic failure of RSIs. Without training these methods for catastrophic failures, we run the risk of repeating same old mistakes (McGrath, 2011).

In sum, while much is known about chosen RSIMMs, concrete utility and robustness of these methods can be fully assessed only by applying them to cases where RSI produced unintended consequences which resulted in catastrophic failure. Such an approach will enable us to understand early warning signs of catastrophic failure of RSIs. It will also allow us to examine the rigor and compatibility of these approaches as their application varies with stages of development (Table 2).

3. Method

We adopted a qualitative research design to apply selected RSIMMs to a case where RSI catastrophically failed. One of the advantages of

Table 2
Examples of real-life application of RSIMMs.

RSIMMs	Stages of Development			Examples
	Before Innovation	During Implementation	After Implementation	
SOI	✓	—	—	Nike Flykint (Childs and Jin, 2018)
SNM	—	✓	✓	Car sharing business in Switzerland (Kemp et al., 2000)
DCs	✓	✓	✓	KLM – The Netherlands (Mousavi and Bossink, 2017)

using qualitative research method is that "*it allows a researcher to see and understand the context within which decisions and actions take place*" (Myers, 2013, p. 5). Banking on this advantage, we wanted to uncover the events, actions, and decisions leading to the catastrophic failure. We choose a case study method for our qualitative design. According to Hall (2006, p. 25), "*if one wants to know why an outcome occurred in a particular time and place, a historically specific mode of explanation may be most useful, as other modalities can rarely explain the exact timing or location of the relevant outcome*." To study catastrophic failure, it was essential for us to explicate why and how events leading to a catastrophic failure occurred over time. Despite the generalizability concerns, case study method is the most appropriate choice to answer the '*why*' and '*how*' questions (Yin, 1994). However, we did not employ traditional legacy of Yin and Eisenhardt in our case design (Piekkariand and Welch, 2018). For a case as old as 100 years (discussed later), it was not possible for us to perform field work or conduct interviews. Therefore, we carried out a historical case study using archival data (Maclean et al., 2016; Mills and Mills, 2018). According to Ventresca and Mohr (2017, p. 805) "*archival methods are those that involve the study of historical documents; that is, documents created at some point in the relatively distant past, providing us access that we might not otherwise have* …" Hargadon and Douglas' (2001) study of Thomas Edison's system of electric lighting and Johnson's (2007) piece on founding of Paris Opera are examples when researchers relied solely on historical archival data for conducting case studies.

Historical case study allows for in-depth understanding of process-based phenomena, underpinning the motivation and consequences of actions and decisions (Maclean et al., 2016). Since we are interested in learning from the process of failure, historical case study is the most appropriate choice.

3.1. Case selection

We used purposive sampling to select a case related to catastrophic failure of RSI. Purposive sampling aids in "*better matching of the sample to the aims and objectives of the research*" (Campbell et al., 2020, p. 653). It allows to select sample that is "*most likely to yield appropriate and useful information*" (Kelly, 2010, p. 317). We selected the case of Leaded Gasoline for this study. Leaded gasoline is produced by mixing Tetraethyl Lead (TEL) with gasoline to reduce the knocking effect in automobile engines. We chose this case because of three main reasons. First, the way leaded gasoline was framed at the time of discovery, it qualifies the definition of sustainability innovation; it was considered a '*new thing*' with promise of long-term shared value creation, by reconceiving fuel market, with minimum environmental impacts. Thomas Midglay Jr., the scientist who discovered the utility of TEL in gasoline (in the 1920s), emphasized on the commercialization of leaded gasoline because it promised clear economic, environmental, and societal benefits:

> "*It is not the purpose of this paper to enlarge upon the benefits of the use of tetraethyl lead in gasoline. It may not be amiss, however, to mention broadly the advantages to the public which will follow upon its (TEL's) general use. These are (1) conservation of petroleum due to increased milage obtainable by using a non-knocking gasoline in a high compression motor, (2) reduction of carbon monoxide contamination of the atmosphere due to increased efficiency of combustion; and (3) reduced first cost of automotive apparatus. So far as science knows at the present time, tetraethyl lead is the only material available which can bring about these results, and the results are of such vital importance to the continued economical use of all automotive equipment that, unless a grave and inescapable hazard exists in the manufacture of tetraethyl lead, its abandonment cannot be justified*" (Midgley Jr, 1925, p. 827, p. 827)

Second, leaded gasoline eventually resulted in a catastrophic failure (Hargadon, 2015). According to an estimate, atmospheric lead, released through leaded gasoline, resulted in the death of around 1.1 million people across the globe (Tsai and Hatfield, 2011). Around half a century after its commercialization, the realization of severe consequences led to complete abandonment of leaded gasoline and TEL during the last quarter of the 20th century. Third, there is a wealth of publicly available archival data on leaded gasoline, which we will discuss in the next section. The case also received significant attention in academic literature and trade journals and magazines, allowing us access to several data sources for triangulation.

3.2. Data collection

The primary sources of data are scholarly papers published in peer reviewed journals and *Toxic Docs*, the world's largest repository of documents on toxic substances. *Toxic Docs* contains around 1990 documents related to TEL between 1910s and 2000s. The archived documents include minutes of board meeting, scientific studies, company memos, public relations statements, personal letters, and political lobbying strategies. The database is maintained by data scientists, academics, and researchers from Columbia University and City University of New York (Rosner et al., 2018). *Toxic Docs*' dataset on TEL was accumulated through records of '*toxic substances litigations*' in the United States (Rosner et al., 2018). It means that these documents were originally filed during litigations as part of *discovery*, a legal mechanism "*where plaintiffs and defendants are required to exchange information and documents relevant to a lawsuit*" (Rosner et al., 2018, p. 4). Given the legal nature of these documents, we find *Toxic Docs*' dataset on TEL authentic and reliable, and suitable to be used in this work (Mills and Mills, 2018).

For academic literature, we carried out a search in Web of Science using following search string: ["tetraethyl lead" OR "leaded gasoline"]. We kept the search limited to original articles published in English language in the field of Business, Management, Environmental Science, and Environmental Studies. The search returned 399 results. Most of these articles were related to the chemistry and hazards of TEL. Similarly, not all documents obtained from *Toxic Docs* were important. We reviewed all files (titles and abstracts of research articles and first pages of all documents obtained through *Toxic Docs*) and organized relevant data based on our framework of analysis, explained in the next section (Fig. 1).

