Technological Forecasting & Social Change 76 (2009) 1222-1239

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Co-evolutionary scenarios: An application to prospecting futures of the responsible development of nanotechnology

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ARTICLE INFO

Article history:
Received 24 November 2008
Received in revised form 15 July 2009
Accepted 17 July 2009

Keywords:
Co-evolutionary scenarios
Selection environment
Nanotechnology
Responsible development
Anticipatory coordination

ABSTRACT

Potentially breakthrough science and technologies promise applications which may radically affect society. Nanotechnology is no exception, promising many benefits through nano-enabled applications across multiple sectors and with the potential of affecting many parts of our society. At present, during its early stages, a wide variety of actors are anticipating both on the potential benefits and risks of the development of nanotechnologies and their embedment into markets and into society.

Those wishing to coordinate and develop appropriate governance strategies for nanotechnologies need to consider both the wide spectrum of nanotechnology research and development lines, the governance landscape surrounding nanotechnology and the application areas it will affect, and how these may co-evolve with each other.

This paper presents a research project that took the recent activities in and around the notion of *Responsible Research and Innovation* of nanotechnologies as an opportunity to develop support tools for exploring potential co-evolutions of nanotechnology and governance arrangements. This involved the inclusion of pre-engagement analysis of potential co-evolutions in the form of scenarios into interactive workshop activities, with the aim of enabling multi-stakeholder anticipation of the complexities of co-evolution.

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1. Introduction

The path to innovation is journey-like, certainly so for radical innovation. Trodden more often, the activities along the path will become more predictable (as with incremental innovation). Retrospective studies of emerging technology applications/products (from disciplines of Management and Sociology of Innovation) reveal that the journeys twist and turn, are non-linear and recursive and are contingent on a variety of forces and dynamics in the environments the hopeful technology may encounter.

For those wishing to enable beneficial technology applications stemming from potentially breakthrough areas of science and technology, such as nanotechnology, this complexity increases as we shift from retro- to prospective analysis of potential paths to innovation and the journeys that will be taken from idea to technical application well embedded in society.

In the field of nanotechnology these challenges are further compounded due to the early stage of nano developments, where promises proliferate around the benefits and risks that may become reality as nanotechnology matures. It is uncertain what sort of sectors will be impacted (or created) by nanotechnology innovations and how the regulatory, economic and societal landscapes will co-evolve.

Therefore, those wishing to develop strategies for managing nanotechnology emergence not only face the general challenge of prospecting possible pathways for innovation they also are challenged to prospect the changing environments and framing conditions that will determine whether an innovation will move from a hopeful proof-of-principle to a product well embedded in our society.

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doi:10.1016/j.techfore.2009.07.015

1.1. Anticipatory coordination for the responsible development of nanotechnology

These general challenges become very specific in the case of nanoscience and nanotechnology. There is a call for anticipatory governance [1] often phrased as the need for responsible development of nanotechnology or responsible innovation in nanotechnology,[1] where activities are underway to enable those nanotechnologies which would provide benefit whilst constraining those that may cause harm. But the potential breakthrough nature of nanotechnologies as enablers of radically new applications may mean a complex reconfiguration of the environments that a nanotechnology innovation may traverse during its 'lifetime' from concept to well embedded technology in our society. The challenge then is how to be aware of the underlying forces shaping this reconfiguration. Only then can effective strategies be developed to shape the emerging nanotechnology governance arrangement.

Such an emerging reconfiguration of actor relations, their roles and responsibilities is particularly striking in nanotechnology in the diverse activities in and around "Responsible Research and Innovation of Nanotechnology".[2] That is why it became the subject of a research project and workshop within a programme of future-oriented technology analysis (FTA) in a nanotechnology research network called Frontiers.[3] The FTA activities in this network revolve around multi-(potential) stakeholder workshops where the aim is to explore the complex dynamics in and around specific areas of nanotechnology important for the Frontiers Network of Excellence (Frontiers NoE). The objective of the programme was to gain a deeper understanding of issues, perspectives and dynamics in order to develop smarter strategies.

As mentioned elsewhere [2,3] such interactive workshops are not an easy task. The focus topics are complex, uncertain and involve multiple actors working at multiple levels shot through with anticipatory strategies and expectations on risks and benefits of the emerging technology field. This creates a requirement for rich and easy to digest strategic intelligence for which can prepare the ground for interactive workshops on complex and highly uncertain topics such as nanotechnology.

This article focuses on the preparation and content of what we term co-evolutionary scenarios — those which focus on revealing underlying dynamics of co-evolution rather than articulating and placing emphasis on desirable end points. This approach is developed as a support tool for Constructive Technology Assessment (Constructive TA), see Box 1, and incorporates what we call "endogenous futures" into scenarios which take actors' initiatives and interactions into account. The latter is important because this form of scenario confronts participants in multi-stakeholder workshops with choices and dilemmas, allowing for more informed strategy articulation through deepening and broadening the understanding of socio-technical dynamics.

Scenarios have often been used to create a synthesis of future-oriented aspects prior to an interactive workshop, and there are many roles that scenarios can play i.e. offering possible alternative futures to assess and evaluate, or for presenting the playing outs of complex processes. The latter is interesting for us, and requires what Haico te Kulve and Arie Rip have termed "pre-engagement" through socio-technical scenario building [2]. It involves the combination of exploration of dynamics using theoretical models and deep case research [4] into scenario narratives which place emphasis on the "how" paths to the future may unfold whilst reducing (but not removing) the emphasis on the "where" the paths will lead to.

1.2. The why and how of co-evolutionary scenarios

In recent years, governance of new and emerging nanotechnologies has become a highly visible debate, disagreements on efficacy of current governance arrangements proliferate, new alliances have been (or are in the process of being) formed to shape possible new configurations of roles and responsibilities in the development of nanotechnology.

Within this context, a key issue for many potential stakeholders, and most of those that were the subject of this FTA exercise was what sort of stabilised governance structure would emerge or would be desirable: what processes would lead to stabilisation, what options are there, should stabilisation be sought at this time or should exploration under uncertainty continue?

The task of creating open-ended and context-rich scenarios encompasses a trade-off between recognizing the complexity of actual dynamics of innovation and the need to reduce complexity, without falling back on the linear model of innovation. Such scenarios should highlight both the multi-level/multi-actor dynamics and the unfolding innovation journeys of technology development have not been developed to date. Such scenarios require insight into co-evolutionary dynamics, of actor activities (including anticipation in the form of agendas and strategies) and of enabling and constraining factors which shape the direction and pace of the co-evolution.

[1] The phrase 'responsible innovation' refers to innovation activities in which social aspects, desirability and acceptability are taken into account. Innovation actors will be responsive and may be asked by societal actors to account for what they do, and in this way responsible innovation is the responsibility of innovation actors, in interaction with various societal actors.

[2] This term was created by the author for the purposes of the project, encompassing the notions of responsible development, responsible innovation and including the notion that this umbrella term covers research, product development and embedment. Responsible (research &) innovation can be read in two ways: one with an emphasis on *innovation*, which requires some responsibility to be successful/acceptable, or another with an emphasis on *responsible* up to and including halting developments along particular R&D or product lines.

[3] The FP6 funded Network of Excellence Frontiers is a network of 14 European research institutes, which aim to coordinate activities in enabling nanotechnologies for research in the life sciences. The Technology Assessment Programme was part of the Science to Industry work package and the Ethical and Societal Aspect package, and was led by the author.

There is increasing recognition that innovation emergence is a non-linear process, not only in the management and sociology of technology and innovation communities, but also by international and global actors.[4] To capture this non-linearity of innovation processes, the metaphor of the "innovation journey" has been used; it refers to the complex twists and turns in the emergence of a new product [5]. Innovation is non-linear, and characterized by learning processes of actors about artefacts and actants. Elements include the convergence and coupling of emerging technical and organisational elements, forks in to a number of potential paths (especially at early stages although forks can be triggered at later stags), dead-ends, setbacks etc. Other characteristics such as shifts and branches are also linked with the metaphor, and are considered part and parcel of the actor-network that carries the innovation as well as the broader landscape which over-time shifts.

If we accept that paths to innovation is journey-like, for the scenarios we must also recall there may be many potential pathways to innovation [6] and each of the journeys down the pathways could involve forks, setbacks, convergence etc. (the stuff of innovation journeys). However, for breakthrough technologies, the factors that shape the pathways may be evolving too! An example could be the regulatory landscape which would enable certain technology options and constrain others. The arrangements of the industrial sector could also enable and constrain certain technology options. Of course the technology options themselves may shape the landscapes that they encounter — could initiate a change in industrial sectors, in regulation etc.

Nanotechnology, even at this nascent stage, is stimulating a lot of speculation on shifts in these landscapes leading to a desire to explore the potential mutual co-evolution of nanotechnologies and the various environments (industrial, market, society, regulation, research, etc.).[5] To this end it was necessary to create a scenario method which incorporated these relationships and how they may play out in the future.

