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From responsible to responsive innovation: A systemic and historically sensitive approach to innovation processes

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ABSTRACT

Responsible innovation has emerged as a field of research dedicated to introduce sensitivity to societal values in innovation processes. However, much of the academic literature on RI deals with single technologies instead of technological systems and is future-orientated without explicitly using specialised knowledge of past developments. In this paper, we present a problem-focused approach to RI that aims to support researchers and stakeholders in developing potential solutions from a perspective of systemic awareness and historical sensitivity. We then describe the application of this approach in an 18 months long interdisciplinary research project on plastics. We show that the approach has generated new and unexpected research projects, formed new inter- and transdisciplinary collaborations, and has impacted some participants' understanding of the systems in which their work is embedded. We conclude that with appropriate willingness to engage by individual researchers, our approach is able to, firstly, influence highly experienced researchers to engage more responsibly with their work, and secondly, to make research projects responsive by including societal concerns and their historical emergence from the start.

1. Introduction

Over the past decade, responsible research and innovation (RRI) has emerged as a policy discourse that attempts to highlight, make visible, and increase the role of societal values in research practice. In parallel, responsible innovation (RI) emerged as an academic discourse and field of praxis to transform innovation practices to become more anticipatory, reflexive, inclusive, and responsive (Owen and Pansera, 2019). The terms RRI and RI are often used interchangeable in the literature, but since we aim to highlight and encourage academic reflexivity, we use RI in the remainder of the paper. RI's focus on value positions held by societal actors about new technologies and their applications has highlighted how over time unintended effects of new technologies become a source of contestation (e.g., Owen et al., 2009; Robinson, 2009; Schaper-Rinkel, 2013). RI has also shown the need for engaged processes of innovation, where interdisciplinary knowledge and inclusion of a diversity of societal and public stakeholders is combined to ensure that technologies are perceived as legitimate (e.g. Fisher, 2011; Betten et al., 2013; Stahl, 2012).

While the increasing attention given to responsible innovation is promising, two gaps require attention. First, RI research traditionally targets singular products, technologies, or business models; it focuses on changes within systems and not changes of systems (Cuppen et al., 2019). While incremental innovation of system components is important, it is generally acknowledged that innovation of systems of provision is required (EEA 2019). More specifically, current sustainability challenges constitute 'wicked problems' and need systems thinking and an understanding of systemic solutions (Lönngren and Svanström 2016).

And secondly, RI currently takes a future-orientated, normative, and prescriptive approach, with little systematic consideration of past innovation processes. RI makes use of methods for scoping desired future states of the world, pathways to achieve them, and means to manage or intervene in the change process if necessary (Ribeiro et al., 2017). This lack of historical sensitivity (Nordmann, 2014) in RI is even more surprising when considering that the 'grand challenges', that are sought to be solved with and through the innovations which are made 'responsibly' (von Schomberg and Blok, 2018), are often the unintended results of solutions to past problems. Informing future decisions by collectively reflecting on the past enables the identification of path dependencies that generate such negative consequences.

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Whereas other papers concerned with methodologies or approaches of RI have, for example, outlined the merits of involving stakeholders in technology design and governance (e.g. Owen et al., 2009), thinking in advance about the use and implementation (e.g. Robinson, 2009), or considering more broadly the inscription of values in technology (Simon, 2016), our paper is unique in that it addresses the outlined gaps, firstly, by starting with a problem and not an intended solution, and secondly, by building topic-specific understanding of the system and its historical emergence that is shared between stakeholders and researchers and that can be considered and re-utilised in the innovation process. In doing so, we make a theoretical and a methodological contribution to RI: Theoretically, we address the gap regarding historical sensitivity by taking the past into account as an integral part of a process of RI. In particular, we argue that historical dynamics should become part of the problem definition and scoping phases of RI. To further this aim we present a dedicated approach for the engagement and pointed interaction of researchers and societal stakeholders to co-identify systemic problems and co-produce systemic solutions, which takes the path dependencies generated in the past as a starting point. Illustrating the merits of our contributions, this paper reports on application and evaluation of our methodological suggestions in an 18-months long interdisciplinary research project on plastic. We show that the approach presented here has created a basis for impactful projects and fostered positive attitudes towards the value of interdisciplinarity, stakeholder engagement, the consideration of systemic unintended effects, and historical sensitivity.

This paper comprises seven sections. Following on this introduction, in the following section we review relevant literature on RI, and how reflection on past technology development can be taken into account. Section three describes the approach we put forward to account for past technology development. Section four present our case and how we approached its analysis. Section five presents the results of an application of our approach in an 18 months long research project on plastics, and section six evaluates this application. The final section briefly discusses our results and reviews the contributions we aimed to make to the literature.

2. Responsible innovation and temporality

RI activities are concerned with the interaction of innovation activities and established biological, human, or physical systems in new or unprecedented ways. Examples include nanotechnology (e.g. Owen et al., 2009; Robinson, 2009), biotechnology (e.g. Betten et al., 2013; Ribeiro and Shapira, 2019), and medicine (Reddy et al., 2011; Sugarman, 2012), but also digital technologies (e.g. Stahl et al., 2014) and social innovation (e.g. Zenko and Sardi, 2014). Such activities following RI principles serve aligned purposes of avoiding unintended consequences and of proactively aligning with societal needs (Ribeiro et al., 2017).

Societal needs are often identified 'responsively' through the engagement of public and private stakeholders through inclusive or participatory approaches as they then influence development efforts (cf. Genus and Iskandarova, 2018). And yet, most innovation activities within RI are identified *ex ante* to public or stakeholder engagement and often follow the continuing development of the aforementioned technologies such as bio- or nanotechnology.

RI seeks to avoid unintended consequences as these pose risks that can be anticipated and managed before innovation is fully implemented (Owen et al., 2009). Further to an early involvement of stakeholders, the avoidance of unintended consequences also enables evolving or anticipatory governance arrangements. These arrangements allow to manage risks responsively and ensure social acceptability and desirability (Robinson, 2009; Schaper-Rinkel, 2013; Som et al., 2010). The notion of 'unintended consequences' is inherently historical in that it identifies occurrences in the present (i.e. a consequence) which are retrospectively understood as unintended by the actors that set in motion the sequence of events that produced the consequence. Thus, in our work we call for, and provide methods for, the active reflection on the past in terms of actor motivations, sequences of events and the emerging negative evaluation of consequences.

Applications of RI almost always follow specific innovations. Whilst these innovations promise to tackle specific issues, RI is mostly motivated by 'responsible' development of technology rather than a 'responsive' engagement with immediate or historic challenges. Although 'responsiveness' has been identified by Owen and Pansera (2019) as a key tenet for RI, they understand this not as a response to past challenges but as a response to diverse voices by "ensuring that broadly configured anticipatory, reflexive and deliberative knowledge has bearing on and shapes the purposes, processes and impacts of innovation and research aimed at this" (p.32). However, Genus and Iskandarova (2018) find this to be addressed only insufficiently, calling for more proactive engagement of stakeholders and society. We consider this methodological focus also reflected in the broader literature, which mostly employs methodologies and tools that envision or engage with futures, and occasionally engage with the present, for example through various participatory and/or anticipatory methods such as backcasting, foresight, scenario planning, technology assessment, or value-sensitive design (Ribeiro et al., 2017). While all these methods may be informed by formalised knowledge or professional or private experiences of the past and present, they bear an important shortcoming: Historical sensitivity is understood as transfer knowledge and not as topical knowledge within its historic and systemic contexts. This means that these approaches treat insights from technologies overall as generic experiences and as sources for toolkits or guidelines which can inform technology development; these approaches start with goals or solutions in mind, rather than with the identification of problems and their systemic emergence within the histories of specific technologies.