We also collected secondary data for triangulation through magazine and news articles, public health records, and independent reports on leaded gasoline. Data triangulation was carried out to enhance credibility of results (Denzin, 2007). The activity of building narratives using multiple sources of data brings greater trustworthiness to researcher's account (Hastings, 2010). It also helps researchers in explaining an event or action through various angles.

3.3. Data analysis

We used process analysis technique to qualitatively analyze data (Fachin and Langley, 2018). This type of analysis allows to "*focus attention on how and why things emerge, develop, grow, or terminate over time*" (Langley et al., 2013, p. 1). Process research dynamically accounts for organizational phenomena as interconnected events and activities embedded in temporality and sequential flow (Fachin and Langley, 2018). Since we are dealing with qualitative data and elements of RSIMMs are sequentially and temporally distributed (Fig. 1), process research is the most appropriate choice for data analysis (Langley et al., 2013).

We followed Maguire and Hardy (2009) and Wright and Zammuto (2013) in data analysis. We first developed a narrative from archival data to broadly understand the (de)institutionalization of leaded gasoline. According to Fachin and Langley (2018, p. 314), "*through narratives, people articulate events and make them meaningful. This involves a storyline or plot with beginning, middle and end, or a movement from past to present to future woven together in a meaningful sequence*." The event-history database helped us in chronologically capturing events and activities that are part of our framework of analysis (Fig. 1). In this

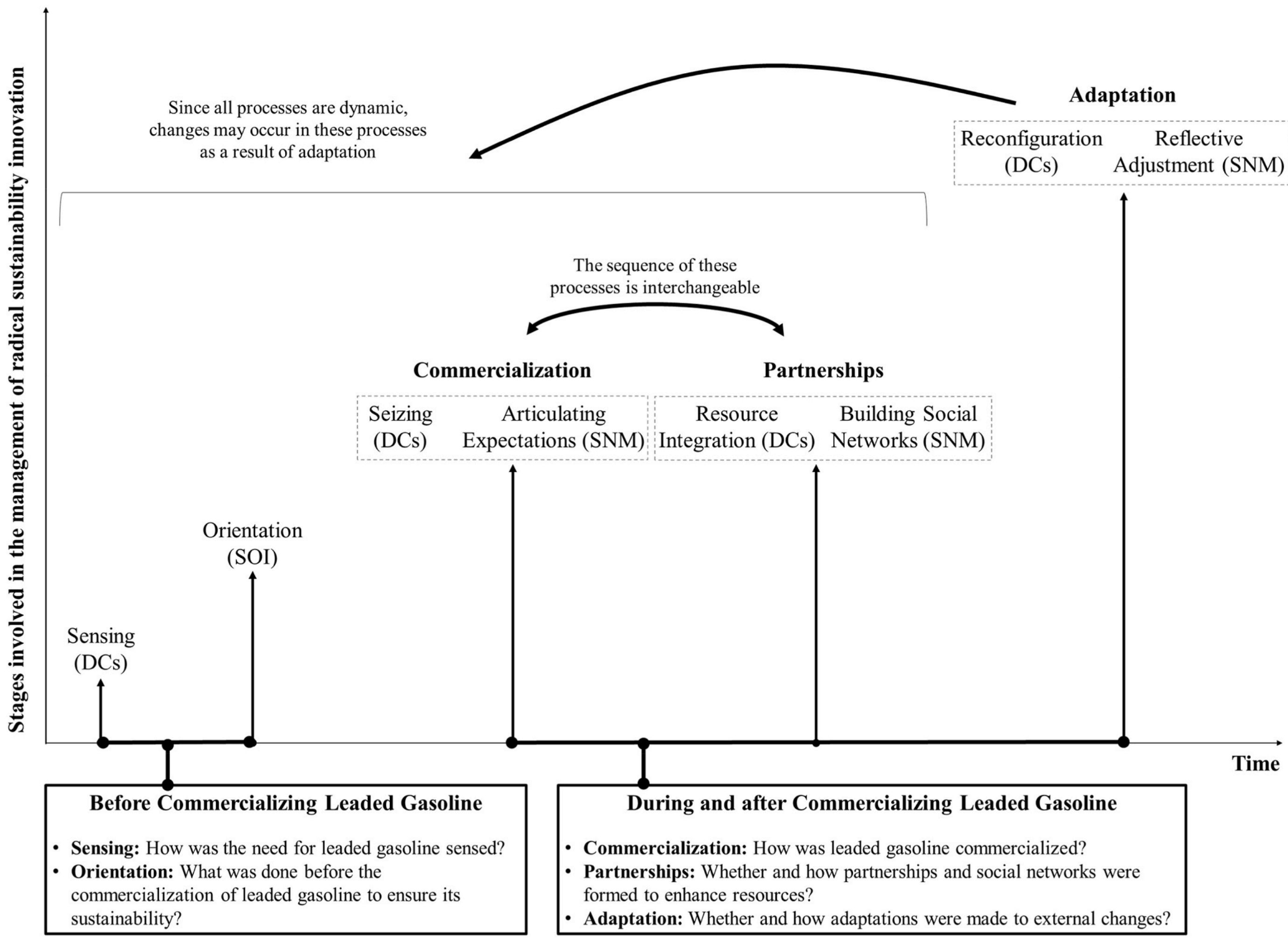

Fig. 1. Framework of analysis (derived from literature review).

sense, we maintain a positive ontological position, i.e., we have *a priori* framework of analysis, based on literature review, that helps us focus on particular aspects of (de)institutionalization of leaded gasoline. For example, after organizing key events and activities through archival data and academic papers, we focused on the first element in framework of analysis, i.e., sensing. We asked: *how was the need for leaded gasoline sensed*? We then scrutinized event-history database to look for '*who did what and when*' and '*who said what and when*.' From this analysis, we were able to draw process-based narrative that explains '*sensing*' in context of leaded gasoline. Subsequently, we analyzed rest of the elements of framework of analysis, including *orientation*, *commercialization* (seizing and articulation of expectations), *partnerships* (resource integration and social networks), and *adaptation* (reconfiguration and reflective adjustments).

Our attention throughout the analysisf remained on the state of change, i.e., how and why leaded gasoline was discovered, commercialized, institutionalized, and abandoned. We simultaneously maintained our focus on the application and utility of RSIMMs in case of catastrophic failure, i.e., whether/how catastrophic failure of radical sustainability can be predicted through RSIMMs, and if so, how RSIMMs can be used to prevent, or minimize the impact of, such failures. We drafted narratives around each element in framework of analysis (Fig. 1). We reviewed secondary data before finalizing narrative on (de) institutionalization of leaded gasoline, which is presented in the next section.