Co-evolutionary scenarios were developed as a theory-informed approach to capture the complexities of innovation journeys and (co-) evolving environments whilst still allowing the formulation of strategies and concrete steps to take action. The key point here is that novelties do not traverse a static landscape made up of various selection environments (such as regulations, markets, policy etc.), but that this landscape is actively shaped in response to anticipations on development and impact of the novelties. The co-evolutionary scenarios should reflect this, and the discussions and interactions in the workshop will, in a sense, be a further, albeit small, element in the co-evolution of innovation and the surrounding selection landscape.

This is a key aspect of modern FTA-connecting complexities of ongoing innovations (and the conditions which frame the creation and selection of options) with the real issue of developing strategic agendas and plans that will lead to action. Some of the implications (including opportunities) of infusing complexity into FTA practices will be discussed.

2. Prospecting innovation: theory and concepts

Recent thinking about innovation adds up to a general idea that technology emergence is a process of innovation and selection shot through with anticipations (c.f. quasi-evolutionary model [14–16] and sociology of expectations) [9,17,18]. Evolutionary theories of technical changes emphasise that for innovation one should think of variation and selection (and retention of those selections). The outcome can stabilise into paradigms [19] and regimes [20]. Variation (or rather novelty creation) and selection however does not occur at random, actors anticipate on futures and these expectations influence their attempts to shape activities [21]. Recent projects such as Socrobust [11] were an attempt at creating anticipatory management and assessment tools for the analysis and improvement of the societal embedding of innovations. Socrobust emphasised the difference between hot unarticulated, open-ended ("fluid/hot") situations and more structured and well articulated, stable ("cold") situations [22]. So far there has been limited investigation into to the transition from one state to the other: what has been seriously "neglected is the processes of solidification and partial irreversibilisation turning the fluid into the stabilised" [9]. Future scripts [23], which focus on actors' estimates about desired futures, also neglects these processes.

In this section I use three building blocks to construct a framework for prospecting innovation: evolutionary models of technical change; the "innovation chain+", and endogenous futures. This framework which can help in structuring large amounts of heterogeneous data, aid the construction of complexity scenarios, and aid in locating and targeting Constructive TA activities. I begin by exploring evolutionary approaches and what they have to offer.

2.1. Lacunae in evolutionary models of technical change

How do innovations come to be selected from a number of possible options; how do some prevail whilst others diminish? Paradigms, trajectories and expectations offer partial understanding of how *new* technologies emerge, but have not answered these questions, nor have they given insights into the transition from unstable to stable situations. The idea from evolutionary economics of a "selection environment" indicates the part played by economic, institutional and social factors in shaping a technology.

[4] Braun for example describes the early notions of innovation as being "characterised by a 'linear' view of innovation as an automatic spill-over process between basic knowledge and technological application" whilst recent notions regard innovation as being "non-linear and recursive interactions between a variety of actors participating in the quest for innovation". [8].

[5] These environments, which enable and constrain certain technology options, I will call selection environments.

Sociologically inclined innovation scholars have focused on analysing and prospecting innovation/selection activities, studying open-ended situations of emergence, and other topics. Against this background I propose that there is a clear gap in the literature so far regarding the shifting natures of selection environments and how they co-evolve and shift with respect to unfolding innovation journeys.

There is a gap in capturing the shifting natures of the *selection environments* and mechanisms of action [14,16,24,25]. As Rip and Schot noted [8], there is a lack of models that can capture this, with little or no focus on the actual shaping dynamics on the innovation journey in the literature. The authors suggest to acknowledge and embrace these dynamics of selection environments but go no further.

Green et al. [16] in their comparison of the techno-economic networks (micro-level analysis stemming from sociology) and techno-economic paradigms (macro-level analysis stemming from evolutionary economics similar to Nelson & Winters natural trajectories) critique both analyses for missing the interplay between both. They suggest the quasi-evolutionary approach citing that Constructive TA could act as a middle point.

Robinson and Propp made a first step through exploring path dynamics [6]. They developed a multi-path mapping approach which would combine path dynamics [26–28] with the sociology of expectations [29] to prospect micro-level innovation chains. They acknowledged the concentric bias of the enactor perspective (technology developers and promoters who project a linear path from their technology option into the future described in Box 1) and attempted to broaden this concentric bias by taking into consideration open-ended nature of their projections and structured explorations of the journey-like nature of actual emergence.

In this project on RRI we add a further conceptualization using the idea of arenas of innovation and selection, with their (evolving) practices and rules. To show continuity with the earlier work, we have sometimes called it "innovation chain plus (IC+)", but it is actually a mosaic of arenas through which innovations traverse (including anticipation on further selections). The advantage of this conceptualization is that it allows selection environments and framing conditions to be an explicit part of the mapping.

2.2. Innovation-Chain+: a mosaic of arenas for innovation and selection

At the time of the Constructive TA project, a method of combining ideas of innovation journeys amidst evolving landscapes (co-evolution of innovation/selection processes and framing conditions) was not available but was crucial in order to get close to the real issues being explored through the CTA. Building of the notions and gaps given above, the Innovation-Chain+ model was developed.[6]

Whilst every innovation has its journey, it is dependent on the techno-institutional landscape. This landscape will have different characteristics at different stages of technology/product emergence and is shaped by broader framing conditions and by anticipatory coordination on the part of technology developers and promoters, as well as those who seek to control and select options. With this in mind, I propose the Innovation-Chain+ framework as a way of presenting this situation. It allows the positioning of the complexities inherent to the reality of innovations, paths and landscapes, whilst allowing the link to the linear model (reducing complexity to achieve outcomes).

It is complementary to the widely used value chain approach, which focuses on stabilised chains of product development. The Innovation-Chain+ is designed for new product creation and thus is useful for locating and framing shifts within certain areas of the chain, in the framing conditions (see coordinating mechanisms) or the whole system, the latter being typical for potentially radical and breakthrough innovations).

Detailing in brief, in this visualization an innovation "traverses" a complex mosaic of arenas of innovation and selection which are affected by broader aspects. Within this mosaic certain technology options are enabled whilst others are constrained. The arenas for innovation and selection are shown here as bubbles where each arena represents a particular socio-technical configuration carrying and being carried by the technical option traversing it. These configurations are entanglements (sometimes regular networks) of many actors, interacting based on regimes of activities.

Thus the innovation journey (represented in Fig. 1 as a branching line) is made up of a path to innovation (a pathway represented by the bubbles in the centre of Fig. 1) where the emerging technology itself which journeys through these bubbles.[7] The technology (and its socio-technical network) shifts and reconfigures based on the arenas it encounters, which themselves are influenced. This model is a complex mix of perspectives, and is a combination of technology studies, innovation and management studies, and path dynamics which adds up to a mosaic of arenas, or game-boards, broadening (although not removing) the linear perspective of chains.

Unlike the linear model, the emergence of an innovation is not pre-determined, it is more reactive and responsive and "journey"-like, hence the van de Ven metaphor is very useful here.[8] The IC+ diagram broadens the value chain model but does not show details of the socio-technical networks. This is a reduction of complexity. However it is important to remember these are backgrounded in the IC+ representation (not removed).

[6] We add the "+" to indicate the broader framing conditions. Robinson and Propp [6] used the innovation chain concept in the context of path dynamics.

[7] Here I make a distinction. Technical innovation is more than a box or device made up of material components and is part of a socio-technical network of actors, artifacts and infrastructures which evolve with the innovation. This reads like actor-network theory (Callon et al on TEN) and so innovation itself is an outcome of alignment and configuration of actors, artifacts and infrastructures. In line with Innovation-Chain+ nomenclature, one could call this Innovation+.

[8] Still the focus of technology developers in their FTA activities, focus on paths (such as roadmapping) rather than journeys. Robinson and Propp expand this path perspective to a multi-path one. In this paper, we shift discussions to the journeys themselves and the arenas that will shape and be shaped by the journeys.