A lack of active reflection on the history of existing technologies in RI is surprising given that the community is not only conscious of its own history (e.g. Owen et al., 2013; Rip, 2014) but also interested in the past unfolding of the technologies or institutions they study (e.g., Scholten and Blok, 2015; Campos et al., 2017). Yet, these insights are kept empirically and methodologically separate from the RI activities that embed future technologies. For example, York et al. (2019) highlight "the long history of the precision medicine field" (p. 340) in their abstract, but their methodology employs imaginaries, scenario thinking, and design fiction without any mention of this 'history' outside of the abstract. As another example, Campos et al. (2017) narrate a "still inconclusive history" (p.18) of the governance of genetically modified mosquitoes in Brazil: they hope that the generated insights would lead to an extended analytical focus, but make no mention of the usefulness of this narration to future technology development or governance efforts of the same or similar technologies.

Proposing a more aligned approach, Nordmann (2014) suggests that a "sensitivity to the contingencies of history" (p. 93) could greatly enhance RI activities as any historically-informed anticipation or judgement of the future may help to or avoid or stay alert to unintended consequences. Seconding this call, Wilsdon (2014) suggests the involvement of more historians in RI, arguing that they can add to RI an

> "ability to unpack assumptions, myths and the lost contexts in which particular policy ideas formed can be particularly useful. Dealing with nuance and complexity in evidence, and how perspective changes its interpretation, are commonplace skills in historical research and could be invaluable for mitigating potential policy failures and controversies, for example, around new and emerging technologies" (Wilsdon, 2014, p. 111).

Seeing that history and temporality in RI form a knowledge base that is often empirically kept separate from stakeholders and researchers who interact with and act within history's impacts, our work builds on the arguments by Nordmann and Wilsdon. As the issues addressed by RI

have emerged over decades and centuries through the interactions of research, innovation, and technology with society, nature, and culture, our contribution aims to introduce topic-specific historical sensitivity.

Building on established methods and approaches used for in RI, the approach we put forward in this paper connects and makes explicit the historical contingency of the research and innovation activities in a co-production approach: Seeking to be proactively responsive to society, our approach generates a shared empirical understanding of issues from which potential solutions are envisioned and tackled by emerging collaborations of stakeholders and researchers. Our approach thereafter suggests following the innovation process and ensures that historical sensitivity and systemic awareness is recast and reiterated into prospective futures.

3. Our approach

Our approach (summarised in Fig. 1) consists of two stages: problem identification and project execution. The trigger for applying the approach is that a set of actors shares an awareness that there is a set of socio-material practices—commercial, private, or otherwise—that creates a societal challenge, insofar that the practices and the social and environmental impact they generate are contested. Using a systemic perspective, the historical dynamics leading to these practices are identified through desk research in step 1. This results in a draft of an historical overview which depicts the emergence of the contested practices, including key events in their contestation, in a timeline. This timeline is critically interrogated by system stakeholders and researchers in step 2. Based on the shared understanding of the systemic issues this interrogation produces, step 3 serves to identify the possible system leverage points for changing practices. These serve as input for a consolidation process (step 4) where researchers and system stakeholders outline one or more concrete projects aiming to develop innovative social or material solutions.

To ensure that these defined projects retain and exploit the awareness of the understanding of the entangled practices, historical emergence, and broader system dynamics generated in the first three steps, the second stage proceeds alongside the execution of the suggested research projects. Step 5 serves to elaborate upon projects by understanding underlying assumptions and thus identifying the non-linear dynamics of the project as favourable or unfavourable results unfold. Finally, in step 6, the key historical insights from stage one are used to explore scenarios that may lead to unintended consequences, such as unwanted social and environmental impacts. It thus seeks to prevent unintended consequences.

All steps are described in detail in the following subsections, before we proceed to describe our implementation and evaluation of the proposed methodology. Since all but the first two steps have been described previously in other academic literature, and in line with our theoretical and methodological aim, our elaboration of these is substantially longer than those of steps four to six.

3.1. Stage 1: interrogate the problem

3.1.1. Step 1: identify and reconstruct historical dynamics to produce timelines

The first step in our approach focuses on identifying and reconstructing in timelines the historical dynamics that lead to currently problematic socio-material practices. Given that the produced timelines are critically interrogated by stakeholders in the second step, it is important that these stakeholders are also involved in selecting the problematic socio-material practices that the timelines will focus on. This can be achieved, for example, through preparatory interviews or a survey amongst stakeholders.

Once the focal socio-material practices have been selected, the main task in this first step is to reconstruct the historical dynamics that led up to the emergence of these practices. It is not necessary that the timelines completely represent the historical dynamics in all their detail, but they should capture the dynamics with a level of detail that is sufficient for people with some background knowledge to be able to critically engage with the timelines and extend and correct them where they deem necessary.

Our approach to constructing timelines builds on our earlier experiences with the reconstruction of socio-material processes (; Boons and Spekkink, 2016; Spekkink, 2015, 2016) and is inspired primarily by process-orientated research that has been done in innovation studies (Poole et al., 2000). It involves gathering data from archival sources on the internet, including news archives, academic publications, websites, as well as various other documentation. Using these data, we construct event datasets (Poole et al., 2000), which record events as brief qualitative descriptions of what happened when. The dataset can take the form of a simple, structured table with columns to record (1) the timing of the event; (2) the description of the event itself in the words of the researcher; (3) fragments text from the raw sources of data that underlie the event, such as images or quotes; and (4) references to the sources of data. If these descriptions are recorded in chronological order, the event dataset can be understood as an atomized narrative of the historical dynamics of concern.

In order to construct timelines from event datasets, it is usually necessary to process the data further. First, socio-material processes are rarely a simple, unitary sequence of events. Instead, they are often

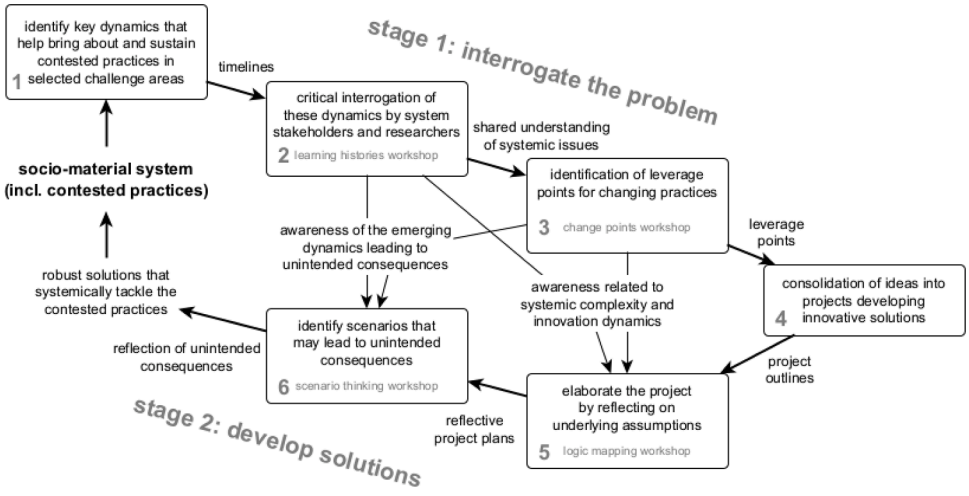

Fig. 1. Overview of our suggested methodology for historical sensitivity and systemic awareness in research projects.

constituted by multiple streams of events that sometimes occur in parallel, sometimes intertwine and sometimes split up into new streams (cf. van de Ven 1992). Rather than thinking of events as forming sequences, it thus makes more sense to think of events forming networks. To reconstruct these networks, it is necessary to identify the 'linkages' that articulate which events lead into which other events. Identifying these linkages is thus an important part of the reconstruction of the timelines. In our approach, the researcher identifies these linkages by comparing event descriptions to identify clues that one event has contributed to the conditions for the occurrence of the other.