4. Results

We will first provide an overview of the TEL and leaded gasoline industry to familiarize readers with the context of study. Next, we will present chronological process-based narrative on (de)institutionalization of leaded gasoline based on the framework of analysis (Fig. 1).

4.1. An overview of TEL and leaded gasoline

Carl Löwig first prepared TEL in 1853, but the chemical became widely popular in 1920s due to its promise of increasing vehicles' engine performance and anti-knocking characteristics when mixed with gasoline (Seyferth, 2003). Besides the technical advantages, leaded gasoline promised sustainable economic and environmental benefits (Midgley Jr, 1925). Unfortunately, those promises did not last, and half a decade after its commercialization, leaded gasoline was completely abandoned due to its catastrophic side-effects.

> "*It is a well known fact that lead is neurotoxic; harmful to humans and damages the central nervous system, kidney, liver and bones. Children are particularly vulnerable to the toxic effects of lead which can lead to a wide range of symptoms, from headaches and stomach pain to behavioural problems and anaemia. Lead also can affect a child's developing brain*" (Sarkar, 2020, 9. 88–89)

The problem with TEL was not only the severity of consequences but also the high likelihood of poisoning because of the possibility of sudden absorption of chemical in human body when brought in contact with skin, or when inhaled (Machle, 1935). However, when large scale production of TEL and mixing of leaded gasoline began, producers of leaded gasoline believed that they had all safety measures in place.

"*These processes (production of TEL and blending it with gasoline), however, are so well controlled and their hazards so fully understood and so vigilantly guarded against that the occurrence of other than the mildest manifestations of lead absorption is very rare in the manufacture of the product and virtually unknown in lead-blending*" (Cassells and Dodds, 1946, p. 681, p. 681)

Leaded gasoline was first distributed in the United States (U.S.) in 1923. According to Machle (1935), no case of lead poisoning was reported in the literature between 1853, when lead was first prepared, and 1923, when the distribution of leaded gasoline started. It was perhaps because TEL was never manufactured, handled, or stored in large enough quantities, before its use as gasoline additive, to cause poisoning. Large-scale production of TEL and its mixing with gasoline in large quantities resulted in series of fatalities at a TEL production plant between 1923 and 1925 (Seyferth, 2003). According to Laveskog and Granyean (1984), there were 139 cases of severe TEL poisoning and 13 deaths within 17 months of large scale production and mixing.

"*A DuPont worker recalled that tetraethyllead at these beginnings was handled in open buckets and that operators dipped their fingers into it in order to test its clarity. Also, controlling the reaction initially was difficult and this led to exposure of the workers to the toxic tetraethyllead. During the first month of the plant's operation a worker died from tetraethyllead poisoning and others had minor cases of poisoning, manifested mostly by neurological disorders*" (Seyferth, 2003, p. 5160 and 5163)

These cases of lead poisoning at the TEL production plant received negative media coverage. Consequently, the Public Health Services of the U.S. started investigating this matter (Nriagu, 1990). The distribution of leaded gasoline was halted in the meantime. In 1926, based on results of the investigation, it was discovered that the small quantity of TEL in gasoline (1000th part by volume) could not harm people or users of leaded gasoline. However, ensuring workers' safety during production, handling, and mixing of TEL was stressed in the report (Needleman, 2000). The production and distribution of leaded gasoline resumed the same year, immediately after compliance with ventilation and personal protective equipment requirements was confirmed. Although some cases of poisoning were reported after the operations resumed, the accidents could not be scientifically linked to TEL. Due to this ambiguity and partly because of the Second World War, opposition to TEL virtually ended (Machle, 1935; Needleman, 2000; Nriagu, 1990).

In the midst of the environmental movement, during 1960s and 70s, many scientific studies criticized negative health effects of TEL and leaded gasoline (Beattie et al., 1972; Boeckx et al., 1977; Patterson, 1965; Sanders, 1964). Soon after, it was realized that TEL was not only hazardous during production, handling, and storage, but its absorption in the natural environment was also increasing lead content in an average human body.

"*… studies led to the conclusion that undue absorption of the automotive lead in the environment has become one of the most common preventable public health problems in our time. The "gift of God" has turned into a curse from the gods and the demand to get the lead out of gasoline therefore grew more strident*" (Nriagu, 1990, p. 22, p. 22)

President Nixon's Clean Air Act of 1963 and establishment of Environmental Protection Agency (EPA) in 1970 marked the fall of TEL and leaded gasoline industry (Needleman, 2000). In 1976, after winning a court case against Ethyl Corp (the producer of leaded gasoline), EPA started phasing out lead in gasoline (Nriagu, 1990). As a direct result, average lead levels in human body started declining, which provided further justification for imposing complete ban on the production, handling, and storage of leaded gasoline(Thomas, 1995).

"*EPA had traveled a long way since the first Criteria draft of 1972. The evidence documenting lead toxicity was now strong enough that the agency, citing the "overwhelming evidence of the threat to humans," proposed to cut the lead in gasoline by 91% in 1986 and achieve a total ban by 1995*" (Needleman, 2000, p. 33, p. 33)

Although the multibillion-dollar leaded gasoline industry was completely abandoned by 2000s (in most parts of the world), the consequences of commercializing leaded gasoline in the first place were devastating. According to simulations, TEL from leaded gasoline caused around 1.1 million deaths across the world, in addition to the loss of 322 million IQ points and an economic loss of $2.4 trillion per year (Tsai and Hatfield, 2011).

4.2. The need for leaded gasoline: Sensing

In 1911, Charles Kettering invented the electric self-starter for internal combustion engines (Kettering, 1915). His invention was a landmark for the automotive industry since it replaced the need for starting engines through hand-cranking, gunpowder cylinders, and other inconvenient methods. By 1915, almost all major U.S. car companies introduced self-starting engines in their cars with the help of Dayton Engineering Laboratories Company (DELCO), owned by Charles Kettering (Palmer, 1915). Not long after, though, customers started to complain about 'knocking' problem, i.e., a sharp metallic sound coming from the engine due to incorrect mixing of air and fuel in the cylinder which resulted in poor engine efficiency (Seyferth, 2003). Although DELCO was blamed for the fault, Kettering was convinced that knocking problem was due to the fuel and not the engine (US Public Health Service, 1925). Meanwhile, DELCO was sold to General Motors (GM), and Kettering established another laboratory in 1916, the Dayton Research Laboratories (DRL), where he started searching for a fuel additive which could eliminate engine's knocking problem.

