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# Indications of socio-economic impacts of nanotechnologies: the approach of impact pathways<sup>1</sup>

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**Abstract.** For over a decade, there have been promises about socio-economic impacts of nanotechnologies. By now they begin to permeate different application domains and in a variety of ways. In parallel, decision makers in various positions call for indicators of socio-economic impact. This paper shows that in their simple versions, such indicators are an illusion. Instead, one can develop more qualitative indications based on emerging pathways in which impacts are co-produced. In earlier open-ended development of technologies, these are exploratory pathways and can be explored as such; one can anticipate actual developments and use sociotechnical scenarios. This approach has been conducted a number of times and exploratory pathways have been developed and investigated in Constructive TA exercises. At some moment in the emergence of a technology, embedding pathways can be traced, and give information on the co-production of impacts. For embedding pathways, there is no experience to-date. To make a first step, we show that one can already identify different types of pathways depending on the constellation in which technologies get developed and embedded. One further conclusion is that the indications will be specific to concrete pathways, and thus will be bespoke impact indications.

**Keywords.** Indications of impact, embedding pathways, impact pathways, socio-economic aspects.

## Introduction

Given the big promises about socio-economic impacts of nanotechnologies one would expect there are attempts to trace and evaluate them. And indeed, the OECD is moving in this direction, cf. its organizing a large meeting with the US National Nanotechnology Initiative on indicators of socio-economic impacts.<sup>3</sup> We will unpack the notion of impacts below. But we still need a working

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<sup>3</sup> This symposium was held in Washington, DC on March 27-28, 2012.

definition for the discussion in this paper. We propose to speak of socio-economic impacts as socio-economic changes that can be attributed to the introduction and uptake of new nano-enabled products and processes.

Attempts to estimate impacts are fraught with difficulties, because there is no linear-causal relation between nanotechnological innovation and impacts.<sup>4</sup> Impacts are heterogeneous, distributed across R&D hubs, value chains and in the eventual use, and more often than not it is difficult to disentangle the web of activities and attribute a specific impact to a single point source. This is a generally recognized issue, but still there is a demand for indicators of impact. This is the second main issue, the need of policy makers and administrators to have indicators, so that decisions can be made on their basis, without having to go into the complexities of the actual developments. A further use is with respect to the need to assess current and potential return on investments by funding agencies, venture capitalists and industrial actors. So there is a challenge: how to develop indications which speak to these decision-making actors and their purposes, without giving up on the actual complexities. We faced this challenge when we were invited to present during the OECD symposium, and from the reactions we received we conclude that we were fairly successful in raising the issue.

We can start with the critical part. Simple economic indicators of impact are an illusion, already because impacts are distributed across value chains .<sup>5</sup> And one cannot trace impacts by just following a technology or a product enabled by a technology and attributing everything that changes to that technology or product. One has to start with the application or an application domain, rather than with promising technological options. The key value added may occur at quite a distance from the laboratory where the technoscientific knowledge originated. Embedding is where final success and final impact are realized and this is out of the hands of the technology developers (although they can anticipate and augment). This point is particularly important to take into account when claims are made about expected socio-economic impact by promoters of newly emerging technologies like nanotechnology. There are many other things than just a new technological option and its expected performance. There are changing business models and evolving value chains; there are framing conditions like regulation; the investment landscape and

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<sup>4</sup> Innovation activities are spread amongst many actors and occurs not as a single point source, but occurs at different stages of development of a new technology. The impacts associated with the innovation process are distributed and will have further effects, shaping the ongoing innovation process and also will lead to second order impacts.