Once the linkages have been identified, it is possible to visualize the timeline as a network of events (we refer to these visualizations as *event graphs*), in which the events are represented by nodes and the linkages between them by arrows. The nodes can be laid out in chronological order (e.g. from left to right) and annotations can be added to summarize the developments that the events represent and to highlight other details that deserve the observer's attention. It is also useful to colour code events to categorize different types of developments that are visible in the timeline. What types of developments to highlight will depend on the topic of concern. See Box 1 in section 5 for an example of a typology that we used in our own application of this approach.

The result of this work is a set of network visualizations of timelines. These should be simple enough to give a 'sense of overview', while complex enough to invite observers to take some time to explore the details of the timeline and ask critical questions about what they illustrate. With regard to level of detail, in our experience, timelines should narrowly fit on an A0 poster while still being easily readable from a metre away. These timelines are the main input for step two of our approach, which is a *learning histories* workshop in which stakeholders critically engage with the timelines.

3.1.2. Step 2: critical interrogation of historical dynamics in learning histories workshop

Our approach to organizing critical engagement of stakeholders with the reconstructed historical dynamics is inspired by an approach known as *learning history*. *Learning histories* were first developed to support processes of organizational development (Roth and Kleiner, 1995, 1998), and subsequently extended to apply to wider systems (Gearty, 2009). In their original implementation, *learning histories* are written documents and possibly other media that are deliberately distributed to aid organizations to learn from their own experience with, for example, organizational change processes. Such learning histories were originally compiled from narratives of the people involved in these change processes, as well as from outsider's assessments. As with the original learning history approach, in our own application a key aim is to learn from past experiences. However, the participants doing the learning are not necessarily involved in the dynamics of interest themselves, or maybe only in very small parts of them if the processes span longer periods of time. However, based on their role and experience in similar processes, it is important that the participants are knowledgeable about the dynamics (or specific parts of these) that are depicted in the timelines. Another difference of our application with the original learning histories approach is that in our approach learning histories are conveyed primarily through visualizations instead of texts.

Our approach involves bringing stakeholders together in a *learning histories* workshop where they critically engage with the timelines produced in step one. The purpose of the workshop is to create broader historical sensitivity of dynamics that contributed to socio-material practices that the stakeholders deem problematic, as identified at the beginning of step one. These socio-material practices can be considered, in the language of learning histories, *notable results* (Roth and Kleiner, 1995), which are well-known situations related to the topics of interest that are variously labelled as desirable or undesirable by different stakeholders—that is, different stakeholders may disagree on what is (un)desirable. Examples of notable results from our own project are the widespread use of single-use medical devices made of plastic, and the accumulation of microplastics in water bodies. After presenting the *notable results*, the stakeholders can be broken up subgroups that are assigned different timelines; unless stakeholders choose groups themselves, we suggest to consider individual knowledge and experiences alongside aims of network and capacity building in the overall research group. The subgroups should be given some time to familiarize themselves with the timeline assigned to them, before engaging in a discussion that facilitates the correction or further elaboration of the timelines. Here, it is helpful to guide this discussion with prepared questions. Stakeholders should also have the means to add their corrections and elaborations to the timelines. For example, when the timelines are presented on posters, stakeholders can add to the timelines with post-its or by simply writing on the posters (see Fig. 2 for examples of this).

The subgroup discussions should be followed by a plenary discussion with two parts. Firstly, each subgroup shares what they found and what lessons they draw from this, which ensures that these lessons are shared amongst the group as a whole. Secondly, all stakeholders should discuss and agree on a set of *guiding principles* that can guide the development of new projects by aiming to discourage these projects from replicating dynamics that have previously led to undesirable outcomes. This ensures that—unlike in other RI-related approaches such as value-sensitive design (see e.g. Le Dantec, Poole and Wyche, 2009)—topic-specific insights are taken forward into a development process. The key lessons from the subgroup discussions and the guiding principles constitute a shared understanding of systemic issues, which lays the basis for step three of our approach.

3.1.3. Step 3: identification of leverage points for changing practices

The third step of our approach consists of conducting a *change points* workshop that allows stakeholders to work around specific topics and issues that emerged from the *learning history*. The *change points* workshop is part of a methodology for group thinking developed by social scientists to explore sustainability-related social or material interventions with broad audiences and untrained moderators (Hoolohan and Browne, 2020; Hoolohan et al., 2018). It was developed for interdisciplinary groups with a shared goal to engage with the complexity of socio-material systems, specifically looking at how everyday practices manifest or influence certain issues and how these might be altered. Furthering the knowledge about general and specific developmental pathways and historical circumstances that lead to sustainability issues, the focus on practices can help to situate the problem, its effects, and potential solutions in the present and the future. Results from the workshop include an understanding of what interventions could realistically bring about change, as well as the actors required to make them.

For this workshop, stakeholders are ideally divided into subgroups that are thematically equivalent or similar to those of the *learning histories* workshop, so that they can build on the results of that workshop, further a shared understanding, and thereby create initial ideas for new projects. This is achieved through the following five steps (based on Hoolohan and Browne, 2020 but without their third step aiming at recognising diversity):

1 Problem scoping to develop a shared understanding of the key problem. While already the *learning histories* workshop can be understood as a problem scoping exercise, the *change points* workshop focuses on one of the identified problems and evaluates it in detail. Participants are asked to explain the importance of the problem, what a successful solution would be, and what critical changes would resolve the problem.
2 Mapping sequences of everyday activities that shape the focal problem to identify points where interventions might be targeted.
3 Mapping broader influences that sustain the sequences of activities identified, and mapping actors that have responsibility and/or ability in shaping these influences.
4 Reframing the problem based on the extended understanding of the problem built thus far to identify avenues for interventions.

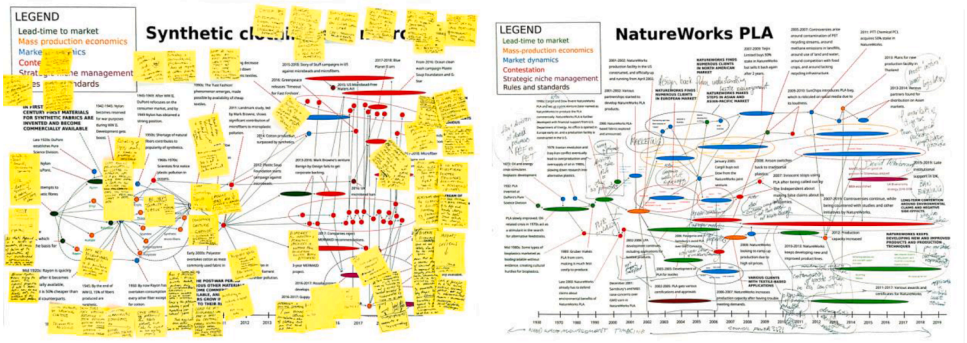

Fig. 2. Photographs of two posters used during the learning histories workshop.