Researchers at DRL tried and tested various fuel additives, including iodine, benzol, aniline, and selenium, which eliminated the knocking problem, however, due to other technical challenges, such as corrosion and carbon deposition in engine's cylinder, none of these materials could be used commercially as an anti-knocking agent (US Public Health Service, 1925). In 1919, GM once again purchased Kettering's DRL and renamed it to General Motors Research Corporation. This time Kettering was appointed as president of GM's Research Corporation. In 1921, Kettering and his team of scientists, including Thomas Midglay Jr., managed to discover the utility of TEL as a viable anti-knocking agent.

Kettering's sensing of opportunity and threat, related to engine knocking, seems to align with the literature (Dangelico et al., 2017; Mousavi et al., 2018). He was quick to scan the environment for cues and signals and promptly reshuffled resources to create value from the knocking problem. However, the dominant logic behind Kettering's perception of opportunity was economic; the search for anti-knocking fuel additive was primarily motivated by the financial incentive rooted in the electric self-starter invented by Kettering. If knocking problem persisted, customers could have rejected Kettering's groundbreaking invention.

4.3. Feasibility of leaded gasoline: orientation

Technical and economic feasibility was carried out before the commercialization of leaded gasoline (Nickerson, 1954), but the risks associated with it were never carefully examined (Blum, 2013). Surprisingly, producers of leaded gasoline did not consider this a significant omission in the feasibility study, even though, evidence suggests that adverse effects of TEL were well known before its large-scale production and mixing with gasoline. According to an Industrial Hygiene Bulletin published in 1924 by New York State Department of Labor:

"*Tetraethyl lead is a remarkably active poison, taking first place among the metallic poisons. It was first made by chemists in 1854. Since that time* *there have been occasional instances of poisoning of greater or lesser severity among workers in chemical laboratories. Quite recently the possibility of using this substance in improving the efficiency of all gasoline motors, and thereby conserving the world supply of gasoline fuel by about one-quarter has been discovered. Moreover, the addition of this substance to gasoline would make possible the use of high compression engines. Hence, the attempt to manufacture it on a commercial basis*" (New York State Department of Labor, 1924)

TEL was a known metallic poison at the time, but the risk of leaded gasoline was estimated rather passively, i.e., through fatality statistics. For example, according to W. F. Harrington, General Manager of DuPont (the large-scale producer of TEL at the time):

"*no men at all in this plant, since we rectified errors and resumed operation in March, have shown any physiological symptoms of poison, so that I can say, and I think I can say with correctness and conviction, that tetraethyl lead can be safely manufactured*" (US Public Health Service, 1925, p. 11, p. 11)

However, the postmortem report of four workers, among several who died of lead poisoning at the manufacturing facility right after the large-scale production of TEL, revealed how naively the chemical hazards of TEL in gasoline were overlooked:

"*… a volatile lead compound was isolated and proved in the brain tissue in two of the four cases. The brain tissue in these cases contained much more lead than is usually found in cases of lead poisoning. This can be explained, perhaps, by a specific attraction of brain tissue for tetra-ethyl lead*" (Norris and Gettler, 1925, p. 820, p. 820)

New York City banned the sale of leaded gasoline after the incident, which compelled producers of leaded gasoline to scientifically examine the risks of radical innovation. Researchers at Kettering's Laboratory conducted several experiments using animals to test toxic effects of leaded gasoline but could not find any significant risks.

"*Tetraethyl lead is introduced into gasoline in amounts so small that the solution lacks these essential toxicological properties of tetraethyl lead. Thus, whereas tetraethyl lead alone, or in high concentration in gasoline, is rapidly absorbed through the skin, its absorption is retarded greatly by dilution in gasoline (i.e., tetraethyl lead per 1000 parts of gasoline by volume). The dilution of tetraethyl lead with gasoline also largely eliminates the danger of lead inhalation*" (Kehoe et al., 1934, p. 4, p. 4)

Meanwhile, Surgeon General of Public Health Services (PHS) also appointed a committee to investigate the matter through scientific experiments (Howell et al., 1926). The committee conducted controlled experiments using five different groups ($n = 252$), consisting of: (i) users of non-leaded gasoline; (ii) users of leaded gasoline; (iii) garage workers or gasoline fillers or truck drivers not exposed to leaded gasoline; (iv) garage workers, gasoline fillers and truck drivers exposed to leaded gasoline; and (v) workers from other plants exposed to lead dust. Clinical analyses of participants' blood and feces samples were carried out. The committee concluded:

"*There are at present no good grounds for prohibiting the use of ethyl gasoline of the composition specified, as a motor fuel, provided that its distribution and use are controlled by proper regulations*" (Howell et al., 1926, p. 196, p. 196)

Regulations proposed by the committee, to be implemented within two years, included (Cumming and Webb, 1928):

- Change the name of the fuel from Ethyl Gasoline to Leaded Gasoline.
- Each filling station must display this name.
- Leaflets should be made available at the filling stations to describe possible dangers and precautions to be taken.

It is apparent that there was a lack of attention to TEL's hazards before commercialization of leaded gasoline. Evidence suggests that the producers significantly underplayed the harmful effects of leaded gasoline. For example, on one occasion, Thomas Midgley Jr. assured the Surgeon General that "*the average street will probably be so free from lead that it will be impossible to detect it or its absorption*" (Nriagu, 1990, p. 19). The deaths of workers, immediately after the large-scale production of TEL, called for serious attention, but poor experimental designs for risk assessment resulted in a missed opportunity.

"*Kehoe's early studies compared lead concentrations in workers in direct contact with tetraethyllead to men in the same plant with other assignments. He designated this second group "unexposed'' controls. When he found lead in the excreta of his unexposed group, he concluded that lead was naturally present in everyone. The presence of it, he argued, could not be taken by itself as an indicator of poisoning. This was a fundamental error, and it was vigorously attacked by David Edsall, Yandell Henderson, and others at the Surgeon General's 1925 meeting, who argued that potentially all workers in the Dayton plant were exposed to TEL fumes*" (Needleman, 2000, p. 20–21)

In the hindsight it seems difficult to comprehend how such mistakes went unnoticed. But it was certainly the '*show me the data*' mentality which obstructed the vision of leaded gasoline producers, as well as the policy makers who, at the time, were probably more interested in economic growth of country than any other indicator of development (Nriagu, 1998).