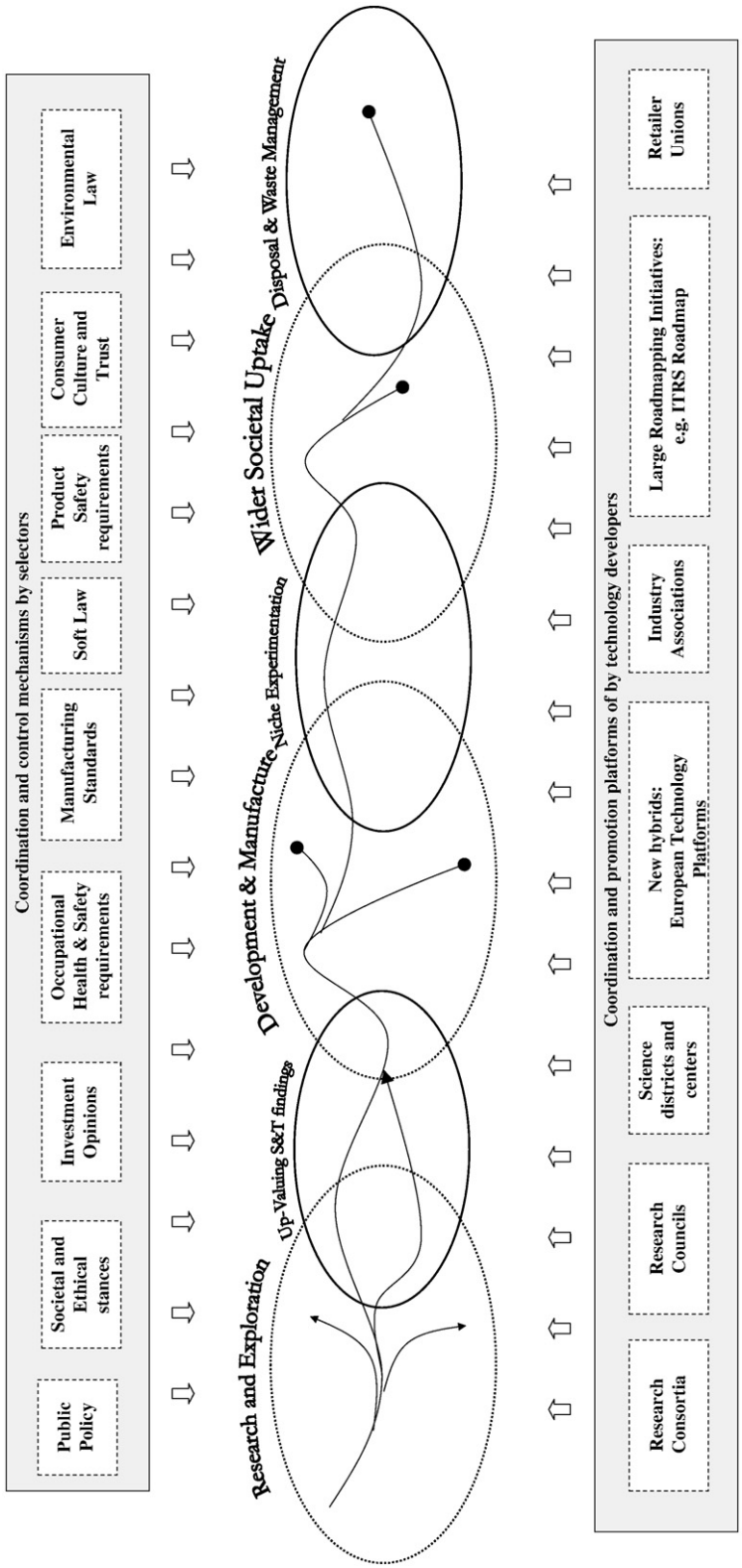

Fig. 1. Innovation-Chain+ as a mosaic of co-evolving arenas of innovation and selection with innovation journeys showing coupling, shifting, dead-ends etc.

For structuring the co-evolutionary scenario narratives, the IC+ provides a "game board" for locating emerging technologies and evolving arenas and thus a way of framing our scenarios. The next step is to introduce evolution over-time, so as to address the other main gap in the literature: how does eventual stabilization occur? For controlling our speculations of actions and co-evolutions of technologies and the IC+ we need some indications of how paths-to-innovation may emerge and how the IC+ may evolve. Paths to the future do not fall out of the sky, they are based on the dynamics of the present: there are endogenous futures embedded in the present which can give indications and insights into the transition from present into future.

2.3. Endogenous futures

While new (emerging) science and technology introduce novelties, and thus potentially breaking up existing orders to some extent, subsequent developments create new patterns that may lead to stable situations. As mentioned in brief earlier in this section, emerging irreversibilities facilitate specific technological paths–making it easier to act and interact–whilst constraining others–making it more difficult to do something else. Emerging irreversibilities can manifest in a number of forms. Entanglements such as sunk investments (and the anticipations on which investments are based) and industry standards are some examples. Emerging irreversibilities are a general feature of social life, and the sociological concept of "institutionalization" captures a large part of what happens. When technology is involved, irreversibilities are further solidified in configurations that work [30]. The concept of "configuration that works" applies to artefacts and systems, and includes (in principle) social linkages and alignments as well.

Another aspect of endogenous futures is linked with anticipation of actors. Expectations can give indications of directions and can transform into agendas which shape action (this is emphasized in the quasi-evolutionary model mentioned earlier). Van Merkerk and Robinson [9] show examples from the field of lab-on-a-chip technology and how expectations have an effect on selection choices of pathways to follow, enabling some options and constraining others. This can occur also at through anticipatory coordination.[9] Studies also show how expectations can prestructure actions through prospective structures [21].

Paths and other stable patterns enabling and constraining actions and views, will shape further development. Thus, they span up an "endogenous future". The idea of "endogenous future" is midway between attempts at prediction (which are always precarious) and the suggestion that everything is still possible (and it is just a matter of actors deciding on what they want to work towards). Further developments are predicated on the pattern of the present situation. Not in a deterministic way: there are always choices and contingencies.

It is here that analysis comes in: of evolving patterns, of dynamics extending into the future, including irreversibilities that arise. This is the task of scenario builder.

Coupling endogenous futures with characteristics of innovation journeys (from historical case studies) within the framework of the IC+ framework helps us structure the complexities and control our speculation in order to make effective and high quality scenarios. The following section will bring us away from conceptual explorations to the real-world of FTA and creating scenarios for a CTA exercise.

3. Evolving selection environments, and their internalisation

3.1. A project is initiated

In Autumn 2007 (as still the case 2 years on) there was an increasing emphasis on societal impact and embedment of nanotechnology applications. Ideas of responsible development of nanotechnology have been in circulation for a while now, but by the end of 2007 they were solidifying into policy and regulation. Thus, there was an occasion to launch a technology assessment exercise, with the aim of bringing together actual and potential players involved in nanotechnology governance to share perspectives, explore possibilities and draw out some recommendations to guide both the Nanotechnology R&D network (Frontiers) who initiated the project as others exploring potential governance approaches.

As part of the project within Frontiers, I carried out case research into the field, analysed the recent history and current situation and developed three co-evolutionary scenarios showing plausible playings out of technology innovations and how they emerged and co-evolved with shifting regulatory, economic, societal landscapes. These provided input into a day-long multi-stakeholder interactive workshop where the complex interactions of potential governance arrangements and stakeholder strategies were explored.

At the time of the workshop (December 2007) the situation in and around nanotechnology involved mostly the discussion of Environment, Health and Safety aspects (EHS/HES) and other nanotoxicity related discussions, in addition, a call for standards in definitions. Actors such as governmental agencies, industry and NGOs were increasingly held accountable for addressing societal concerns, feeling pressures to incorporate ELSA and HES into their ongoing activities (similarly with corporate social responsibility). Thus, at the time, there was something at stake for these actors and a willingness to participate in discussions and workshops on the nano governance issue.

[9] For example the nanoelectronics industry coordination efforts described in [34] which would lie in the coordinating bodies box of the IC+ diagram. Also [35] describe nanodistricts and the role of technology platforms which came about through institutional entrepreneurship between the framing conditions, the bubbles and the coordinating bodies.