5 Turning ideas into actions by identifying what actions are required for the interventions and the foundations need to be laid for these actions. This step also involved thinking about evaluation.

The result of this exercise provides 'raw ingredients' for project ideas, in the form of ideas for interventions that need to be taken, by whom these should be taken, and how the success of interventions could be evaluated. These ingredients are further developed in the final step of stage one of our approach.

3.1.4. Step 4: consolidation of ideas into projects

The final step of stage one is to take forward the insights and ideas about interventions that were developed in the *change points* workshop and shape them into concrete project proposals. This process needs to be reflective about the historical sensitivity and systemic awareness built in the previous steps. We furthermore propose that engaged external stakeholders should be key drivers and motivators to firstly formulate and secondly achieve the objectives identified in the project proposal. Acknowledging that context and demands in every project are different, we suggest no specific format for this step.

3.2. Stage 2: develop solutions

3.2.1. Step 5: elaborate the project by reflecting on underlying assumptions

Stage two of our approach builds upon the insights from stage one by making sure that the lessons are re-iterated and maintained in the project execution, preventing them from fading away as participants' attention is directed primarily to the execution of their projects. Stage two of our approach thus aims to create a space for reflection alongside and across projects that often lacks in those projects themselves and specifically focused on applying the lessons learnt in stage one. Accordingly, step five consists of a *logic mapping* workshop in which the proposal and its assumptions are transformed into 'pathways to impact' that can be used as a more elaborate and reflective project plan. For most projects, this workshop might be most beneficial in the beginning of the project, but if there are possible technological bottlenecks this workshop could also be conducted—or outcomes discussed again—after first findings. *Logic mapping* is often used in project planning and evaluation, and represents a usually linear flow of elements during and after a project—inputs, activities, outputs, outcomes, and impacts. It is often conducted as a group exercise to bring groups together and create a common discussion ground for project evaluation or planning (McLaughlin et al., 2015).

The aims of this workshop are to identify 'pathways to impact' by firstly identifying steps to scale or to impact, and secondly by uncovering underlying assumptions and requirements. This builds on some exercises from the *change points* workshop in step three, that aimed at identifying involved actors and practices; it is supposed to make explicit, for example, the specific contexts, involved actors, required funding, related government action, or changes in societal attitudes that are required or desirable for a project to be successful or impactful.

The *logic mapping* should furthermore reveal—and can be guided by a moderator in such a way—that there are feedback loops in the research and implementation process that seek to keep in sight and manage some of the dynamics explored in the *learning histories* workshop in step two. We propose that feedback loops highlight the continuous adjustments and the necessity for iterative and collaborative, non-linear innovation that is crucial for engaged innovation activities, and for which Campbell and Carayannis (2016) have suggested "a more direct and parallel coupling of knowledge production and knowledge application, where there are mutual interferences and parallel as well as parallelized interactions between basic research and knowledge application" (p.2).

3.2.2. Step 6: elaborate scenarios that may lead to unintended consequences

Aligned with the anticipatory dimension of RI, in which a variety of pathways with a variety of intended and unintended impacts are explored, the sixth and final step of our proposed methodology concerns the 'what if' question (see Owen et al., 2013) through a *scenario thinking* workshop (Wright and Cairns, 2011). Within the context of a project's current and anticipated trajectory, such questions need to be discussed early enough to have an impact on the research process, but late enough to be meaningful. Depending on the project purpose and project duration, this step may deal with the immediate research outcomes but can also help plan a research agenda and provide crucial input to future funding applications.

We suggest that this workshop builds on and makes strong use of the historical sensitivity and systemic awareness raised in steps two and three. Ideally, the scenarios explicitly reflect on the identified historic dynamics and challenges from the *learning histories* workshop, as well as the gained insights about the complexity of practices involved in any specific system as uncovered in the *change points* workshop. We specifically suggest to keep in mind the intertwined systems of policy, innovation, the respective system of provision which a project targets, and the broader public.

With this final step, it is intended that all stakeholders have gained a shared, topic-specific, historical sensitivity and systemic awareness for their research project. By now, robust solutions should have been identified, elaborated, and can be developed further—possibly with additional interventions for reflective and responsive research practice.

4. Case and methods

Our approach was developed as part of an interdisciplinary project: *RE3: Rethinking Resources and Recycling* project at The University of Manchester and was funded as part of *UKRI's Plastics Research and Innovation Fund*. A primary aim of the fund was to enable strategic networking and novel collaborations in order to explore new ideas and innovations that have the potential to solve the plastics challenge. In line with the aim of the fund, our project realised an open-ended,

stakeholder-led, and historically sensitive approach which using the approach outlined above incorporated instead of prescribed the identification of societal or industrial needs. The authors of this paper were all involved in developing and executing the presented approach.

In the first six months of the project we executed stage one of our approach, which were the only activities within the project at that time; approximately equal time was dedicated to creating the timelines (step one) as to conducting the workshops and generating and identifying proposals for the remainder of the research project (steps two to four). This stage accordingly focused on networking, systems comprehension, issue identification, and group formation. By the end of stage one, project proposals were evaluated by the steering board, and overall six projects were taken forward.

Originally, we did not intend to continue our approach alongside the execution of the projects, but towards the end of the first stage, many participants and the project management board expressed their interest in further reflective activities. The main concern was that the immediate challenges of the project would make it more difficult to reflect on, reiterate, and apply the gained historical sensitivity and systemic awareness from the first project stage. Thus, stage two was conceived in an attempt to develop a methodology that would allow us to create spaces and moments for reflection within the project group, as it builds on and extends the previously attained historical sensitivity and systemic awareness. Since the Covid-19 pandemic had started during stage two, all *scenario thinking* workshops were conducted online. Workshops were not conducted with one of the six project groups because the project had established its own methodology of engagement and reflection.

By the end of the 18 months funding period, the conducted projects reached a level of clear articulations of solutions that could be implemented by project partners, which allowed us to assess the reported experiences of the process of responsible innovation and the perceived usefulness of (steps within) our approach. We did not aim for a methodologically thorough assessment based on outcomes of the project, but instead we evaluated how the process (our proposed approach to include historical sensitivity and systemic awareness) unfolded in practice, and how the involved participants experienced this. As such it is also not our aim to evaluate the course of specific projects within RE3, but rather to outline the usefulness of our approach for the overall project. To this end, we collected a diversity of evidence to reflect on and evaluate our approach:

1 Outcomes of plenary discussions in stage one, and group discussions in stage two, which helped us identify what important points and insights of our methodology were.
2 Our own notes and reflections on workshops, both to continuously improve how we conduct them and to understand their overall usefulness. Additionally, workshops in stage two were video-recorded and transcribed for further reference.
3 The change and reformulation of project proposals, ideas, and discussion points both within stage one and within each project in stage two.
4 Participants' reflections on the project in general and our approach in specific through semi-structured interviews, which were also transcribed.
5 Outcomes of the project work, including funding applications and policy insights, where our approach or results thereof are referenced or highlighted.