<sup>5</sup> A value chain is ‘the series of activities required to produce and deliver a product or service’ (Porter 2001). The chain is constituted around the activities required to produce it, from raw materials to the ultimate consumption of the finished product. Elements of a value chain have been described in terms of comprising suppliers, manufacturers, distributors, and consumers. For example, one of the better-researched chains - the wireless communication (mobile phone) chain, includes equipment companies; infrastructure companies/network operators; Steinbock 2003), who interact with a multitude of specialised companies (software intermediaries; financial intermediaries; content providers; resellers (Peppard & Rylander 2006) which in turn engage with the end customer (Li & Whalley 2002). Scanlon (2009) includes a ‘reverse supply chain’, which re-connects the user with the original equipment manufacturer whenever phones are returned for repair or disposal.

policy instruments may change; and consumer behavior and perceptions and assessments are not static. This has to be taken into account, somehow, rather than just extrapolating from expected performance.

In saying all this, we are preparing for the constructive part of our paper. First, identifying and estimating future impacts requires stories about how things will go. Second, there are patterns in the stories to be told about future impacts, about pathways that are followed, through which eventual impacts appear. The notion of ‘impact pathway’ is the key novelty in our approach, and is the basis for the development of indications of impact. We have made room for such an approach by speaking of indications rather than indicators.<sup>6</sup> Indications can be numbers, but are essentially stories about impacts, sometimes with a lot of numbers in them, and at other times not.<sup>7</sup>

Working with impact pathways can build on insights from innovation studies and technology studies, which have traced innovation, uptake and embedding processes retrospectively. The new step is to consider expected impacts linked to the uptake and embedding processes. Strategic choices often have to be made at a time when the actual impacts are not visible yet. Such a prospective analysis is possible because there are ‘endogenous futures’; we will come back to this notion below. Here, we note that there are two different situations.

At an early stage, an emerging technology is a bundle of promising options, and the pathways that can be traced are about further development in various value chains; we will call them exploratory pathways. The first-round impact here is the combination of further performance in particular applications, and shifts in the constellation of actors and interactions, e.g. new business models. At a later stage (but overlapping with the first) uptake and embedding in society can be traced in embedding pathways. It is only then that further socio-economic impacts can be identified (prospectively). For the earlier stage, we can build on our work on sociotechnical scenarios for domains of nanotechnology which focus on the emergence and unfolding of innovation in context. For the later stage, we will develop a typology of embedding pathways to show the direction of further work.

This is not the whole story, of course. In particular, in the discourse about the promise of nanotechnology, by promoters and policy makers, and occasionally by industrialists, eventual impacts can be pushed in terms of promising performance and application of particular R&D fields of nanotechnology such as nanofluidics or nanobiosensors, or in arguments about the contribution

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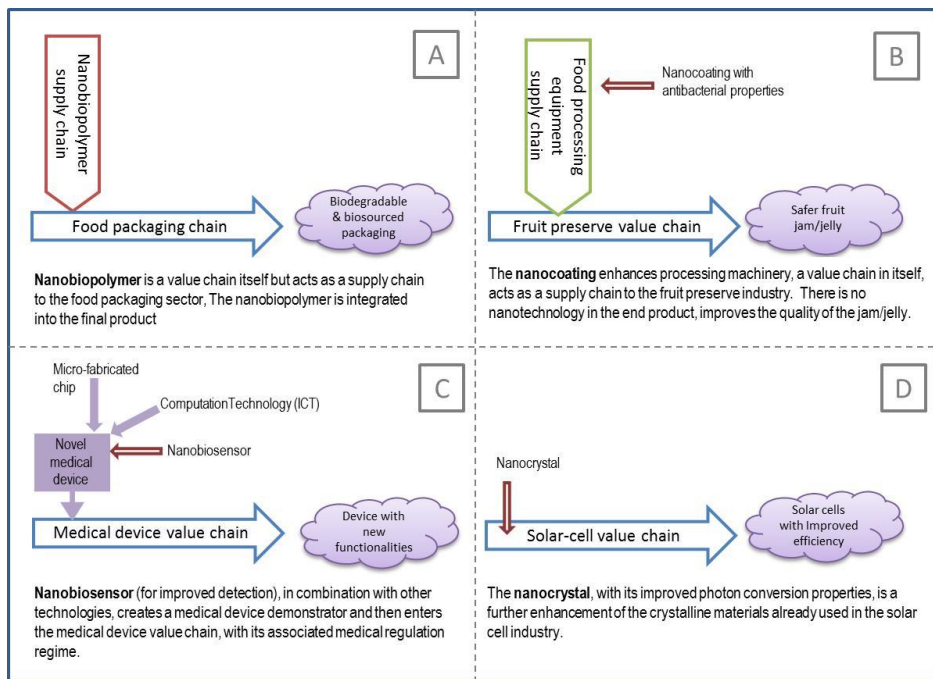
<sup>6</sup> The term “indications” has been used for this reason before, e.g. Van der Meulen and Rip (2000). Lepori and Reale (2012) argue that there is a need to make a distinction between data and indicators, and offer three distinct types of indications. Descriptors describe an aspect of reality without leading to further interpretation (simple statistics); Markers are used in place of quantities that cannot be measured directly (for example patents as a marker of technological outputs); and Indicators which explicitly build connections between quantities and non-observable properties.