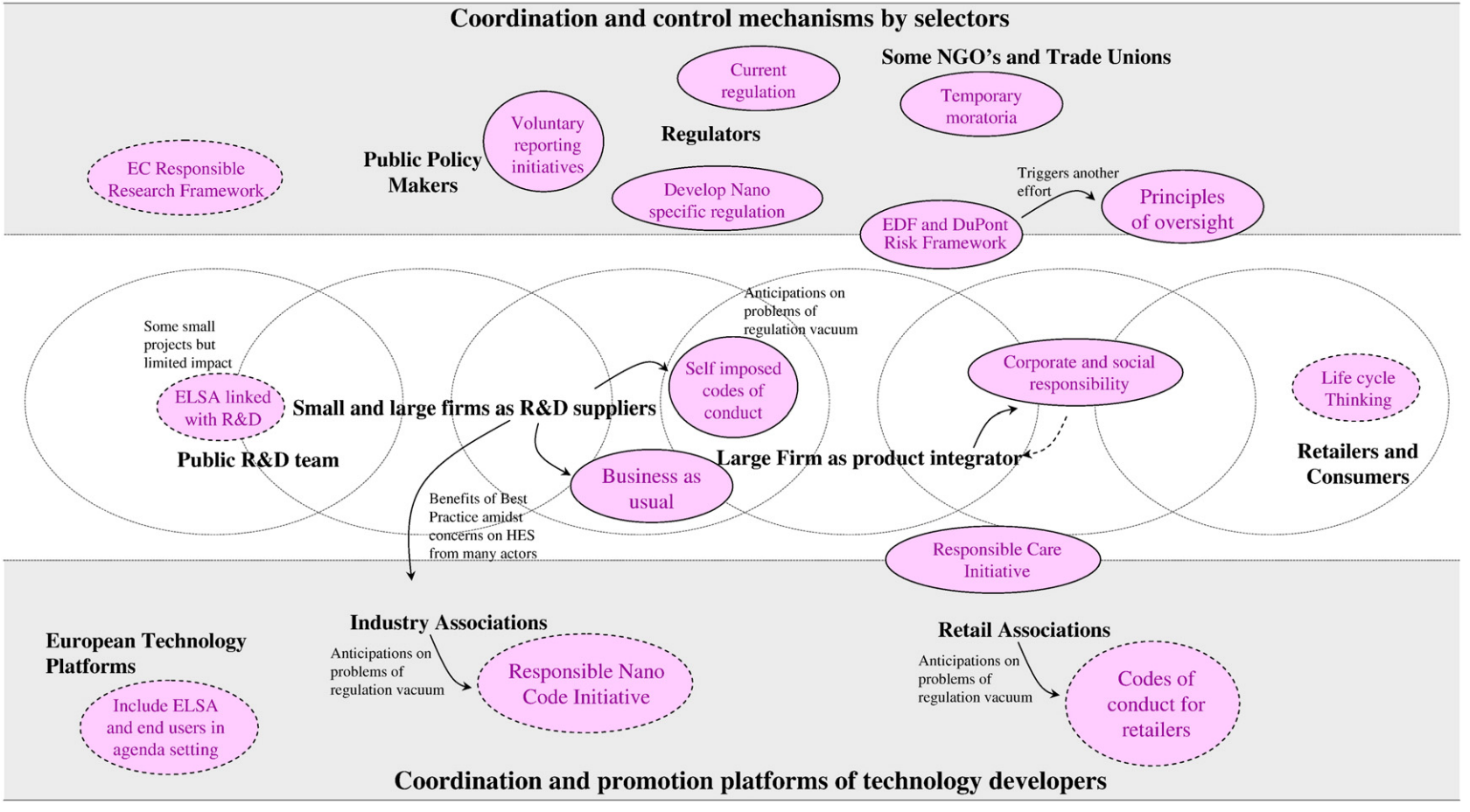

Fig. 2. Here I position (in the IC+ framework) the actors that were active at the time of the workshop and RRI elements that were visible. The key question in this Constructive TA exercise: how will these elements add up and shape innovation and selection processes?

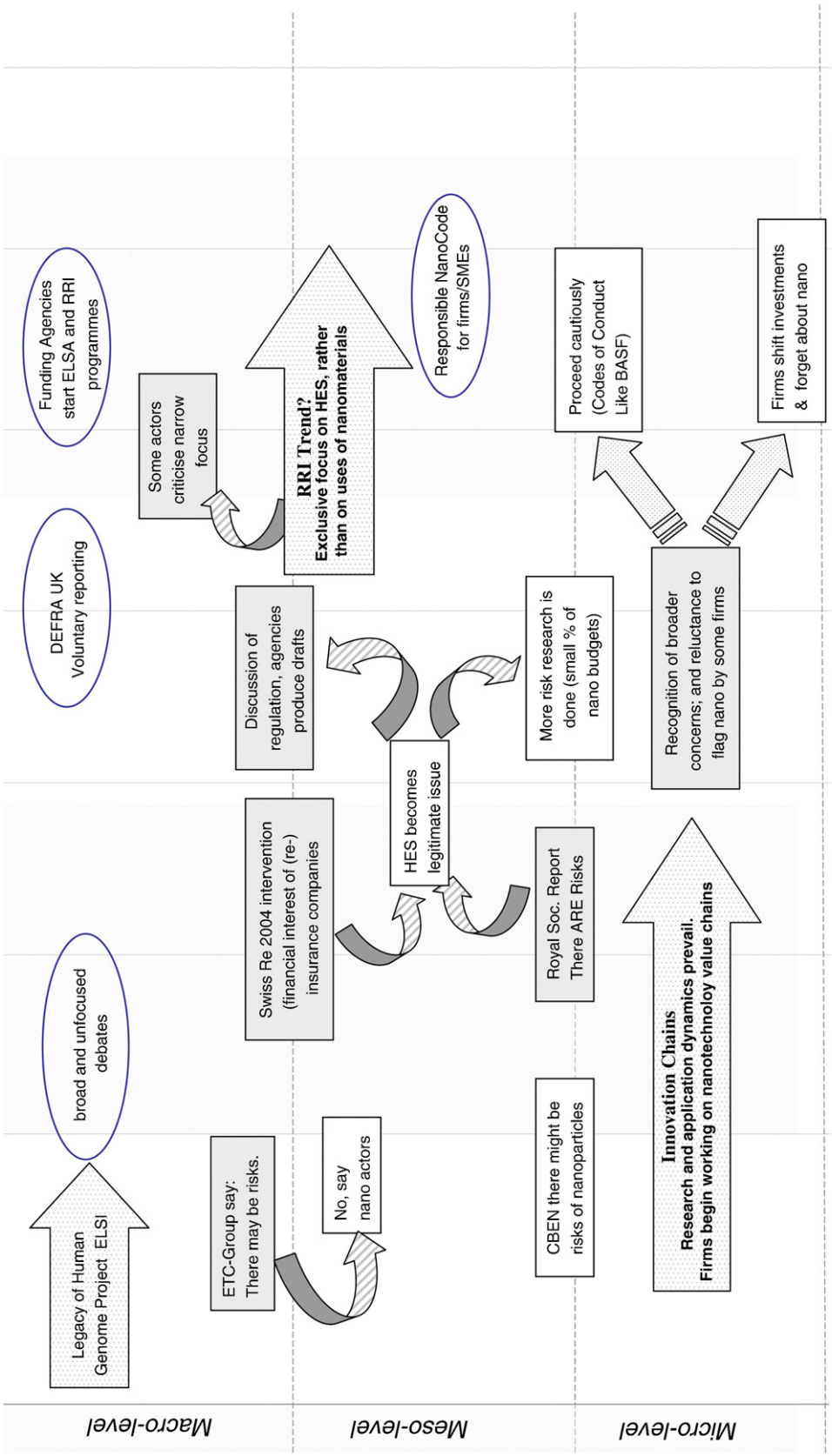

Fig. 3. Evolution of governance, 2000–2008.

Box 1
The Constructive Technology Assessment goal of reflexivity rather than prediction.

For early stage and highly uncertain fields of technology development, prediction is a tough task. Another approach would be to shift the focus of strategy articulation away from relying on prediction in its strictest sense, and stimulate a process of reflexive anticipation through controlled speculation based on exploring the underlying dynamics of emergence. Constructive Technology Assessment (Constructive TA) [6–10] as a reflexive strategy articulation support system taking as its starting point ongoing socio-technical dynamics is particularly suitable for such a purpose.

The creation of visions of possible futures in Constructive TA is based on analysis rather than brainstorming. This is possible because there are emerging irreversibilities in ongoing socio-technical developments, based on shared agendas, mutual dependencies and network ties — there is an "endogenous future" [11]. While actors will always take enabling and constraining factors in the situation into account, Constructive TA adds to this because of a broader & deeper understanding of socio-technical dynamics.

In the case of the Frontiers NoE for nanotechnology, the programme involved research and preparation of these scenarios an input to 1-day multi-stakeholder workshops, where the complexities of the case, as well as the exploration of positions, stances and perspectives of the stakeholders, where probed and explored.

The interaction of the participants with the scenarios and each other are important aspects of the Constructive TA. Different types of participant have different assessment routines and practices, and one must acknowledge these bring them out in the scenarios and create opportunities to become more reflexive of how the different participant groups make assessments. Garud and Ahlstrom [12] describe two perspectives of such technology assessment, those of technology developers and promoters they term "insiders" (that focus on innovation through enactment cycles) and "outsiders" (who focus on comparing and selecting options through selection cycles). This has been developed further by Rip [13] and colleagues into a way of framing various ways of assessing technical novelty and its development. Rip and Garud et al. speak of bridging events, where real learning occurs when insiders and outsiders meet and probe each other's assessment worlds. The bridging events can occur in an ad-hoc way, or could be orchestrated — the method put forward in the Constructive TA within Frontiers.

In this way, Constructive TA is an instance of the general shift in management (and tailored foresight) away from prediction towards reflexive anticipation and strategy making. If van de Ven's comment is true "Management can't control innovation success, only its odds" [5] then this implies a shift from deterministic approaches to foresight and strategy towards the creation of circumstances and conditions which enhance the chance of success. Good preparation and anticipation of possible problems in the innovation journey increase these chances of success. [12]

To this end, Constructive TA develops endogenous futures into scenarios which not only take actors' initiatives and interactions into account but also the surrounding or ensuing dynamics and shifts in agendas that slowly become irreversible. Scenarios are not used anymore to extrapolate particular developments into the future but rather, to enhance the reflexivity of actors regarding strategic decisions which can modulate these developments, and larger lock-ins (irreversibilities) which constrain such actions and impact on unforeseen or sub-optimal trajectories of socio-technical developments. This reflexivity allows for a trying out of different possible paths, and this actor learning is captured in the term "complexity". This learning links up with the complexity of evolving (governance and other) environments. Working with such scenarios in strategy-articulation workshops is a means of testing the scenarios while probing and modulating participants' worldviews.