In order to collect this evidence, every workshop (3 in stage one, 10 in stage two) was moderated or observed by one or more authors of this paper; reflective notes were taken immediately afterwards (often based on rough notes made during the workshop). We also collected emerging documentation, such as notes from independent observers, draft proposals, and digital or analogue (visual) representations of workshop results. In stage two, we furthermore video-recorded and transcribed all workshops. To keep track of the projects in stage two and be able to prepare and moderate the workshops, we had many formal and informal conversations with and observations of the project groups, for example in dedicated calls or by joining team meetings. In addition to emails, we had between two and four contacts with each project group or individual members in advance of each workshop.

At the end of the project duration, we conducted semi-structured interviews to evaluate our approach, focusing on the participants' overall experiences with RE3, their specific project work, as well as each workshop they participated in. Conversation flow and specific questions considered both previous conversations with this participant and the knowledge of the interviewer—the same author who engaged with the individual projects most closely—about the progress. This allowed us to gain feedback on our emerging summative evaluation. We interviewed in total 26 project members—7 Principal Investigators, 7 Research Associates, 7 other internal participants, and 5 external stakeholders—, representing participation in all different stages and sub-projects of RE3, affiliations to the university, and career stages. These interviews were transcribed and the transcripts were shared amongst the authors.

For our analysis, we firstly re-arranged this collected data both by workshop and by project, and additionally kept more general utterances of RE3 overall. Based on this data with substantially reduced complexity, two members of the research team then discussed the impact of each of our interventions on the project overall and on individual projects. To contextualise evaluations from interviews, we also considered the participants' overall engagement as well as changes thereof. No further feedback was gathered before writing up this article.

5. Results of the application of our approach

Step one. The project began with an opening workshop, where all involved researchers and stakeholders co-created through brainstorming, clustering, and prioritising a list of six clusters of *notable results*, which, as introduced previously, are considered well-known situations that are labelled in different ways by different stakeholders and thus potentially contested:

1 unintended effects of plastics application: e.g. e-waste, microplastics, material without financial or social value
2 socio-cultural practices shaped by, and shaping, plastics application: e.g. plastic as an material answer to everything, take away boxes and cups, single-use for hygiene
3 areas of application: e.g. mixed materials, sports gear, disposable nappies
4 potential for technological innovation: e.g. plastic-free single-use items, everyday items, PVC, lightweight materials
5 plastics application driven by convenience: e.g. food trays, water bottles, plastic bags
6 public perception of the impact of plastics application: e.g. amount of plastic v fish in sea, focus on consumer v. industrial waste, food packaging

Based on this, a shortlist of eight potential topics—notable results that were considered part of many of these clusters—was created and through a ranking survey amongst the involved stakeholders and researchers prioritised. The project's management team then selected three of the most highly prioritised topics to construct a timeline for; these topics were considered to both reflect key challenges in the UK plastics system and the project's diversity in terms of actors involved in the subsystems; these three topics were: (1) single-use medical devices in healthcare; (2) the occurrence of synthetic fibres in water bodies; and (3) the rise in use of bioplastics.

The first three months of the RE3 project were then dedicated primarily to the development of a *learning history* timeline for each of these three topics. This was done by three research associates who used a variety of online accessible sources, ranging from academic publications

to websites of key actors, to collect data on major historical developments, and subsequently compiled them into event datasets. One of the research associates and the principal investigator of this part of the project then coded the event data (e.g., to identify linkages between events) and subsequently created the visualizations of the timelines. The timelines attempted to capture the key developments that led to notable results regarding the use of plastics such as inventions, market dynamics, or changes in legislation or market dynamics. Events in the timelines were colour coded, expressing different internal and external pressures or developments (for an example of these categories, see Box 1, and of *learning histories*, see Fig. 2). These dynamics are selected from theorising on transitions towards more sustainable technologies (see Köhler et al., 2019), and aim to provide participants with a language to express and examine their understanding of the technological and systemic change visualised in the event graph.

Step two. We conducted a *learning histories* workshop at the end of the third month of the project. The 23 participants were divided into three similarly sized groups based on experience and expected interests, as well as with the intention to create opportunities for networking. The subgroups were given time to familiarize themselves with the timelines before engaging in a discussion on (1) what important developments and notable results were missing; (2) what key actors were in the developments; (3) at what points in the timeline alternative directions could have been taken and how; and (4) what lessons could be drawn from the foregoing.

In the plenary discussions, participants highlighted firstly how key insights on how problems around plastic waste emerged in the three topics, and secondly the challenges this raises for their potential research projects. Recognising that the *learning histories* workshop is a key contribution of our overall approach, and the identified challenges for conducting and implementing research are taken up again in stage two, we briefly summarize these insights and related challenges here:

1 *Value conflicts.* — *Insight:* Materials and products that we associate with environmental problems were often introduced as solutions to other problems. Plastic waste problems developed as unintended side effects of earlier solutions (e.g., replacing scarce natural materials with synthetic materials, preventing the spread of infectious diseases in hospitals). A reversal of these solutions may bring back the original problems.

   Challenge: We might not be able to solve all plastic waste problem without making sacrifices with regard to other values (e.g., healthcare concerns). How do we appropriately balance between different values in the development of solutions?

2 *Temporality.* — *Insight:* Some negative side effects were hard to foresee and only became obvious when they started to materialize. However, methodologies to anticipate longer-term consequences of solutions are generally lacking. Instead, there tends to be a strong focus on short-term economic efficiencies and short-term solutions for urgent problems.

   Challenge: We need a process or methodology that allows us to anticipate problematic side effects that might follow from the solutions we develop today. In addition, we need to make sure that short-term solutions to urgent problems do not take us away from solutions that are desirable on the long term.

3 *Governance.* — *Insight:* Interventions were not always based on a careful consideration of what the best point of intervention in a system is and were instead defined by what was in the 'sphere of influence of actors'. Preventing solutions from causing new environmental and social problems requires a systemic approach in which simultaneous interventions are made in multiple parts of a system (e.g., widespread use of PLA has negative environmental consequences if we do not also overhaul waste management infrastructures). However, a systemic approach is rare as actors interacting within the system generally take responsibility for a relatively small part of it. As a result, potentially good solutions lead to negative consequences, because other parts of the broader system are not addressed.

   Challenge: Developing systemic solutions presents us with significant coordination problems. How do we develop the governance capacity required to tackle these?

Step three. The *change points* workshop was held two weeks after the *learning histories* workshop, with some of the 22 participants having joined previously, while for others it was the first workshop. At the beginning of the workshop, the key lessons and guiding principles drawn from the *learning histories* workshop were presented. In addition, updated versions of the timelines, incorporating some of the additions and corrections of the stakeholders, were on display in the workshop space.

During this second workshop which was guided by professional facilitators, participants were again divided into subgroups; three continued to focus on the three topics that were the basis of the original event graphs, and a fourth one with a more regional focus was added, firstly, to account for emerging topical differentiation of one group and, secondly, to allow for the development of projects that could make use of the city as a living lab and keep local stakeholders involved. In line with the prompt to focus on a specific problem within their original topic, all groups narrowed down the scope of their interest.

Step four. The *change points* workshop laid the basis for several project ideas, which we chose to further develop and consolidate through another workshop: a *sandpit* workshop (EPSRC, n.d.), but with abbreviated length and complexity. Thematically, we maintained the

Box 1
Socio-material dynamics that we found useful in generating event graphs.