<sup>7</sup> Actually, quantitative indicators have stories inside: about the construction and justification of the numbers that are taken to speak for impacts.

of nanotechnology to sectors and grand societal challenges like sustainable agriculture or old-age diseases like Alzheimer's. This is not just rhetoric to be contrasted with impact pathways. Promises can lead to actual requirements on further development, and thus have a certain predictive value (with all the provisions we indicated above). The challenge of reducing complexity productively

Nanotechnology is an open-ended, enabling technology, based on the manipulation of nanoscale structures and the exploration of their properties. This provides a diverse array of nanomaterials and nano-objects that promise to play a role in many sectors, both in products and in manufacturing processes. In such an open-ended technology there is a variety of options which can be linked to value chains in existing domains. To indicate the variety, we provide, in Figure 1, examples of a number of different ways nanotechnologies link up with value chains and enable products.

The schematics in figure 1 are self-explanatory, simplified representations of complex configurations of actors and innovation processes. They illustrate the key point: since nanotechnologies are enabling, they add value to new products and applications depending on what is happening in these domains. Defining impact indicators valid across domains and pathways may not be completely illusory, but definitely creates challenges.<sup>8</sup>



<sup>8</sup> A further feature is that, in some cases, a single nanotechnology may enter a variety of value chains. One example is a chitosan based nanobiopolymer developed which has antimicrobial properties, useful for coating surfaces that will come into contact with food, and is also a naturally occurring biomaterial (Robinson and Saxl 2013).

**Figure 1.** Four examples where nanotechnologies affect a value chains leading to products (the red arrows in the diagram indicate where nano enters the game).

It will be clear that there are many intervening factors that play a role, which holds even more strongly for the uptake and embedding of the application in society (the clouds in figure 1). By the time this is happening one can start tracing socio-economic impacts, but prospective estimation to create indicators that can guide choices and decision making is a challenge. If prospective indicators are to be used at all, they must be an input in discussion of the future co-production process, rather than short circuiting discussion.

In spite of the complexities we can move forward. Productive reduction of some of the complexity is needed, so as to be able to explore exploratory and embedding pathways. The notion of ‘pathway’ itself indicates the type of reduction that we envisage. Through interactions and external pressures, certain developments become more probable. For example, actors other than the initial nanotechnology developers become important, and their positions and perspectives have to be taken into account by technology developers and producers. The schematics presented in figure 1 already provide an insight into the different actors that will be involved in the innovation pathways that nanotechnologies may become part of. Can we anticipate on these in the early stages of emergence? There are pressures already in the world of nanotechnology to do so. One example is the call (and action) to include Life-Cycle Analysis early in the design of products

Stabilization may occur. In general terms, there will be interactions and emerging mutual dependencies (entanglements, cf. Rip 2010) which continue to have effect. In other words, irreversibilities emerge, which will be reinforced when actors invest in the paths that appear to emerge. Thus, an “endogenous future” is spanned up. The notion 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 patterns in the present situation, but not in a deterministic way: there are always choices and contingencies.