4.4. Commercializing TEL as a gasoline additive: Seizing and articulating expectations

GM patented 'the use of TEL in gasoline' in 1923 (Nriagu, 1990), and contracted DuPont to produce TEL at large scale (Seyferth, 2003). Meanwhile, Kraus and Callis developed a superior process for the production of TEL, and registered a patent under Standard Oil Company (Seyferth, 2003). Since the 'use' patent was with GM and the 'produce' patent was with Standard Oil Company, both companies, along with DuPont, joined forces in 1924 to establish Ethyl Gasoline Corporation (EGC) (Needleman, 2000; Seyferth, 2003). Kettering was the president of EGC, while Frank A. Howard of Standard Oil and Thomas Midgley Jr. were first and the second vice presidents. Main tasks of EGC were to produce TEL and mix and market the final blend of leaded gasoline (Rosner and Markowitz, 1985).

In 1926, Thomas Midgley Jr. patented (US Patent No. 1,573,846) the mixing of TEL in gasoline for increasing engine efficiency. After this patent, likelihood of market competition virtually faded, as the only way left to complete with EGC was to introduce a replacement of leaded gasoline for efficient engine performance, which was nowhere in sight at the time. As expected, the demand for leaded gasoline skyrocketed soon after the use of TEL was declared safe (Kehoe et al., 1934).

It is noteworthy that while the small-scale retail of leaded gasoline at the beginning resembled niche formation, the reason for starting small was not experimentation; it was the constraints of production and supply that restricted large sales. Quantities of leaded gasoline sold in various parts of the U.S. in 1926, 1927, 1928, and 1929 (9 months) were 79.4, 288.8, 527.8, and 821.3 million gallons, respectively (Kehoe et al., 1934). Continuous increase in sales of leaded gasoline indicates that the objective of starting small was to take time for establishing supply chain and increasing production capacity, and not experimentation. The production and use of leaded gasoline kept increasing over time, not only in the U.S. but throughout the world. According to an estimate, between 1926 and 1985, around 20 trillion liters of leaded gasoline were produced, and in the late 1960s, around 90% of all cars in the U.S. were running on leaded petrol (Nriagu, 1990).

Maintaining production scale and distribution to a reasonable level for a considerable period of time would have allowed TEL and leaded gasoline producers, as well as policymakers, to observe its broader impacts (Caniëls and Romijn, 2006). Although a network of actors was engaged during product development, this group adopted monopolistic business approach from the beginning, by using patents as barrier to control entry in the market. Had there been more stakeholders involved during the early phase (1920s and 30s), better alternatives to TEL might have been discovered, as claimed by many authors (Kitman, 2000; Kovarik, 2005; Sarkar, 2020). Instead, producers of leaded gasoline pushed for it to become industry standard. And the negative effects of leaded gasoline were made to appear as *disputed science*. Also, while the economic and social benefits of leaded gasoline were emphasized in the marketing campaigns (Rosner and Markowitz, 1985), the potential negative effects were disregarded completely, depriving people of the critical information about the hazards of leaded gasoline. Such an obstinate behavior raises question "*whether industrial and scientific progress for the convenience and comfort of mankind is worth the risk of a polluted environment*" (Sarkar, 2020, p. 90)?

4.5. Partnerships for leaded gasoline: Resource Integration and social network

As noted earlier, the most significant partnership in context of leaded gasoline was formed between GM, Standard Oil, and DuPont to establish EGC, a joint venture to integrate resources of three major players in leaded gasoline industry. However, the goal of this partnership was predominantly to generate more revenue. EGC was not specifically mandated to examine the hazards and risks of leaded gasoline (Seyferth, 2003).

Besides this primary partnership, there were many instances when Midgley Jr. and his team joined hands to sought advice from researchers at various top universities and research institutions in the U.S., including Harvard, Yale, Cornell, and the University of Chicago (Nickerson, 1954), however, these brief associations were established to increase the technical performance of TEL, i.e., the anti-knocking characteristics. Environmental risks and health hazards associated with leaded gasoline were not given priority in these conversations. In fact, EGC seemed reluctant in providing TEL samples to independent researchers who expressed an interest in running experiments to explore hazards of leaded gasoline. This was apparent from Robert A. Kehoe's (the director of the Medical Department of EGC) response to D. W. Bronk's (Maloney Clinic, Philadelphia) request for TEL sample in 1940.

> "*Some time ago I was informed that you made the request through your purchasing agent for the purchase of some tetraethyl lead for experimental purposes. A safety engineer of the Ethyl Gasoline Corporation has reported to me that he has looked into the uses to which you wish to put tetraethyl lead and in his words he has stated that you "wish to produce chronic lead poisoning in cats, rats or other similar small animals", by exposing these animals in a respiratory chamber to known concentrations of tetraethyl lead. My opinion has been asked as to whether the tetraethyl lead should be supplied for this purpose. I may say that I see no reason why it could not be supplied for experimental work. I do have certain reservations, however, as to whether you will accomplish the purpose for which you wish to use the material. Accordingly I am writing to you on this point before arriving at any conclusion as to whether some supply of tetraethyl lead should be provided*" (Kehoe and A Letter toBronk, 1940)

Social networks and partnerships in leaded gasoline industry were monopolistic (Kitman, 2000). Since commercial logic was dominant in the primary alliance, patents were used as legal barriers against new entrants. Also, producers of leaded gasoline were not interested in partnering with other researchers who were interested in toxicological studies of TEL and leaded gasoline. They were preoccupied with the idea that '*their science*' was the '*right science*.' For example, when Kehoe was asked to review an article co-authored by Patterson, who challenged former's view on lead by showing that the human lead burdens at the time were 600 times higher from the humans of the pre-technological era, Kehoe replied as follows:

> "*I should let the man, with his obvious faults, speak in such a way as to display these faults … The inferences as to the natural human body burden of lead, are I think, remarkably naive … It is an example of how wrong one can be in his biological postulates and conclusions, when he steps into this field, of which he is so woefully ignorant and so lacking in any concept of the depth of his ignorance, that he is not even cautious in drawing sweeping conclusions …*" (Kehoe, 1965)

Simplistic dismissal of others' perspective blinded the producers of leaded gasoline from other possibilities. The egotistic behavior of producers and top managers perhaps did more damage than any other factor leading to the failure of leaded gasoline industry.