- **Socio-material dynamic**: a process that is instrumental in producing a notable result. A dynamic involves the interplay between social, cultural, economic, and material factors.
- **Contestation:** events where a proposed or realised practice of one actor is challenged by other actors
- **Market dynamic:** the interplay of demand and supply for finished products and the materials necessary to produce them
- **Mass production economics:** the process of upscaling production of products to exploit the cost advantages of large-scale production, leading to a supply push of the materials and products involved
- **Rules and regulation:** defining explicit formal limits to production and use of products
- **Lead time to market:** the process necessary between the invention and the actual making available of a product/service to users
- **Strategic niche management:** the managed experimentation of new materials, technologies, products and practices with the aim of making them more widely available to users

subgroup structure created previously. Since we again allowed additional participants to join the discussion, many of the now 33 participants brought in new ideas, started new discussions, or repeated previous ones. This was in line with funding suggestions, but contrary to the idea of building shared language (see a discussion on this in the next section).

Ultimately, seven projects were proposed for the second part of RE3 based on the series of workshops; they were broadly related to the three topics and retained or regained some of the original ideas what RE3 could achieve, but were also substantially changed in comparison (see Fig. 3 for a genealogy). One of these projects was later taken forward through other funding sources because of particular project requirements that could not be met within the scope of RE3. An additional project was not originally proposed at the workshop, but called for by project participants and the management board. This project was what would become stage two of our approach. It would cut across all other projects and aimed to ensure that reflections on historical and systemic awareness continued throughout stage two of RE3.

Each project received funding for one or two post-doctoral research associates for durations between 3 and 10 months and all projects promised collaboration across faculties during the research process. Societal partners were suggested as project participants for all projects and engaged to varying degrees for the provision of samples, supply of data, advice on methodology, insights on the implementation context, and as beneficiaries of the proposed solutions.

Step five. We continued our approach throughout stage two with five of the six projects taken forward within RE3. For most workshops we arranged in stage two, only the university-affiliated project team attended, but one group additionally invited external stakeholders, and another group invited further university researchers not originally part of the project. Overall, this led to group sizes between four and twelve participants. The *logic mapping* workshop was held between two and six months after the project start. We prepared a logic map based on our informal conversations with the group and used the workshop to uncover and later question the underlying assumptions of the project. We achieved this by systematically discussing the dependencies, preconditions, and potential conflicts for key elements of the logic map, for which through continued questioning we aimed for participants to make explicit even obvious preconditions and see whether they would be fulfilled.

We furthermore highlighted problems emerging problems reflective of the insights derived from the *learning histories* workshop, specifically focusing on *temporality* through the different stages of the logic map, and *governance* by involving the question of scaling-up and coordination between different actors. Within the workshop, many groups identified feedback loops in the usually linear logic maps, which highlighted that research and implementation activities would need to iteratively change based on specific outcomes in calculations, laboratory trials, sustainability assessments, or the field. Finally, we encouraged the groups to adapt their project to the new insights, such as to liaise with new stakeholders, consider different funding streams, or adding new tasks. For example, one group established in the workshop, that a changed waste management infrastructure would not be possible without any impact on households, ultimately leading the inclusion of field studies with consumers into a consecutive research proposal.

Step six. Similar to the *logic mapping*, we prepared scenarios of potential unintended consequences in advance and thereby decided against advice and common practice that scenarios should be developed by participants (e.g. Bryson et al., 2016), as well as our own intuition that participant-led identification of scenarios would increase their reflective learning experience. However, we made this decision because we wanted to keep the workshop short as in the burgeoning Covid-19 pandemic we were only allowed to conduct online meetings, and people bemoaned too many and too long online meetings.

We prepared a set of four to six scenarios for each project, which were built on (1) concrete plans and often reiterated and scaled up problems that emerged during the *logic mapping*; (2) the dynamics of change that emerged from the *learning histories* workshops; (3) the awareness of the complexity of socio-material practices from the *change points* workshop; and (4) the preparation of qualitative system dynamics models on the basis of the project proposal, insights from the *logic mapping*, and the academic literature from which we identified feedback loops or system archetypes (cf. Senge, 1990) which might lead to unintended consequences. Based on these explorations, we suggest that unintended consequences may either emerge from a misunderstanding of, or uncertain assumptions about actors and their behaviours and practices; or from an inadequate model of the system and its causalities and boundaries. The developed scenarios that may lead to unintended consequences may occur during the implementation, through changes in the targeted system, or even in associated systems.

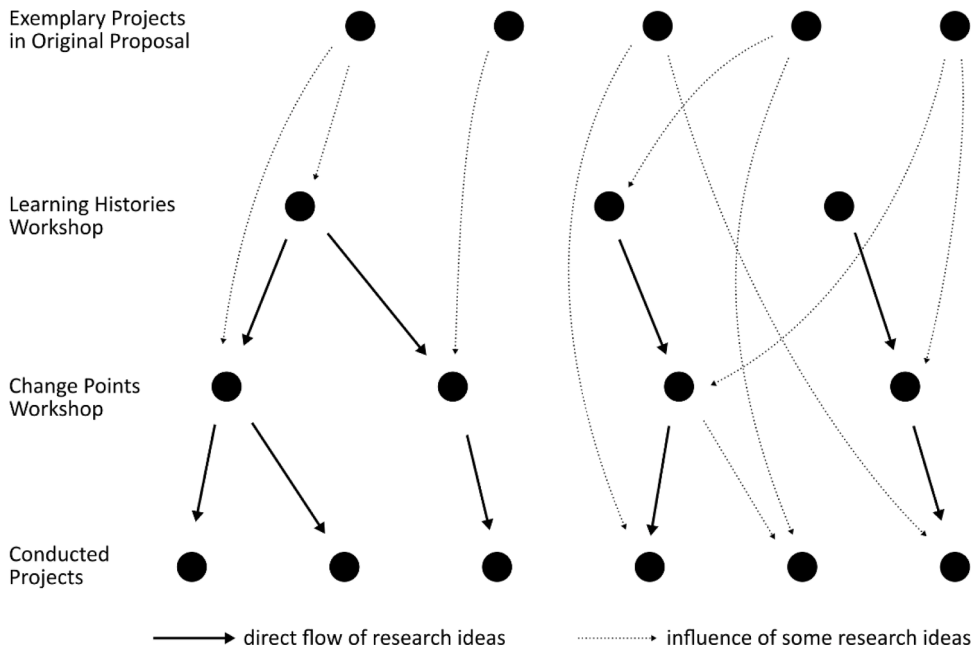

Fig. 3. The flow of ideas for the conducted projects as it emerged throughout the different steps of stage one of our approach.

In the workshops, we then linked these identified types of potentially problematic scenarios to the dynamics already introduced in the timelines (see again Box 1), to the challenges that emerged from the *learning histories* workshop, and to the insights from the *change points* workshop, thereby aiming to increase the recognisability of the problem and stimulate creative solutions. Given these conditions, many scenarios were not new to participants, but the workshop often encouraged them to develop concrete ideas to assess and mitigate the scenarios. The types of scenarios we identified and discussed with the groups were as follows:

1 Regulation or regulatory change required to scale up a specific practice. This mirrored the dynamic of rules and regulations (Box 1) and the challenge of *governance*.
2 Lack of compliance by organisations and possibly individuals/the public. This may lead to failed implementations in the long term and mirrored lessons learnt from the *change points* workshop as well as the challenge of *governance*.
3 Differing or iterative temporalities, such as when certain changes require newly built or readjusted infrastructure, a renewal of long-running waste management contracts, or introduced regulations. This is mirrored the previously identified lead time to market dynamic (Box 1) and the challenge of *temporality*.
4 Uncertainties about the actual research and implementation process in the future, as well as the specific understanding of change. Issues such as differing environmental assessments when scaled up, or a lack of consideration for specific parts of the developed solution often involving people hint at the role of practices, as well as the dynamics of mass production economics and contestation (Box 1) and the challenge of *value conflicts*.
5 Effects in spatially and/or temporally remote systems, for example through upscaling, or replacement of technologies. This may include the decommissioning of waste incineration plants, or long-term effects on waste picking practices or clothing factories in the Global South, which are far from ideal and yet provide livelihoods that may be affected. This relates to mass production economics as well as market dynamics (Box 1) and all three challenges identified in the *learning histories* workshop.