It is here that analysis has to come in: of evolving patterns, of dynamics extending into the future, because of irreversibilities that arise. Endogenous futures are not just a fact of life, they can be analyzed and put to use, for example in creating scenarios that assist actors in articulating strategies (Robinson 2010, Parandian 2012). This controlled speculation based on insights into the dynamics of innovation and knowledge of the technology domains, its actors, actions and expectations has demonstrated its value for early developments of newly emerging technologies like nanotechnology. We propose that a similar approach is possible and of value for the later stage of actual product development, market or sector introduction and embedding in society. More

complexity has to be addressed then. The existing literature on introduction and embedding in society offers retrospective case studies, and draws out *ad hoc* lessons. Our notion of ‘impact pathways’ thus creates an agenda for further work. In this paper, we can only explore some possibilities.

For the open-ended stage, we can build on the socio-technical scenario approach as we have developed it as part of Constructive TA of nanotechnology (Robinson and Propp 2006, Rip and te Kulve 2008, Parandian and Rip 2013).<sup>9</sup> Organic large area electronics is an interesting case in this respect because of the waiting games and attempts at breaking through them that occur (Parandian, Rip and te Kulve 2012). We will discuss this in the next section. The first-round impacts that occur are about new business development and new technical development, and articulation of what is possible and desirable. In principle, one could take a next step and speculate about further uptake and embedding in society by fixing an outcome of a scenario, and take it from there.

For dedicated developments in the subsequent (but overlapping) stage we can be more concrete by focusing on nano-enabled products in different domains, where potential impacts can already be identified. We will use the case of nano-enabled sensors in a variety of contexts. Through this example, we show that there are different types of impact pathways, depending on the constellations that shape the dynamics of uptake in the various domain/application contexts. The question of constructing indications then proceeds in two steps: first, identify the type of pathway that is applicable; second, fill in the specifics and estimate impacts.

## **Exploratory pathways articulated in sociotechnical scenarios**

The domain of Organic Large Area Electronics is an interesting site to discuss exploratory pathways, and we can build on earlier work (Parandian 2012, Parandian, Rip and Te Kulve (2012), Parandian and Rip 2013). We will start by sketching the domain.

The domain of Organic and Large Area Electronics (OLAE) is attracting interest because of its promise to replace silicon-based electronics, at least where performance requirements are not very high. But it is in an early stage of development, it is a field of opportunities where open-ended promises dominate and new products are almost absent, or at best tentative. For actors, there is a

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<sup>9</sup> A related approach which explored open-ended roadmapping was combined with the socio-technical scenario for lab-on-a-chip technologies (Robinson & Propp 2008), for telemonitoring technologies (Elwyn et al 2012) and for deep-brain implants (Robinson et al. 2013). This made explicit the open-ended nature of promising new technologies based on mapping the expectations landscape of technology developers and potential users. This can be contrasted with traditional roadmapping which has a well-articulated goal as the key-stone to the approach (Propp and Rip 2005 ATBEST report).

quandary: it is important as well as difficult, to explore futures of OLAE and its embedding in society.

Indicative for the open-ended character of the domain is that various adjectives are used to characterize it, e.g. flexible, organic, large area, plastic and polymer electronics. The key novelty is that semi-conducting devices are processed on flexible semi-conducting polymer substrates (for instance, plastic foils), with large area, low cost production techniques of printing processes using highly functional materials. These developments are part of different traditional value chains and will have an impact on their linkages, including new business models for firms faced with these linkages, for example, printing firms making inroads into the electronics sector. Electronics manufacturers may move to OLAE, but then cannibalize existing product portfolios. Material suppliers (big chemical companies) are proactive, but eventual forward integration will compete with own clients. Printer manufacturers become key actors when they change their present business model, with profits based on inks, to profits based on equipment and service. New types of firms like design houses of OLAE materials may emerge.