4.6. Adapting to external changes: Reconfiguration and reflective adjustment

Between 1924 and 1948, until the patent for mixing of TEL in gasoline expired, EGC was sole domestic producer of leaded gasoline (Hay, 1998). This monopoly resulted in EGC's strong grip over leaded gasoline market, and therefore, no significant change is discernible during this time (Harbeson, 1940). However, after the expiration of patent in 1948, DuPont and EGC started producing TEL independently (Seyferth, 2003). Soon after, other actors, such as PPG Industries and NALCO, emerged as prominent TEL producers. Moreover, in 1960s, utility of Tetramethyl Lead to enhance the anti-knocking characteristics of TEL was recognized (Nriagu, 1990). In order to keep pace with these developments, EGC had to adjust its primary product (TEL) to retain market share. Although EGC predominantly remained one-product company until 1960s (Seyferth, 2003), the firm kept rolling research programs for technical improvements in leaded gasoline. For example, in 1959, EGC patented the addition of Iron Pentacarbonyl in TEL to increase its performance and optimize the use of TEL in leaded gasoline (Seyferth, 2003). Besides these technical improvements, the fear of replacement of TEL kept EGC engaged in developing better alternatives, but the firm remained unsuccessful as none of the other anti-knocking agents could compete the economic viability of TEL at the time (Seyferth, 2003). EGC's research programs also looked into advanced proprietary methods of TEL manufacturing but these efforts also remained unfruitful.

In 1962, in a twist of plot, GM and Standard Oil sold EGC to a small group of independent investors (Kovarik, 2005). It was perhaps the beginning of the end which the parent companies could foresee. In fact, in 1970, GM announced to comply with the Federal regulation to install catalytic converters (designed for unleaded gasoline) in all new vehicles.

> "*… another major blow to organolead antiknock additives came in January 1970, when the president of GM announced that GM planned to install catalytic converters in its new automobiles in order to meet the Federal Government's air quality requirements of the automobile engine exhaust*" (Seyferth, 2003, p. 5175-76)

Since EGC's most profitable business segment was leaded gasoline, the company engaged with EPA in a legal battle to challenge phasing out of leaded gasoline (Kitman, 2000). The initial decision against EPA was overturned by the full U.S. Court of Appeals for the DC Circuit in 1976, which turned out to be the final nail in the coffin leading to a complete phase-out of leaded gasoline. Fortunately for EGC, it became world's largest producer of organo-metallic chemicals by 1983 (Kitman, 2000). The corporation diversified its business to other chemicals, plastics, and aluminum products, and also invested in the pharmaceutical business, biotech research, and the semiconductor industry. Eventually, EGC came to terms with the abandonment of leaded gasoline. The firm is presently operative in the U.S. and is a subsidiary of NewMarket Corporation.

> "*The company's annual report for 1996 revealed a long-running strategy: namely, using Ethyl's significant cash flow from lead antiknocks to build a self-supporting major business and earnings stream in the petroleum additives industry*" (Kitman, 2000, p. 191, p. 191)

History of leaded gasoline shows that the developers and producers of leaded gasoline got caught in cognitive traps, content with the commercial success of their innovation. They seemed insensitive to the need for reconfiguration or reflective adjustment at any point. This mindset is evident from the following statement of Frank Howard, vice president of EGC:

"*Should we throw this thing (leaded gasoline) aside? Should we say, 'No, we will not use it,' in spite of the efforts of the government and the General Motors Corporation and the Standard Oil Co. toward developing this very thing, which is a certain means of saving petroleum? Because some animals die and some do not die in some experiments, shall we give this thing up entirely?.. I think it would be an unheard-of blunder if we should abandon a thing of this kind merely because of our fears.*" (Kitman, 2000)

As first step of adaptation, an organization must realize and assess the situation in an unbiased fashion, which was not the case with EGC. The firm and its top management team seemed visionless to the fact that science is an evolutionary process, and the workers dying in TEL factories were dying for a reason, which science, at that time, perhaps could not explain (Nriagu, 1990). EGC also did not make enough efforts to understand the scientific rebuttals presented by other scholars. The firm significantly lacked dynamic capabilities.

4.7. An integrative model for management of radical sustainability innovations

The results of leaded gasoline case study suggest that RSIMMs (SOI, SNM, DCs) would have been extremely valuable if these methods were applied during development, commercialization, and maturation of TEL and leaded gasoline business. It appears that these methods could have picked early indications of catastrophic consequences immediately after the large-scale production of TEL and its mixing with gasoline. Lead gasoline would have been a 'niche innovation' by the time when there were 139 cases of severe TEL poisoning and 13 deaths within 17 months of large-scale production and mixing. However, we must also consider that the primary problem at the time was not the absence of innovation management but the prevalence of '*show me the data*' mentality. Science at the time was disputed, and we can only corroborate in the hindsight how TEL and leaded gasoline industry catastrophically failed. Since SOI, SNM, and DCs are all scientific methods, it is possible that these methods could also be disputed at the time. It is extremely difficult, if not impossible, to speculate which method would have been more useful in case of leaded gasoline. A somewhat conservative approach in this situation is to integrate the three methods in a manner which minimizes the margin of error. Each method functionally complements the other (Fig. 1). Therefore, we can identify blind spots in any given approach by integrating them together.

We propose a preliminary Swiss Cheese Model (Fig. 2) to integrate RSIMMs. Proposed model provides protection against unintended consequences through a series of barriers (Reason, 1990). In Fig. 2, each slice of cheese represents a line of defense against unintended consequences of RSIs, and the holes in the cheese indicate the potential of failure of each method. Application of SOI, SNM, and DCs in series will ensure that radical innovation must pass through a series of aligned holes before it could lead to catastrophic failure, which has lower probability in comparison to a situation where we have only one piece of cheese, i.e., one line of defense. In this sense, each method can fill in for the weaknesses of other methods. Hence, overall outcome will be more sustainable and consistent with the purpose of innovation. Nevertheless, keeping in view that these methods are product of scientific knowledge, there remains a chance for the holes to align. In such a case, it is our opinion that the safety of people and the planet should be considered paramount and further debate should ensue before the product is consumed by masses. Our opinion, however, is open to suggestions and criticism of other researchers in the field.

5. Discussion

In this section, we discuss research contributions and theoretical and practical implications along with limitations and avenues for future research. This work makes several significant contributions to the sustainability innovation literature. In previous studies, RSIMMs were not tested for the boundary condition of failure, i.e., catastrophic failure (McMillan and Overall, 2017), leaving room for blind spots in application of these methods. We have empirically demonstrated that the three methods discussed in this paper can be used at various stages of radical sustainability product innovation to avoid unintended (catastrophic) consequences. We can imply with confidence that these methods can generate early warning signs of catastrophic failure and can prevent, or minimize the impact of, such failures, especially because each method offers unique benefits at different phases of innovation. For example, SOI is useful at the planning and development stage. SNM offers value during incubation and testing phase. And DCs work best after commercialization for adaptation and reconfiguration.