6. Evaluation

Our paper argued for the involvement of historical sensitivity and stakeholders already in the problem scoping phase of RI. In the following we will evaluate based on the previously outlined sources, how our approach of engagement and pointed interaction (1) leverages historical sensitivity and systemic awareness for more responsible and responsive research and innovation activities; (2) subsequently maintains this perspective with continued interventions in projects; and (3) impacts involved researchers' understanding of tackling societal challenges.

6.1. Stage one: creating new perspectives

Most interviewed participants were positive about how the *learning histories* workshop helped to understand unintended consequences of interventions based on historical examples, as well as how the timelines helped to create awareness of the broader historical and systemic context of the topics to be explored in RE3. One external participant expressed that it managed "to put, you know, the whole issue of the use of plastics in healthcare into some context and how it's progressed over the years; that was good" (External participant, #18), while others stated that "I'm totally sold on the concept of like looking backwards as a way to look forwards" (Principal investigator, #05) and that "I think the learning histories sort of method for getting those rich pictures … is really powerful" (Principal investigator, #02). Participants also expressed appreciation for how the *learning histories* workshop helped set up the follow-up workshops by identifying key lessons and challenges associated with the topics. It was in the *learning histories* workshop "where beginnings of project ideas were first formed or planted" (Internal project participant, #20) and many found that the workshop served as a catalyst for identifying necessary changes or ideas for further research. The complexity of the timelines was largely seen positively as a tool to strike conversations and derive insights, but there was criticism towards their incomplete and work-in-progress appearance, the facilitation, and the seemingly unclear aim of the workshop.

The *change points* workshop helped our respondents to further crystallize their ideas and make steps toward project proposals. The structured approach of this workshop was lauded by some respondents as a good tool to spark debates around new topics, with one participant noticing that "I really liked that [structure] because it just gives you a bit of a map. So I actually kept it. … It just serves as an aide-memoire when you're thinking about talking to [collaborators] about an idea that [even] you've got no idea about" (Principal investigator, #10). The structure had helped them to apply a systematic perspective in the development of project proposals by explicitly drawing attention to the broader influences that shape socio-material problems. However, opinions diverged about the professional facilitation, group allocation (some internal participants were put into new groups), and that groups picked one problem in the beginning which "maybe also narrowed things down too much from the outset" (Research associate, #16).

Our respondents saw the *sandpit* workshop as essential for taking the outcomes of the *change points* workshop further, shaping them into concrete proposals, and forming teams to work on the projects. Overall, our respondents indicated that, together, the three workshops helped them to build and germinate their ideas which were rooted in societally relevant problems. However, at the time of the interviews a year after finalising stage one, many participants could not remember clear connections especially between *learning histories* and *change points* workshop, with some participants suggesting that these workshops could have been adjusted better to each other. To bridge this gap, we had reiterated the lessons learnt from former workshop in the latter, but given the feedback, some further conceptual integration would have been useful. Some participants also thought that the *learning histories* workshop did not appear connected to the remainder of the project, possibly because of its different setup and starting points unrelated to potential research.

Furthering the issues of connectivity throughout the process, repeating lessons and building on a shared language was made difficult by changing research teams and the fact that not all participants joined all workshops, which was also a key criticism of some respondents. Some participants in the *learning histories* workshop had seemingly disappeared afterwards, and some participants were only involved in the *sandpit* workshop and had thus missed part of the discussions that led up to the project proposals. This reveals an important tension between the need to involve participants in all steps of the process to build historical sensitivity and systemic awareness, and the design of *sandpit* workshops that emphasizes the possibility for people to join even if they had not previously been involved. It was suggested, that running *change points* and *sandpit* workshops on consecutive days might have helped to alleviate both personnel changes and a loss of momentum. In the second stage, this problem was exacerbated with the recruitment of new research associates and changing responsibilities at partner organisations and stakeholders, so that much shared understanding needed to be rebuilt.

In addition, since the evaluation interviews were conducted at the end of the project, despite verbal and visual prompts it was difficult for our interviewees to recollect their impression of specifics of the workshop design and interconnections: all three workshops were held within a few weeks, two had the same facilitators, and many respondents only joined some but not all of stage one. Documentary traces of the process allow a more nuanced picture of the impact of our approach. Comparing the proposals that were delivered at the end of stage one with the exemplary projects of the original project bid (see again Fig. 3) and the groups' notes from the workshops reveals that insights from and

discussions during the *learning histories* and *change points* workshop influenced the evolution of projects. In these conversations, topics broadened, narrowed, or were refined through interdisciplinary and stakeholder engagement. For example, one research project dealt with recycling of single-use medical devices. This topic was not considered initially in the project proposal but instead was selected through stakeholder engagement, elaborately discussed in workshops, and shaped through ongoing stakeholder engagement. In fact, many PIs thought that they had found new ideas and application areas in the process, such as one PI who without RE3 "would never have been working on [this topic]" (Principal investigator, #10), and another one thought that their first project "emerged entirely out of conversations with stakeholders and our other project … is completely different to what we had initially proposed in the grant application" (Principal investigator, #05).

Based on discussion notes or transcripts of meetings from all steps of our approach, we furthermore note that linkages to past lessons were made occasionally, especially in inter- or transdisciplinary groups and between those who attended most or all workshops. Here, speakers explicitly referred to topical conversations at a previous workshop, while at other times it served as an example to illustrate an argument, or was a reiteration of shared knowledge or insights that had been built in any of the previous steps. This includes the historical dynamics illustrated in the *learning histories* workshop listed in Box 1, the challenges derived from the *learning histories* workshop, or insights from the *change points* workshop, including that previous interventions were not always based on a careful analysis.

6.2. Stage two: retaining perspectives

During stage two, project groups had their day-to-day research activities to perform, so that our support through the *logic mapping* and *scenario thinking* workshop was also in retrospect considered a helpful and relevant support in the project. However, it did not work out for everyone, such as one project lead who was grateful for these workshops in relation to the progress of the project but thought this "didn't succeed with me in the sense that I was too focused and always am too focused on the day-to-day nitty-gritty sort of stuff' (Principal investigator, #10). One external participant considered these two workshops essential to "look at the project in a holistic way and … to bring [in] the learnings from it and … focusing on outcomes and things like that" (External participant, #18). Even more so, it was considered a good way to bring the whole project group together, and to exchange perspectives on specific issues or the research trajectory.