Product-market combinations like flexible OLED (Organic Light-Emitting Diodes) light sources and displays, electronic labels for packaging, or cheap flexible solar cells integrated in various applications ranging from roof tiles to smart fabrics, offer functionalities which are not served by conventional rigid silicon-based electronics technologies. Which direction to pursue is not obvious, however. There is uncertainty about user interests and priorities, and thus also uncertainty which markets might be served and when technologies can eventually profit from large scale commercialization. There is also uncertainty about regulatory aspects and customer and social acceptance. The net effect of these uncertainties is that the various business actors are reluctant to be the first to invest heavily in a new development. The situation can be characterized as a waiting game. Actors realize this, but cannot simply break through the waiting game.<sup>10</sup>

One can see endogenous futures at work here: the waiting game still continues in spite of attempts of actors to change it (Parandian and Rip 2013). The immediate impact of OLAE would then be zero (other than that actors want to keep the potential of OLAE on their radar, in case the situation changes). The shaping of the future is not deterministic, however. To explore possible changes, analysts can create scenarios, as actors do in an informal way when they attempt to mobilize allies and opportunities to break through the waiting game. In such scenarios, exploratory pathways of OLAE are presented and the impacts that will occur, e.g. new products and new industry structures (in a broad sense of the term), become visible.<sup>11</sup> Such processes have been studied in industrial

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<sup>10</sup> See Parandian 2012, Parandian et al. 2012 and Robinson et al. 2012.

<sup>11</sup> Such scenarios have to be informed by insight in dynamics of technological development, innovation, sector structures and embedding in society. The quality of the scenarios is in their richness and (narrative) plausibility. It is well known, but bears repeating, that the aim of scenarios is not to sketch a most probable future, but to lay out relevant possible futures that can be taken into account in the present. Narrative plausibility has to do with the sequence of events and evolving patterns



economics, but retrospectively. In order to create indications of impact, one has to be prospective, and this is what sociotechnical scenarios can do in a grounded way.

In Parandian 2012 (see also Parandian and Rip 2013) three different ways of breaking through the waiting game (at least, attempting to do so) were imagined and developed into scenarios, based on an overall diagnosis that a breakthrough could happen top-down, bottom-up, and at an intermediary level. The top-down route started with a concerted effort, enabled and financially supported by the European Commission, to develop applications, particularly for lighting, to mobilize users, and to include further stakeholders like environmental groups. The second scenario started with the decision of the UK government (later joined by other governments) to use procurement, a well-known approach to support and stimulate new technology to materialize the promises of OLAE. The third scenario started with actors in the product value chains willing to come together and coordinate, inspired by what had happened earlier in the semiconductor industry. We present the second scenario in some detail.

In the second scenario, the actual procurement program was linked to the challenges of security, and focused on e-passports with OLAE-enabled RFID and display. This initiative was welcomed by other countries facing security problems, and these (especially Spain) became partners in the procurement program. This very visible program was an argument for promoters of OLAE to push the German government to also stimulate OLAE. Given the long-standing interest in photovoltaics, OLAE was presented as the next step, organic photovoltaics. The German technology policy tradition was not keen on procurement but went for supporting pre-competitive development focusing on generic problems like encapsulation techniques. At the generic level, there were spillovers between these two developments. Then, the procurement program collapsed because it turned out that security, now of the passport holders, could not be guaranteed. One effect was that use of RFID shifted away from such sensitive and demanding applications to ‘safe’ applications like retail and entertainment. Organic photovoltaics had profited from the technical progress in the UK-led consortium, particularly encapsulation techniques (insofar these were available publicly or through bilateral agreements). It could not deliver on all its promises, but there were important applications because of collaborations in the building sector.

One sees the importance of value chains: existing ones, new linkages, and sometimes transformations (as with the new alliance between materials companies and printing companies). In terms of impact pathways, the reader might be concerned that the scenario is predicated on the occurrence of the UK procurement program as an attempt to break through waiting games. So it is a “What if?” scenario. Such scenarios have been used to explore speculative futures (say, what if Putin (Russia) and Obama (US) agreed on the future directions of the world?). But, the “what if”

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(Abbot 1992). In the case of OLAE, additional/specific plausibility derives from our building on insights from innovation studies and sociology and economics of technology.

starting point is not speculative, but based on insights of innovation and innovation policy studies, and our multi-level approach. The three scenarios actually cover the three main possibilities for intervention in a waiting game, depending whether it starts at the top, at the intermediary level (as in the scenario we presented) or at the bottom level.