The case of TEL and leaded gasoline also enlightened us about a

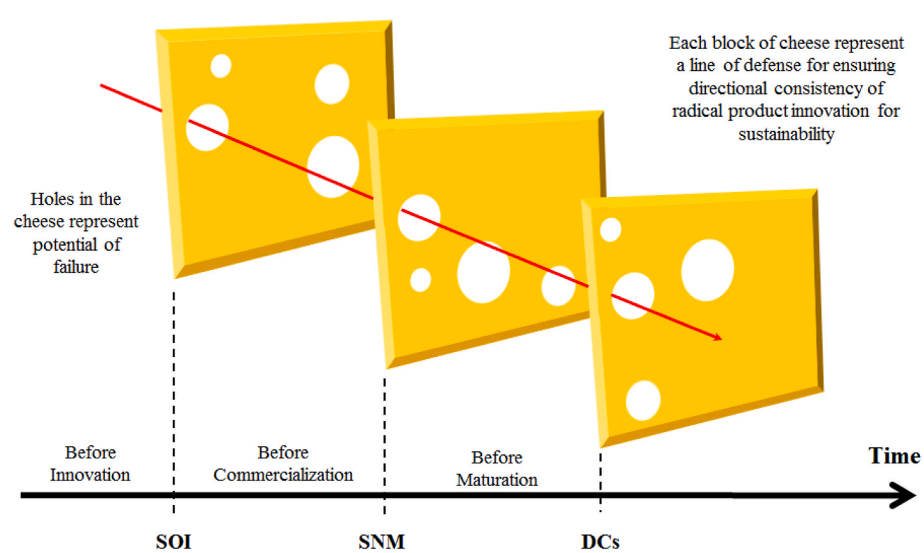

Fig. 2. Swiss cheese model for integration of SOI, SNM, and DCs.

much deeper problem—how disputed science can be leveraged to gain commercial benefits, even if such advantage incurs significant environmental and social cost. The case study revealed that top managers at EGC held 'static cognitive frames' (Raffaelli et al., 2019), which is why they were convinced that *their science* and *their data* were right, outrightly rejecting the possibility that their experimental design may be flawed. They lacked *reflective thinking* which allows managers to step-back from the immediate situation and think outside the box by gathering and processing more information (Jia et al., 2021). The theory of bounded rationality suggests that humans tend to make sub-optimal decisions because of limited decision-making ability, these include cognitive limits, time limits, and information limits (Cyert and March 1963). In case of leaded gasoline, it is evident that top managers at EGC did not only make sub-optimal choices due to decision-making limits, but they also demonstrated egotistic behavior (Kehoe, 1940, 1965). To enforce reflective and rational thinking and to overcome the likelihood of egotistic behavior, we proposed a Swiss Cheese model for preliminary integration of RSIMMs at three different stages of innovation. The idea is to increase layers of protections against possible catastrophic failure of RSIs. It was easier for the developers and producers of TEL and leaded gasoline to find their way through a single line of defense, i.e., experimentation, but once other means of ensuring directional consistency are in place, such as life-cycle assessment, stakeholder involvement, and creation of social networks, it will be less challenging to predict the likelihood of catastrophic failure of RSI and timely avoid such a disastrous accident.

The integrated Swiss Cheese model of RSIMMs has unique significance for stakeholders' involvement in RSI. In case of TEL and leaded gasoline, the monopolistic setup did not allow stakeholders to get involved to an extent that they could influence the producers of leaded gasoline. Developers and producers of leaded gasoline failed to partner with other actors who could criticize or complement their innovation, and an absence of '*another pair of eyes*' led to extreme consequences. With DCs and SNM integrated in the Swiss Cheese model of RSIMMs, we expect future RSIs to fully capitalize on stakeholders' insights. Stakeholders' significance for RSIs has already been acknowledged in literature (Goodman et al., 2017; Juntunen et al., 2019). However, previous scholars studied stakeholders' role in context of innovation performance, i.e., benefits in economic, environmental, and social dimensions (Ghassim and Bogers, 2019; Juntunen et al., 2019). Our unique focus on unintended consequences and catastrophic failure complements previous works. It allows researchers to rethink the temporal dimensions of performance of RSIs. TEL and leaded gasoline were hailed for economic growth, ecological benefits, and job creation for nearly half a century, after which the unintended consequences were realized, and damage done by the radical innovation outweighed its benefits. Even after around 70 years of so-called high performance, leaded gasoline was abandoned because of its side-effects. This line of argument signifies the importance of time-dimension in sustainability innovation research (Bansal and DesJardine, 2014). It emphasizes that researchers should find better ways to integrate 'time dimension' in operationalization of RSI performance. Static view of innovation performance has only limited utility.

Our findings have major implications for policy literature on sustainability. Since the pace, scale and scope of transformation are shaped by the policy conditions (Fitch-Roy et al., 2020), the case of TEL and leaded gasoline leaves us wondering how these factors are determined by political actors. Like RSIMMs discussed in this paper, policy makers need some tools to ensure a fail-safe condition for policies related to RSIs, especially when such innovations can negatively affect public health. For example, recent debate around mandating COVID-19 vaccination saw polar differences of opinions across the globe. The governments did what they had to do, but we do not have any means besides current scientific knowledge to confirm the efficacy of these vaccinations and long-term safety of people. Ironically, the case of TEL and leaded gasoline, and several other similar cases, including chlorofluorocarbons (CFCs) and Dichlorodiphenyltrichloroethane (DDT), show us that science is an evolving process—a means rather than an end. Then the question is how much we can trust on scientific knowledge at any given point in time? Perhaps our excessive dependence on, and obsession with, radical scientific discovery is making it more difficult for us to achieve sustainable development goals. May be there are other, more effective, ways of dealing with sustainability challenges. For one, there is an emerging debate on 'degrowth' which calls for "*radical political and economic reorganization leading to drastically reduced resource and energy throughput*" (Kallis et al., 2018, p. 292). We will always run the risk of experiencing unintended/catastrophic consequences with RSIs, but 'degrowth' promises to tend to the carrying capacity of the planet with negligible probability of failure (Hickel, 2021). However, literature on degrowth is still in infancy, and thus, requires a comprehensive cost-benefit analysis in future before it can be considered to replace RSIs.