However, reflections on the usefulness of these two workshops varied by project. The applications of these workshops most positively remembered were those two projects where not directly involved researchers were invited. That mirrors an understanding that a diversity of viewpoints and expertises is highly relevant for systemic awareness. In both cases, the *logic mapping,* revealed that the projects had no clear implementation strategy yet, suggesting that any future research was highly dependent on data still to be collected in experiment or field trials, or evaluated once it had been supplied by the external stakeholders. The workshop was also said to make the researchers more aware of the long-term goals of their external partners, thus increasing the contextualisation of the project at large and keeping the systems perspective in sight. One researcher thought that "the conversations that we'd had before that point were more practical day to day, like 'can you send the samples?', … 'where might this fit into your business?' whereas the [workshop] was a bit more global" (Research associate, #14) and was considered to have had an impact on the research trajectory.

In the *scenario thinking* workshop, which was largely evaluated as good and appropriate despite the averse conditions, it was considered useful that some key issues were picked up, some of which had been previously mentioned but not discussed in detail. They were able to spark new discussions, and lead to creative yet meaningful engagements with systemic solutions. The PI of one project reports:

> "[The first scenario] started to get people over this barrier … of saying 'can't do that'. They started to look at the bigger picture of the whole project which then of course came to fruition by the time we got to [another scenario] … that has now led to [a new research proposal]" (Principal investigator, #10).

Interviewees from other groups considered these two final workshops not consistently useful, and the timing of the workshops was mentioned as the key reason for this. This appears to be caused by how the workshop mismatched the dynamics and progress within the project, and were considered to have helped early on in the project to think it through or jumpstart it. Nonetheless, it was acknowledged to bring everyone onto one table and get a different perspective on the project. As problems of stage two, it was remarked that it was not always clear how things could be taken forward from the workshop; furthermore, not everyone wanted to or was able to participate in the workshops, and frequent changes in personnel made the building of shared understandings difficult. Cross-project interaction or collaboration was missed by a few respondents.

6.3. Overall reflections

Overall, however, our approach was evaluated positively by most participants. The most compelling evidence in favour of this is that some established professors considered it worthwhile to continue in two ways: Firstly, stage two of our approach was only conceptualised after project participants asked for further guided, systemic engagement. And secondly, within the funding period, three projects had applied for further funding, highlighting in their respective proposals prominently the stakeholder-engaged, interdisciplinary nature of their responsibly-conducted project; two of these proposals included a version of our methodology and named one of the authors of this paper as a co-investigator.

Statements by most of the involved PIs during the evaluation interviews mirror such rather positive attitude, highlighting that they appreciated this project as a way to do research differently, for example through its approach of inter- and transdisciplinarity, as a structured approach for RI, or as a new means for collaboration. As key learnings, they reported changes that may be understood as increased historical sensitivity and systemic awareness, such as that they had never valued stakeholder engagement as much as they do now; emphasising that university knowledge, experiments, and desk research alone were not sufficient for the complex issues that their project sought to tackle; that they had learnt important skills of collaboration and engagement; and that they learned thinking in systems, flows, and implementations, and not just in laboratory trials and underlying theories. One PI, a professor and highly-cited scholar in their field, highlighted the broadened scope with which they now looked at RI; they mentioned that as a result of RE3 they had not only experienced a systematic way of dealing with RI, but also started questioning other projects as a member of funding panels:

> "… that was a big project and one of the recommendations I've given is to ask the project to go back and outline to me how they … ensure that they have 'no-regrets' solutions. But what I did find out is that they, like me before, don't have a framework of looking at this and they are making major decisions … All you can say is that [RE3] has helped me to, when I look at other projects, to question how they systematically are looking at the process of responsible innovation. … What is their process for making sure that they are looking at this wider issue?" (Principal investigator, #22)

Phrases such as "'no-regrets' solutions" do not only reiterate some of the vocabulary we had used throughout RE3, but also highlight the impact that 18 months of inter- and transdisciplinary engagement and working towards RI can have for world-leading researchers. Insights about the inability to solve systemic issues in monodisciplinary groups were also echoed by others: Another PI and established professor

believed that in their whole career, RE3 was the one project that had changed the way they researched the most. They highlighted that previously they had overestimated the ability of "social things" to sort themselves out and now were very fond of inter- and transdisciplinary collaboration, as "anytime you silo any project, it is inherently limited" (Principal investigator, #05). Similarly, one internal participant with a leading engagement role in their faculty acknowledged that RE3 and the gained systemic awareness made them consider to more often involve social scientists in science and engineering research projects.

Overall, we contend that our approach of building on historical sensitivity and systemic awareness was fundamental to the formulation of research projects, new research groups, in some cases the progress and development of the research project, and for many especially senior participants also formed a new understanding of research not as a monothematic endeavour but as a responsible and responsive process of engagement with diverse experiences and expertises. We believe that for some groups our approach was crucial to not only create a research group and topic, but also to create a lasting shared understanding, references, and vocabulary to discuss innovation and its implementation in a meaningful way. However, for participants as well as for us it is impossible to separate the contributions of our different steps in the aftermath. Improvements in implementing our approach can be made. In stage one, we could made and then have highlighted connections stronger, been more transparent in group formation and participation requirements, and evaluated our approach more synchronously. In the second stage, we could have tried to improve the timing of the workshops, encouraged groups more strongly to invite their external or additional internal stakeholders to our workshops, and increased cross-project exchange.

7. Discussion and conclusion

The RI approach presented and illustrated in this paper seeks to generate increased awareness of the systemic and historical embedding in which the development of new technologies takes place. Regarding our theoretical contribution, we have deepened the understanding of historical sensitivity by highlighting how 'unintended' consequences are produced as the result of socio-material dynamics. Identifying those dynamics in relation to the challenges that a new solution seeks to address helps to generate awareness that informs a more systemically orientated process of RI. It is our methodological contribution to provide a detailed approach, which generates awareness, and then builds on this to create solutions which better fit with value positions articulated by participants.

As the empirical evidence of the application of the approach indicates, it generates two types of changes. First, increased awareness is shown in evaluative statements of most participants, which indicate that the historical and systemic perspective provides insights that are new and unexpected, even when actors have already spent many years as actors in the systems of provision under study, or as researchers working on this topic. Secondly, we observe definite changes in actions. This is most clearly evidenced by participants making substantial changes to the original proposals that describe the development of innovative solutions, with some groups discarding their earlier ideas altogether, while others making significant changes to include the insights gained in the first stage of the approach. This is further evidenced by researchers building on what they learned in developing new research proposals, some of which have now been funded.

The empirical work also shows that the proposed approach does not guarantee positive results. To some extent this is due to the 'normal' dynamics of such processes, where some participants are more receptive than others, especially when they join the approach at a later date. This points to a key lesson: as the approach invites new participants up until the end of stage one, there is a risk in bringing in participants that lack the awareness generated with others. It then depends on which persons are grouped together whether lessons learnt are communicated across the 'old' and 'new' participants. One way to remedy this has been to 'remind' participants about lessons from earlier steps in the approach.

There are two limitations which require attention. First, regarding the evaluation especially of the second stage of our approach, we should note that much of this work was done under adverse conditions, with reduced possibility to have face-to-face interactions. Facilitation of RI requires such interactions, as they enable participants to effectively communicate not only the arguments, but also the emotions that arise when discussing the societal values at stake in developing socio-material solutions, such as for plastics applications. Secondly, while plastics is a material with widespread applications, it still constitutes one (embedded; Yin, 1994) case, and applications to other technologies causing urgent problems are needed to assess more definitively the effectiveness of the approach we have developed.

CRediT author statement

Malte B. Rödl: Formal analysis, Investigation, Data curation, Visualisation, Project administration, Methodology, Writing - original draft, Writing - review & editing

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