This example uses a “What if?” approach (assuming one type of breakthrough) but is not just speculative. This was appropriate for this domain where waiting games were what was at stake. Other dynamics could play a role in exploratory pathways. Elsewhere, we have shown that waiting games are endemic in newly emerging technologies, with their indeterminate nature (Parandian et al. 2012). The promise push of new opportunities, combined with a reluctance to invest in them, is a general phenomenon, which returns when we discuss uptake and embedding in society of new technological options. It may not lead to waiting games in the specific sense we have used the notion (and phenomenon) here. But there is definitely ambivalence about newly emerging technologies. The hype (& disappointment) cycle is an example how this ambivalence works out (Fenn 2008).

First round lessons from this discussion are that the route to indications proposed here has a double role: first, showing potential impacts; second, showing the conditions under which these impacts will be realized, so that reflexive action becomes possible: if we don’t want these impacts, we should change the conditions.

Eventual socio-economic impacts are shaped/mediated/enabled by what is happening in this earlier phase. Which products will actually be developed? What value chains and linkages will emerge? In other words, when we turn to embedding in society (in the next section), this is partially predicated on what has been happening already. But it will add further transformations, and this may require further imaginative scenario work.

## **Different types of embedding pathways**

There is a large variety of applications and their embedding. There are domains where nanotechnology enables improvements, as with coatings and fibers, and with silicon-based semiconductors. There are also domains where improvements go together with new functionalities. We will not attempt to give a comprehensive overview, but instead focus on a particular domain in order to show how the notion of impact pathways works out there. We will use the domain of nanosensors, i.e. nano-enabled micro-systems that sense and sometimes also diagnose features of the body, the situation or the environment. There is a variety of embedding pathways in this

domain. Identifying them is a first step towards constructing types of impact pathways that can be used generally.

Nanosensors are a growing area in nanotechnology R&D (Cui et al. 2001, Anker et al. 2008). One area within the field of nanosensors is labeled nanobiosensors (Foster et al. 2013, Robinson et al 2013), which utilizes biomolecules to detect targets. A biomolecule is bound to a substrate such as nanoparticles, nanowires, nanotubes, thin-films or a planar surface, the choice depends on the environment in which the nanobiosensor will be applied and the object(s) to be sensed (the target). The interaction of the target with the biosensor can be measured either directly or indirectly via changes in color, fluorescence and electrical potential of the sensor. Also, when placed in arrays, multiple biomolecules are fixed to a substrate allowing many things to be measured simultaneously.<sup>12</sup> Thus there are a variety of technology options, functionalities and configurations within the sub-field of nanobiosensors.

Returning to the broader field of nanosensors, there are promises of applications in healthcare (Hao and Foster 2008), leisure (Foster et al. 2013), aeronautics (Szu et al. 2005), and agriculture and water management (Robinson and Morrison 2011). What is visible is that there are types of patterns in innovation process and the embedding of nanosensors in a variety of industrial sectors and in society. Through investigating the multiple promises of nanosensors (Robinson et al 2013), we can identify different embedding pathways in which nanosensors affect socio-economic impact in one or another domain through various applications

We find four distinct, but not mutually exclusive, embedding pathways in this domain. These pathways may not be visible in exactly the same way in other domains, but the overall methodology remains applicable: Theoretically and empirically informed identification of pathways is possible, and allow realistic identification of how and where to look for impacts that are chain-linked to the original knowledge-based intervention.