It is not in the scope of this paper to detail the case history of the emergence of RRI for nanotechnology, but to highlight some of the key aspects which informed the scenarios. For a detailed account of the developments of the nano risk debate and the key elements of RRI see van Amerom and Rip [35] and Kearnes and Rip [36].

By the end of 2007 a large number of soft law proposals were on the table, including codes of conduct for nanotechnology, some prepared by authorities like the European Commission, others offered by one or another firm, or proposed by a consortium. The proposed codes of conduct were the tip of an iceberg of a larger movement towards responsible innovation, increased political and public scrutiny, and the need to explore and develop recommendations for what one could call good nano-practice.

At the same time, researchers (for example in the Frontiers NoE) and other actors in and around the nano-world were becoming concerned about hype and bubbles bursting, about pressures towards valorisation of research as well as lack of uptake in sectors that could profit from the possibilities offered by nanoscience and nanotechnology. There was a widely recognised uncertainty about the potential impacts and risks, whilst in the meantime proposals for regulation were being formulated and various NGOs were taking positions, often advocating a precautionary approach (cf. Principles of Oversight) up to a moratorium (cf. ETC-Group and others). And there was additional uncertainty about consumer and citizen reactions to new nanotechnology-enabled products and processes — fears of a public backlash and of barriers to public acceptance.

Box 2
Scenario 1 summary.

The nano umbrella term becomes more specific (in funding mechanisms) — now defined in terms of potential sectors that will be impacted by R&D lines. In turn, potential consumers (and other impactees) can now be identified (the general public translates to specific publics) and technology developers begin to start anticipating on societal acceptance of products.
Proliferation of engagement/communication approaches at the micro-level allows justification of "societal awareness" as a strategy for ensuring "societal acceptance". Concerns are voiced by media, by civil society on effects on Food, Lifestyle, Health, Privacy and Human rights — an outcome of the increased specificity of nano. At the micro-level these broad discussion are termed as "a separate issue for longer term speculation".
Ad-hoc public engagement exercises act as a lubricant to continue nanotechnology developments across the board. However, one project in particular captures people's attention, named "NanoDiaBlog" — it is created as a web-based discussion forum (based on a Wikipedia model transparency is enhanced). Over time, the NanoDiaBlog project actually fulfils the promise made by its initiators (much to their surprise) as creating an informed general public, in addition it forms a community of scrutiny and debate, both positive and critical. Although not an official body, the NanoDiaBlog community is deemed a high quality indicator of the populace (in any case the populace who takes an interest) and principles such as precaution, inclusiveness (transparency), integrity (protection for whistle blowers), ongoing assessment (constant vigilance), and the need to interface promoters and selectors, arrive on governmental agendas. Thus perfunctory public engagement exercises have the unintended outcome of creating a sustainable forum for engagement and action.
Taking advantage of this, a firm developing food-packaging sensors uses the blog to collect data on user preferences allowing targeting strategies. One outcome is with Radio-Frequency Identity Devices (RFID) tracking of goods through food packaging contains labels, similar to health risk labelling with the privacy risk label "This product is system tracked" placed on food packaging (a response to bloggers' insistence on transparency). Acceptance of the label was initially turbulent but general agreement of labelling and the "right to choose" (the label could be peeled off and so no further tacking possible) enabled wider uptake.

3.2. The scope of the workshop and the nano context at the time

From the situation outlined in Section 3.1, responsible (research &) innovation can be read in two ways. One with an emphasis on innovation, which requires some responsibility to be successful/acceptable, or another with an emphasis on responsible up to and including halting developments along particular R&D lines. Fig. 2 takes Fig. 1 and shows some of the activities in terms of coordination, promotion and control. This shows the status of the IC+ game board at the time of the workshop and was the starting point for the development of realistically complex scenarios.

Emerging paths and patterns that shape (enable and constrain) the future are particularly visible in the coupled evolution of research, production and use of nanoparticles and the consideration of risks of nanotechnology.[10] Fig. 3 visualizes this (up to 2008). We can see the importance of "new actors" in the shaping of emerging governance patterns and industry structure, of NGOs such as the ETC-Group, and of re-insurance companies shaping the emerging path of RRI. Dynamics are visible at all three levels, although there is little alignment yet. The repeated occurrences and acceptance of acronyms such as ELSA (Ethical, Legal, Social Aspects) and HES (Health, Environmental, Safety) in discourse on, and governance of, nanotechnology research and in the mobilisation of funding, indicates emerging alignment between societal concerns & allocation of resources.

There is an opening for consideration of soft law due to actors (firms in the main) anticipating (and thus proceeding with caution). Also, regulators recognise that there are openings but are unclear on how to target nano broadly beyond the current focus on nanoparticles. Firms are reluctant to start reporting–the DEFRA voluntary reporting initiative was mentioned as having limitations–but there are also voluntary initiatives in the pipeline and new ways of managing them e.g. the Risk Framework for Nanotechnology put forward by the unusual alliance of DuPont and Environmental Defence.

Irreversibilities are visible already. There is a lock in around RRI in the focus on HES issues. This would have consequences for other elements as resources are shifted away from them (path dynamics). Engagement with various publics is on the agenda (UK government initiatives, and elsewhere) but have been ad-hoc and mainly centred around technology developer outreach programmes. Also, there is something like a regulation void, and commentators have suggested that the soft law initiatives and voluntary codes occur exactly because of this void. Others (like the Commission of the European Communities) argue that there is no real void, because existing law and regulation is sufficient, at least for the time being. Thus codes are on the agenda, although there is anticipation that proliferation of codes of conduct and other forms of soft law, may remove the pressure to develop regulation.

[10] I have placed innovation journeys at the micro-level, technology developer coordination attempts at the meso-level and selector coordination and control at the macro-level. This is for ease of showing linkages and emerging entanglements across levels. Conceptual development of this multi-level perspective has been explored elsewhere [2].

Box 3
Scenario 2 summary.

Drug delivery becomes a key driver in nanotechnology. Rapid developments in nano means the consequent burgeoning number of delivery methods leads to increasingly bewildering regulatory protocols. Anticipation on further regulatory delays sees shift in private investments from nano to other promising technologies. NGOs, concerned about 2nd generation effects of nanoparticles argued for a moratorium on nanoparticles for medical purposes until toxicity tests tailored for these particles would be done.

In reaction to these concerns Dr. Würzel (a researcher on nano therapies) argues on the ZDF TV news show that successes have outweighed the fatalities: "Fatalities occur all the time! My staff is combating a serious disease which causes hundreds of thousands of deaths per year in Europe alone. It would be unethical to stop clinical trials for a drug that works better than others." The following Spring, as a response to the prior press coverage and the ZDF news item, many patients with lung cancer go to the lab. As ever more patients converge on his lab, coverage shifts towards headlines like "From battling disease to battling the health authorities": regulatory authorities become the enemy, obstacles to patient therapy. In the meantime, for the health authorities, the issue of proper clinical trials became an ever-increasing issue.

Lack of lifecycle thinking in nanoparticles and engineered tissue causes real concerns by both environmental agencies (the former) and clinicians (the latter). Production, storage and distribution in both the manufacture of nanoparticle based therapeutics and use in the clinics is an ongoing concern, as well as quality control of nanoparticles and bioaccumulation uncertainties (particularly in liver, spleen and bone marrow).

Public funding agencies form a blanket ban on financing nanoparticulate delivery systems. Private sector continues, voluntary reporting prevails but confidentiality of development hampers transparency (issues of competition) and thus watchdogs find it difficult to access data to assess practices. SME's, already severely hampered by lack of public financing (linked with university ties) can't cope on own with voluntary regulations, bypass it (for purposes of survival).

By 2012, health care authorities would not certify the approach without clinical testing. This leads to precaution by health insurance companies to cover the procedure. The further effect is that this medical option becomes available only to those who can obtain it in another way through private clinics.

These elements provide building blocks to create three scenarios each of them a plausible story about how they might play out (including twists and turns). In the next section I show one of the scenarios, which focuses on evolving governance mixes. The other two scenarios focused on engagement and actor strategies, and on hype and mobilizing resources (promise requirement dynamics).

4. Summary of the scenarios

Taking Fig. 2 as the game board, identification of some of the endogenous futures[11], three co-evolutionary scenarios where created and fed into a Constructive TA workshop. The scenarios hang together with many elements being interchangeable. They do their job by emphasising tensions occurring in the Innovation-Chain+ frame and place into context possible playings out, based on expectations and path dependencies that are crystallising out of the present (endogenous futures). They not only provide a platform for positioning the tensions, but also the perspectives (shown in Figs. 2 and 3) which allow for location of actual selection forces and mechanisms of action. This is important, especially in this workshop due to the focus on governance. What mechanisms should be modulated or augmented? Can we include forms of anticipatory actions or FTA mechanisms that are reflexive of the wider complexities of new and emerging technologies? Who should be involved and when?