Our research also has implications for *speed of innovation theory* that deals with organizational (technical/internal) view of innovation in terms of *high speed to market to gain competitive advantage* (Kessler and Chakrabarti, 1996). It argues that high innovation velocity allows firms to disrupt the advantage of their competitors and create advantage for themselves, but firms that are slow to market face adverse economic outcomes (Ferrier et al., 1999). However, strictly economic explanation of innovation speed poses a dilemma. While innovation speed allows focal firm to gain competitive advantage, our results show that high velocity of leaded gasoline was one of the reasons that led to its catastrophic failure, as it provided only little time for planning, experimentation, and adaptation, subsequently increasing the margin of error. Based on our research, we contend that overemphasizing innovation speed can lead firms to situations where they risk losing reputation at the cost of *speed to market*, as we saw in case of EGC. However, there is an opportunity for future researchers to address this dilemma, i.e., what is appropriate speed for RSI that enables firms to gain competitive advantage with minimum likelihood of failure? Relatedly, although our integrated model (Fig. 2) provides multiple layers of protection against catastrophic failure of RSIs, it is highly likely that the extended protection will reduce the speed with which innovations reach the market. In future, researchers should focus on the effects of this 'safe-slow-effect' on competitiveness of firms.

Finally, our research has implications for sustainable new product development (SNPD). In practice, SNPD extensively relies on Life-Cycle Assessment (LCA) for modeling environmental and social (in some cases) impacts of new products during their lifespan. Firms use software programs, such as GaBi and SimaPro, for conducting LCA (Herrmann and Moltesen, 2015). Although these programs offer reasonable initial estimates of impacts, the mechanical, data driven approach can confound important variables in the complex human-environment systems (Yang and Heijungs, 2019). For example, there is evidence of temporal issues with life cycle assessment (Lueddeckens et al., 2020), i.e., what should be the time horizon of assessment and weighting impacts. Perhaps it is the same reason why the hype around bio-fuels fizzled out over time (Hansen and Große-Dunker, 2013). Subjectivity is embedded in sustainability, and therefore, top managers and leaders should use their judgement in assessing the life-long impacts of sustainable new products. Data-based analyses alone should not be used for making SNDP-related decisions since it could lead managers into data traps, as seen in the case of leaded gasoline.

Like any other research, our work also has some shortcomings. One of the limitations of this research is the choice of case study. Since we study an extreme case to represent boundary condition of failure (McMillan and Overall, 2017), the adverse consequences of leaded gasoline were perhaps so immense that any method may seem to offer promising results. Since we have already covered catastrophic failures, future researchers should study other levels of failures to assess responsiveness of RSIMMs (McMillan and Overall, 2017). Also, some may argue that the choice of case is inappropriate to study RSIs, as it involves petroleum industry, but this criticism holds a hindsight bias. We want to emphasize through this study that diffusion of innovation is a function of its subjective framing rather than technical specifications (Suddaby, 2013). The producers of leaded gasoline were successful in framing their product as sustainable innovation (Midgley Jr, 1925). And leaded gasoline is not the only case, there are several other examples, including CFCs and DDT, where, in the hindsight, we can argue that the innovations were unsustainable, but it is important to study these cases over a long period of time to understand that these innovations were framed, advertised, and perceived as any other sustainable innovation. In recent times, scholars and managers have been facing similar challenges with biofuels and nanomaterials (Hansen et al., 2009; Nawaz et al., 2019).

Another limitation is the potential of bias in existing literature. Since we now know that leaded gasoline produced catastrophic consequences, the producers of leaded gasoline are widely blamed and shamed. Although we have tried to remain objective in our analysis, there are relatively fewer sources supporting Midgley, Kehoe, and Kettering's position as against the works published at odds with them. While their demise has perhaps closed this chapter, there are ways to overcome this shortcoming in the future. One such approach could be to apply RSIMMs to a recent failure of radical sustainability innovation. Although historical case studies have many advantages, it may also be interesting to test RSIMMs in contemporary technological, social and political settings where actors have greater knowledge of unintended consequences and are already exposed to tools that deal with the likelihood of failure.

We studied catastrophic failure of RSI from an organizational perspective. Future researchers should focus on the societal view of such failures. For example, researchers can explore how stakeholders, with lower power over the firm, make organizations liable for failure of RSIs? There is also a need to study *diffusion of innovation* from a catastrophic failure's perspective. Innovation diffusion theory maintains that, in terms of adoption of innovation in the society, subjective meaning/ framing of innovation can be more important than technical specifications. From a consumers' perspective, it raises question whether/how mass market adapt against such an innovation when information about likelihood of catastrophic failure is available? Finally, in the backdrop of *open innovation*, which offers a setting susceptible to miscommunication and unclear objectives, it is the right time to ask how RSIMMs can be integrated within collaborative networks to ensure adaptability of RSIs.

6. Conclusion

Our goal in this study was to apply RSIMMs to a catastrophically failed RSI in order to: (i) identify shortcomings of these methods against the understudied boundary condition of failure (catastrophic failure); and (ii) understand how catastrophic failures can be avoided, or unintended consequences can be minimized, in the future. Results suggest that RSIMMs could have offered substantive insights into the hazards of leaded gasoline if these were applied during development, commercialization and maturation of TEL and leaded gasoline industry. The complete disregard of environmental and societal cost blindsided leaded gasoline developers from the catastrophic risks their innovation posed. The relentless pursuit of economic gains outweighed environmental and social concerns, which eventually became the reason for the abandonment of the billion-dollar leaded gasoline industry across the globe.

The results of this study also highlight a graving concern that disputed science can, at times, be leveraged for economic gains. In case of leaded gasoline, the developers were reluctant to consider the possibility of flaws in their experimental designs. The notion of '*my science is the right science*' prevailed from both sides, which created more uncertainty instead of a positive scientific debate. While we cannot fully investigate and resolve scientific disputes in a single study, it is possible to increase layers of protections against the potential of catastrophic failure by integrating RSIMMs at various stages of innovation. In this way, if a blind spot goes undetected during, for example, development stage, it would be possible to discover it subsequently during the commercialization stage. Multiple layers of protection significantly reduce chances of catastrophic failure of RSIs. Based on the results, we proposed a Swiss cheese model (Fig. 2) for integrating the three methods discussed in this work. Nevertheless, there remains a chance for the holes in the Swiss cheese (shortcoming of each method) to align, although the probability of this happening is fairly low. In such a case, it is our opinion that the safety of people and the planet should be considered paramount and constructive scientific debate should ensue. Even the slightest possibility of a catastrophic failure should be seriously taken into consideration. Safety and sustainability of RSIs must always take precedence over purely economic and political rationales.

CRediT authorship contribution statement

Waqas Nawaz: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Methodology, Roles/. **Hassan Bashir:** Conceptualization, Project administration, Validation, Investigation, Methodology, Roles/.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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