Contrary to many traditional scenario building techniques, these co-evolutionary scenarios do not present mutually exclusive futures. In this way they are similar to the functions of expectations — the scenarios can be read and discussed as anticipations (1st order learning), but they also have a performative function in that they can lead to 2nd order learning on how to build more context-fitting scenarios.

Below I summarise the three scenarios developed for and in the workshop in the form of key threads and storylines. For reasons of space only one example (scenario 3) is given in full in Section 5. The example helps to illustrate elements such as "paths" and "endogenous futures".

4.1. The three scenarios

At the time of the workshop, in general most public engagement activities initiated by R&D actors focused more on enlightening the general public on the potentials of nanotech R&D-engagement as a lubricant against public friction. Stirling [31]

[11] This was done through interviews and case analysis to find expectations of various actor groups and entanglements between groups and particular elements of RRI.

Box 4
Scenario 3 summary.

By mid 2008 the patchwork of codes of conduct, best practices and measures of responsible innovation remains misaligned, but allows progress in technology development through self-regulation and self quality control. The codes are particularly enabling for medical devices, providing some guidelines for nano alongside existing regulation of medical devices and so self-regulation of new nano-enabling components can continue.

A case of focused alignment of R&D agendas in national initiatives can be seen. One example, Finland begins to invest in nanotechnology for paper processing (a major contributor to the Finnish economy). The specificity of the case related to opportunities to cut costs, reduce use of chemicals and improve manufacture. The lack of standards helps this growth and large investments are made leading to positive gains.

Early engagement exercises and high profile projects such as Nano Jury UK and others lead to the inclusion of "engagement programmes" in technology R&D programmes to inform and communicate the benefits of nanotechnology. There is a proliferation of such projects across (and initiated by) the nano R&D domain focussing on enabling public acceptance. Although no linkages between the projects occurs there the ethical and risk debate, begins to separate to "real issues" (of health, environmental and safety issues of nano production) and speculation on broader ethical debates around Human Enhancement, Justice, and theological issues.

Monitoring signatory compliance becomes a major issue. Code initiators attempt annual monitoring through direct contact to signatories, by asking them to volunteer time to report. Comparative and systematic methods do not exist. There is a lack of watchdogs; self-regulation and voluntary reporting go unchecked. The Precautionary Principle is promoted within codes but framed by self-assessment mechanisms (degree of precaution unclear). Innovation actor's quality not assured. Voluntary codes align best practice but have little effect on worst practice due to regime of patchwork of codes (so good become better, worst remain worst).

Gaps in regulation widen as nanotechnologies become increasingly more complex — existing laws which could be applied to products (medical devices) are less equipped to oversee products and processes such as active nanostructures which cross many sectors and can be applied in many settings.

The accident with the Finnish worker opens up nano governance once again and a number of lines of R&D grind to a halt pending further investigation. Those wishing to exact change are faced with an entangled web of best practices, codes with varying degrees of transparency in how they are acted upon.

By 2014 the proliferation of nano and its increasing complexity hits home when consumer organisations try to target concerns, no inroads. Liability becomes the issue. When problems begin to occur with certain products secondary effects, lack of regulation means it's difficult to find who is liable. Public remains skeptical, voicing failures such as "lack of transparency" and "unclear accountability".

Governmental watchdogs begin to emerge and the clamour to catch up leads to numerous temporary moratoria. Regulatory actions retroactively cover all Nanomaterials and products on the market become identified and recalled pending certification.

identified three motivations for engagement which I adapt slightly below: (1) Instrumental motivations — legitimising R&D activities as a policy to ensure that technology is not held back by public skepticism; (2) Normative motivations — participation is a good thing in itself; (3) Substantive motivations — can lead to a better end product [32]. The scenario in Box 2 revolves around these three meanings and links them up with overall strategies in motivations for engagement around nanotechnology.[12] The scenario focused on the engagement aspects of RRI, the roles of various actor groups, the strategies and how the interactions played out.

The scenario in Box 3 looks at a specific cluster of innovations in nanoparticle based drug delivery. Tensions in this scenario include the issues of timeliness of engagement — when to incorporate actors? Early stage technologies are fragile and too early selection may inhibit novel solutions. The same for regulation-nanocodes enable in this scenario but the lack of regulation and eventual loss of the support of public organisations means limited access to the novel therapy. Again it describes actor strategies and the eventual entanglement of actors and the RRI elements to allow certain paths and inhibit others. In this case a technology

[12] NanoDiaBlog crosses all three motivations for engagement. The normative motivation is set down in the EU Action plan and leads to instrumentalist approaches being used when engagement is operationalised for R&D activities. This approach to engagement stems from an anticipation by nanotech developers of public friction, which leads to enlightenment and legitimisation strategies. NanoDiaBlog provides a space for other actors to shape the context from instrumental to constructive criticism (whistle blowers have a space to proclaim and civil society to discuss and mobilise opinion). One technology entrepreneur uses the NanoDiaBlog with a substantive motivation for engagement — to improve the product. Using the space to probe concerns, he incorporated the option of peel off RFID labels to empower the consumer with "the right to choose".

option emerges but is only available for a limited number of people. It integrates elements of hype cycles, roles and responsibilities of researchers and the issues around risk of nanoparticles.

The scenario in Box 4 will be shown in more detail in Section 5.

4.2. The effect of these scenarios in the workshop

The three scenarios together covered the various positions and expectations of those actors active in the debate around RRI. The day-long workshop was comprised of a number nanotechnology researchers, a ministry of health representative, a large chemical company, a trade union representative, a nanotechnology industry association, researchers interested in NGO activities, and a number of technology assessment scholars.

The elements and actors were recognised by the participants, with praise about the plausibility of such scenarios. Analysing the scenarios in depth in the workshop was not part of the exercise, but the participants were asked which elements they found the most striking or important. These provided the basis for the discussions in the workshop which covered locating the responsibility of risk evaluation in the value chain, the ethics of promising (by researchers and firms), the ethics of engagement (not incorporated in the scenarios but stemming from the discussions) where including NGOS and civil society in research agenda setting causes tensions for the R&D agents (who work in an open-ended manner, shifting and adapting their agendas — where if they agree societally desirable end points, their open-endedness is reduced somewhat).

The co-evolution of regulatory approaches and technology options was also discussed throughout the workshop, although not directly quoted in the discussions, the co-evolutions described in all three scenarios where picked up and discussed.

What was important in such a multi-stakeholder setting, was the inclusion of all active actors in the scenarios. This meant that for certain actor strategies, say a firm or ministry, they could refer to scenario elements and discuss around these, allowing an easier route to some of the key issues.

A full analysis of the workshop interactions will be given elsewhere. [33] In the following section I will give a full scenario (Scenario 3) with annotations showing the key elements in the narrative. I will then in Section 6 discuss the technique and how it fits into the emerging menu of socio-technical scenarios.

5. An annotated scenario

Below is shown a full scenario. It is difficult to find the best way of annotating the text. Here I insert the comments within the narrative. This makes for difficult reading, but reveals the various elements of the scenarios as they appear. The annotations are given within the scenario text, after the relevant section of the narrative, in square brackets and in italic. At the beginning of an annotation, an indication of the type of dynamic involved in the scenario text is given, emphasized by underlining the comment.

By mid 2008 the regulation void continues and soft law is taken as an interim solution to allow nano to go ahead *[Observed misalignment: there is no new nano specific regulation so soft law is taken as a solution. This was one vision of the future proposed by a number of codes of conduct tabled in the December 2007 EU meeting. Unresolved tension: this element linked up with the difference between two regulation reviews in the UK during 2006. HSE executive saying current regulation was enough. DEFRA saying there are gaps [37].].* Industrial consortia and research networks develop agreed best practices, which are self-imposed and a number of codes emerge and are agreed to [Coordination of governance stemming from technology promoters — see Fig. 1.]. Government instigated voluntary reporting, after the initial disappointment in the UK, begins to increase moderately. Reporting (when it happens) goes through the consortia (which act as a broker to maintain anonymity) *[Unresolved tension: government actors attempt voluntary initiatives but there are tensions. This was the case at the time of writing w.r.t. the UK voluntary initiative. Attempts at coordination from selectors have limits. Thus technology promoters dominate.].*

Not all actors in R&D sign up to the codes, the broadness of principles causes concerns with some actors — a large pharmaceutical company states, "The lack of clarity and small print is unsettling for early stage technologies. Uncertainty in possible inroads for litigation and liability is not covered by such codes, for this reason our company will not sign up" *[A strong position: this is a stylised quote announced by a large pharmaceutical company in a meeting in November 2007 on Nanomedicine [38].]. Conversely, code promoters state that "The breadth of codes is what gives it validity in current climate of high uncertainty" [An opposed strong position: In debates I have observed, code promoters argue that the broadness is the reason why codes are good. This was taken from interactions I had with code developers [37].].*

The patchwork of codes of conduct, best practices and measures of responsible innovation remain misaligned, but allow progress in technology development through self-regulation and self quality control *[Misalignments enabling for some: A continuation of the situation given in Fig. 3 becoming an emerging irreversibility (not quite path dependency but a situation becoming increasingly entrenched of a patchwork of soft law options. Pressure to consider broader (ELSA) aspects: researchers and technology developers do not feel pressure and continue with their R&D unabated. This was inspired by interviews at an annual meeting of the Frontiers NoE, where researchers were anticipating that the EU responsible development code may affect funding.].*

The codes are particularly enabling for medical devices, providing some guidelines for nano alongside existing regulation of medical devices (such as ISO 14971 for Medical Devices), and so self-regulation of new nano-enabling components can continue *[Enabling aspect of soft law entrenchment: the codes are positioned here as useful additions to existing (well regulated) areas like medical devices [6].].* By the end of 2008 advanced cantilever arrays and the long-awaited integrated micro-fluidic devices (lab-on-a-chip) begin to enter prototype phase with start-ups begin to emerge (and flourish) to take the university research to the market,

with the prospect of takeover by larger firms in 3 to 4 years *[Aspects of translation through Innovation-Chain: Innovation Journeys shift from gestation period to start-up phase. This section also illustrates techno start-up strategies.]. Similar developments can be seen for crime scene investigation and civil security technologies, where advanced diagnostics, forensics and identification technologies were the focus — stimulated by government grants, small companies begin to commercialise this technology [Broader context of comparable innovation journeys: these other fields are added to compare to the medical device innovation journeys later in the scenario.].*

A case of focused national initiatives can be seen. One example, Finland begins to invest in nanotechnology for paper processing (a major contributor to the Finnish economy) [Anticipatory coordination and lock-in: in Finland, sunken investments enable further development (but create constraints later on in the scenario)]. Focused investments included nanofiltration (for effluent treatment), nanocoatings (for pigment and texture) and nanodiagnostics (for monitoring quality) and nanocharacterisation (for deeper understanding of paper materials). The specificity of the case related to opportunities to cut costs, reduce use of chemicals and improve manufacture. The lack of standards helps this flourish and large investments are made leading to positive gains *[A governance option of no standards: there is a tension, standards are enabled because they reduce uncertainty but also constrain a variety and new ventures. This section shows a playing out of a continuation of the current situation].*

Other governments look at Finland's targeted explorations and developments in nanotechnology for the paper sector *[Lock-in as path enabling: other governments look on with envy at the focus of Finnish nanotechnology. This is a mirror of anticipatory coordination in other geographical regions [39,40].].* Government official "Nanotechnology promises to revolutionise all industry sectors, paper production could seriously be enhanced through nanotechnology and as a small country, Finland should focus resources on what is most beneficial for us." Other national governments look with envy at the rapidity of developments of the targeted nano programmes of Finland.

Early experiments and high profile projects such as Nano Jury UK and other engagement exercises lead to the inclusion of "engagement programmes" in technology R&D programmes to inform and communicate the benefits of nanotechnology. There is a proliferation of such projects across (and initiated by) the nano R&D domain focussing on enabling public acceptance. Although no linkages between the projects occurs, the ethical and risk debate begins to separate to "real issues" (of health, environmental and safety issues of nano production) and speculation on broader ethical debates around Human Enhancement, Justice, and theological issues *[Forking and division of RRI labour: RRI topics begin to fork as actors focus either on Speculative Ethics [41] and near-term Health Safety and Environment issues. This creates a gap in ethics of the present and near-future.].*

Monitoring signatory compliance becomes a major issue *[Tension: observed in many discussions of voluntary codes.].* Code initiators attempt yearly monitoring through direct contact to signatories, by asking them to volunteer time to report.

Comparative and systematic methods do not exist. There is a lack of watchdogs; self-regulation and voluntary reporting go unchecked. Responsible actors, who have followed a particular code of conduct, flag their level responsibility by highlighting the following of codes as a sign of good governance *[Tension: I imply in the text that the "good guys" can make themselves visible through such initiatives whilst the "bad guys" remain below the radar.].*

5.1. 2009–2010 nano development boom

The self-imposed standards for manufacture work as a minimum safety requirement, but are at a considerably low level (minimum damage but some damage all the same) *[Selectors attempt at modulating governance arrangements: the narrative shifts into the perspective of NGOs and Trade Unions. The question of risk thresholds is often discussed especially around consumer safety and occupational health and safety. Here the NGOs and Trade Unions try to shape but have little effect because of the lock-in enabling technology development but constraining comparative selector input.].* Some issues of workers safety voiced but related to non-nano issues and passed to others. Calls for moratoria continue from a number of civil societies and labour organisations based on some occupational health issues but have little effect. This is in part due to the governance arrangements being firmly centred on industry consortia *[Tension: Del Stark (ENTA) in a meeting in Brussels [37] pointed out that trade secrets in manufacturing would be a problem for voluntary reporting of use and processing of nanomaterials. He suggested that an industry association (such as his own) could play that role.].*

Emergence of platform technologies with applications in multiple sectors and comprising of ever increasing complexity of functional nano-elements (multifunctional tailored nanoparticles, highly integrated Lab on a chip, Moore than More integrating of semiconductors and molecular electronics *[Tension: increasing complexity of governance of platform technologies. This highlights another issue of where to locate responsibility for nanotechnology in applications, as nano is an enabling technology, and just contributes to the functioning of a large system. Key question: why focus on nano?].*

5.2. 2011–2012 nanoproducts proliferate

The Precautionary Principle is promoted within codes but framed by self-assessment mechanisms (i.e. the actual degree of precaution is unclear) *[Tension: here the precautionary principle is placed up front in the text, and to emphasize that there can be degrees of precaution. Having been to a number of meetings on risk, I see that many technology promoters take an adverse stance towards precaution, connecting it to a halt (moratoria) on technology progress. This was placed in the text to provoke a discussion.].* Innovation actor's quality not assured. Voluntary codes align best practice but have little effect on worst practice due to regime of patchwork of codes (so good become better, worst remain worst) *[Dilemma: attempts to regulate through voluntary initiatives*

aimed at temporary governance of developments are expected to reduce pressure on regulators — so not supplanting regulation but inhibiting it all the same (regardless of good intentions). Taken from a discussion with a representative of Greenpeace UK.].

Codes are not intended to supplant regulation but in practice reduce pressure on regulators causing delays in regulatory mechanics. Regulators rely on current law (or modifications of them) for nanomaterials and applications. REACH[13] is used but is identified as a blunt instrument by labour organisations as it fails to cover certain substances in very small quantities *[Differing positions between enactors and comparative selectors: REACH has been positioned as enough already by manufacturers, whereas labour organizations are concerned that it isn't refined enough.].*

A regulatory task force is set up by the British Government to identify possible regulatory gaps that could be filled *[Potential path shifting event: taking a trigger from the labour organizations, UK government explores regulatory landscape. The report shows various gaps and issues (this was the case with the DEFRA report already. However in this scenario it is not immediately taken up. Here it is recognized as a good report but no further action initiated (until circumstances change).].* The report pushing for mandatory government oversight, identifies many gaps but the major emphasis lies on the fact that nano regulation is difficult due to increasing complexity — law is less equipped to oversee products and processes such as active nanostructures which cross many sectors and can be applied in many setting.

5.3. 2013 house of cards collapses

As ever-increasing complexity of nano, and various incidents cause concerns, the governance arrangements become questioned and regulatory concerns begin to emerge in many countries as calls for further investigation *[Lock-in becomes more visible as selectors wish to coordinate action: as nano develops, civil society, NGOs and governments become more concerned but find no clear inroads into the governance arrangements — a lock-in which is difficult to open up without major investment of resources.].* However, there is alignment in the complicated relationships between technology platforms (multi-functionalised nanoparticles, and other functional macromolecular systems) and the various applications/sectors (they have become embedded), and this befuddles GOs, NGOs, and Civil Society.

Then a worker in paper factory, being treated for liver damage because of alcohol abuse, is found to have peculiar lesions of the liver tissue not related to alcohol abuse. Further diagnostics reveal nanoparticulate aggregation directly linked with the Finnish paper mill (specificity of tailored nanoparticles enables the identification of source of particle) *[Trigger creating window of opportunity for repositioning and realignment of nanotechnology governance: a triggering event occurs which raises the issue of toxicity and exposure. This element of the narrative was inspired by NIOSH 2004 which raised concerns around the manufacturing of nanoparticles. I do not mention that nanotoxicity is the cause of liver damage here, I leave it open. Because hazards and exposure issues are not known, it is difficult to decide whether nano is the problem or not. The uncertainty is the issue].*

In the field of medical diagnostics, nano-enabled chips were beginning to be integrated into clinical practice *[What previously enabled technology development constrains its embedment into markets: as medical nano enters the clinics user issues begin to emerge (previously unarticulated requirements come about). The issue of MRSA links up to discussions on new standards for medical devices. This example is linked to a presentation given by manufacturing firm in the London meeting November 2007 on Nanomedicine].* The lack of nano specific regulation allowed innovations to proliferate but transition into the clinic became fraught with many other challenges related to user needs and user practices. Methicillin-resistant *Staphylococcus aureus* was found on a number of devices, which led to an enquiry on methods of sterilisation and exploration of bio-fouling. Technical complexity becomes an issue.

A number of legal actions were filed against medical device companies, which in turn causes health insurance companies to withdraw their backing of the devices in their coverage. One medic was quoted saying "The technologists missed the boat early on, they should have listened to user needs rather than contemplating far off utopian and dystopian sci-fi futures" *[Consequence of division of RRI labour: clear issue of speculative ELSA in contrast to near-term ELSA [41].]. In contrast diagnostics for crime prevention and other non-health related applications continue to flourish [A fork: other devices are enabled whilst the medical devices are constrained.].*

The Finnish case sparks of a chain of enquiries into nano-regulation, and a number of lines of R&D grind to a halt pending further investigation *[Finnish case triggers a temporary moratorium: because of huge sunk investment Finland begins to suffer.].* Finnish economy begins to suffer due to the high sunk investments into nanotechnology based infrastructure. Public outcry as consumer organisations identify major issues in a number of sectors which could hold potential risk with no protection for the consumer (the house of cards collapses) *[Window of opportunity for selectors: consumers and NGOs are able to raise concerns, the lock-in can now be unlocked, and previous (technology promoter dominated) governance arrangements collapse.].*

5.4. Total recall

By 2014 Nanotech employs approximately 2.3 million workers globally. Nano has become a many headed hydra which is difficult to tame, one popular scientific journal headlines "One look at the Nano Medusa turns regulators to stone". This is picked up by other media, and phrased and framed in different ways. The proliferation of nano and its increasing complexity hits home when consumer organisations try to target concerns, no inroads. Liability becomes the issue *[Entrenched patchwork and lack of*

[13] REACH regulations–Registration, Evaluation, Authorisation and Restriction of Chemical substances (EC 1907/2006)–which entered into force on 1 June 2007. Reach applies to chemical products above a certain volume of production (1 tonne), while some nanomaterials will be produced below that level.

standards causes complication: complexity of nano and the lack of coherent regulatory infrastructure means big delays for certain areas.]. Reference to UK government report of 2012 identifying gaps — stimulates finger pointing at regulators for not following up. When problems begin to occur with certain products (secondary effects), the lack of regulation means it is difficult to find who is liable. Public remains skeptical, voicing failures such as "lack of transparency" and "unclear accountability".

Governmental watchdogs emerge and in the clamour to catch up this leads to numerous temporary moratoria. Regulatory actions retroactively cover all nanomaterials and products on the market become identified and recalled pending certification.

Whilst regulators scramble to catch up, the ever-increasing complexity delays the process even more. Whilst for nanomedicine and bionanotechnology the clamour for tests and rapid certification hampers technological progress, other nano-promises as in "Beyond Moore" (nanoelectronics and nanophotonics) take the lead — for the time being *[Winners and losers are mentioned here. Highlighting that this is not a dark scenario, but a situation which enables some options and constrains others.].*

6. Evaluation and discussion

These co-evolutionary scenarios can prepare the ground for discussion of complex potential radical technologies via the combination of endogenous futures, the IC+ framework and deep case research into actors and their activities. The process provides a means for the creation of rich, context aware and plausible scenarios, which are accepted as legitimate and controlled speculations by participants of Constructive TA workshops. In this case they were used by participants as a resource for discussing the complexities of potential multi-actor multi-level de/re alignments and the effects on nanotechnology emergence.

Here they show that the patterns that were becoming stabilized by 2007 (identified through exploring endogenous futures) continue to shape development and that twists and turns are to be expected as well (characteristic of innovation journeys). While in the annotated scenario, the Finnish worker case, and some of the actions and reactions given are contingent, there is a certain plausibility to their occurrence, and the responses and eventual outcomes are shaped by what is in place already, and thus not completely contingent.

In that scenario I could include anticipations from the world of nano, fears of being locked out of the debate through lack of transparency, of maintaining a patchwork of soft law options to facilitate nanotechnology innovation, positions taken on precaution, the emergence of windows of opportunity for action (stemming from the Finnish worker case being part of the co-evolution of emerging nanotechnology options in paper production and risk and regulation landscape), entanglements due to sunk investments (Finnish policy), collective decision on technology developer side for soft law, etc.

As some of the annotations indicate, the scenario introduces actors and their activities, responses and shifts that have a certain plausibility given what is happening already. Because of this, participants in the workshop can't dismiss them, they have to reflect on them.

Participants in the workshop recognized the dynamics given in the scenario narratives. Elements were picked up, and further responsibility issues were discussed, like how governance arrangements affect cowboy firms (and other organizations) versus good firms. This scenario worked well in terms of showing interactions and outcomes shaped by earlier patterns ("endogenous futures"), and in terms of encompassing variation and contingencies. The scenarios also worked well in terms of stimulating productive discussion in the workshop. This can be seen as a stakeholder "endorsement" of the approach (which is an important indicator how well workshops like these are working). The evaluation of my workshops for Frontiers show that learning about other perspectives occurs, however it does not yet mean that the scenario method has proved practical in the long term (in the practices of the participants), this is part of ongoing assessment [33].

However, as mentioned in Section 4.2, these types of scenarios do stimulate discussions, and provide both a place for exploring different actors' positions and strategies as well as providing key elements and aspects in context. The context is important as it shows the co-evolutionary nature of emergence.

Making some of the emerging pathways explicit, through exploration of endogenous futures and their playings out in scenarios, helps in creating more reflexive strategies. It does this in a form that is usable and makes sense. IC+ emphasizes the overlapping mosaic of arenas of innovation and selection shape and are shaped by the innovations that pass through them and so helps in identifying actors and their strategies. This aids the scenario creator, in my case I could place amidst the three scenarios some major stances and strategies of various actors, and based on expectations analysis and the concept of emerging irreversibilities, show how actors interactions and reactions would co-evolve with the broader IC+ landscape.

6.1. A new member to the socio-technical scenario family

Co-evolutionary scenarios can be created and are productive as an input in Constructive TA type workshops. Their productivity depends on the trade-off between the need to reduce complexity to make it manageable (while keeping the complexity visible), and the risk of bowing to the concentric bias of enactors who need scenarios to guide them to identify and overcome barriers to introduce "their" nanotechnology into society. The IC+ framework provides a gameboard to bring together linear/concentric perspectives with complexity, and thus helps with the creation of scenarios.

These scenarios embrace complexity by referring to the emerging natures of both the innovation chains and their environment. Both are complex, and there is co-shaping. So the scenarios provide a grip on complexity —through actors pro-actively shaping chains and governance, and through lock-ins and selection. In workshop situations they act as a way to provide controlled speculation into easier to handle forms, to enable those who do not have a propensity towards elaborate anticipation to observe patterns, evaluate the scenarios and interact within multi-stakeholder workshops.

The scenarios use endogenous futures, not as a way of extrapolating trajectories but to foreground what may happen as activities play out, and certain entanglements of actors and their activities prevail in one direction or another.

The co-evolutionary scenario approach is a contribution to the growing field of socio-technical scenarios [3]. Other members of the family include regime transition scenarios[14], broadened concentric scenarios[15], multi-level scenarios for evolving industrial sectors[16,17], and actor-centric scenarios revealing the visions carried by various actors [34].

Co-evolutionary scenarios make a modest, but important, contribution to this family by combining concentric and multi-level approaches through emphasizing co-evolution. As is already clear from the evaluation of the workshop, such scenarios support strategic anticipation. If that informs interactions, it will lead to anticipatory governance.

Acknowledgements

This project was conducted within the framework of the Frontiers network of excellence and the NanoNed programme (www.nanoned.nl). Particular thanks should go to Dr. Tilo Propp and Prof. Arie Rip, whose constructive comments enabled (and quite rightly constrained) the co-evolution of my own intellectual entanglements and the crafting of this text.

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[14] Targeted (and used) for transition policy.[4]
[15] Used for open-ended roadmapping by technology developers at early stages of development [6].
[16] Used for exploring industrial/sectorial alignment/misalignments.
[17] See Haico te Kulve's work on Food Packaging for a thorough description of this approach [2]. Also see the work of Alireza Parandian, Delft University (NL) on multi-level analysis of body area networks (to be published in 2010). Also the multi-level approach similar to [2] was used in one of the Frontiers Constructive TA exercises on the drug delivery sector, but from a researchers perspective (the tension of exploration and exploitation).[33]

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