### ***Embedding Pathway A: A path clearly marked out***

This pathway occurs when there is a combination of high performance technology with small dedicated markets. For example, in the aeronautics and space industry, the large organized design and deployment process means that the intended impacts of a nanosensor technology in this specific domain can be well articulated, since the majority of elements are explored, developed and utilized either in house, or with tight coordination through systems engineering processes. In

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<sup>12</sup> Arrays have been made using a number of different biomolecules, but have tended to concentrate on proteins (or parts of proteins) such as antibodies and enzymes, or DNA and RNA. These are quite mature technologies, having been developed and marketed by a number of companies for use in basic research, and diagnostic sciences (including forensics and medicine).

this way, potential impacts can be clearly defined and evaluated. One can use the original goals linked to technology readiness levels as impact descriptors as these are realized.<sup>13</sup>

Embedding pathway A is common in large scale innovation organizations. In aerospace, organizations such as NASA, ESA, Lockheed Martin and Astrium have large systems engineering processes which integrate the various technologies into working configurations, such as space systems and aircraft. There is a highly structured and closely-connected value chain

The embedding pathway is marked out in the early stages of the project, this is because potential impacts are tightly coupled to the design, development and deployment process. Indications of impact can be linked to straight-forward statistical measures.

### ***Embedding Pathway B: One road leads to another***

This pathway occurs in highly structured closely-connected value chains where the demonstration of the technology in one domain leads to exploration of its application in another domain. One example is diagnostic technologies to be used in hospitals. Medical nanosensors (Grim et al. 2004, Ercan et al. 2011), which require near zero-failure rate for the detection of elements in blood, lymph and urine demonstrates value and application in agriculture (Grieve 2009). In agricultural production, sensors and diagnostic devices allow farmers to closely monitor environmental conditions, plant and animal health, and growth. As part of precision farming or high-tech nurseries, they can facilitate targeted and early intervention, thus increasing productivity and decreasing the use of agrochemicals like antibiotics, pesticides, and nutrients. However, uptake of nanosensors in the field of precision farming is heavily dependent on its demonstration elsewhere, its cost, and its reliability (Robinson and Morrison 2011).

Embedding Pathway B represents socio-economic impact in one domain enabling further development and embedding in another domain. Tracing impacts related to pathway 2 would require monitoring possible branching (Van de Ven 1999) and jumping from one domain to another (cf. medical to agriculture).

### ***Embedding Pathway C: Loopings related to evolving user-context***

An example is point-of-care diagnostics, where traditionally the point of care is the clinic or at a patient's home where a clinician visits. Performance for these technologies must be relatively high and based on reliability, but the market can become large, when roles of doctors, health care professionals and patients (and insurers) shift. Interesting in this respect are attempts to control

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<sup>13</sup> An example is the use of advanced magnetic nanosensor technology for exploration of Mars or Mercury (Nanowerk 2013). For more details on the technology, see Sensitec GmbH : [http://sensitec.com.p-ad.de/english/technology/mr-sensor-technology/mr\\_sensortechnologie.html](http://sensitec.com.p-ad.de/english/technology/mr-sensor-technology/mr_sensortechnologie.html)

the emergence of self-diagnosis with point-of-care devices, and potential self-medication, at least in the Netherlands (Krabbenborg 2013). In the scenario that was constructed, patients circumvented the attempts at restricting the availability of point-of-care diagnostic kits by buying on Internet, from a Czech company that had a license from the Dutch device manufacturer (Krabbenborg 2013).

This embedding pathway involves a co-evolution of the technology and its use-context. Initially there were market projections by technology developers for the new technology on the basis of existing user roles and their responsibilities (point-of-care diagnostics, in usual settings such as hospitals and clinics). After introduction and uptake of the novel technology there is an intermediary social impact involving changes in roles and responsibilities of both users and technology developers, including new actors emerging in and around the value chain, in this case patients with the point-of-care devices who can self-diagnose and perhaps self-medicate (circumventing the clinics to a certain extent) and also seek out diagnostic kits themselves on the internet (circumventing national health agency's restrictions).

Indications of impact are linked to the first order development, such as performance of the technology and penetration into user area (this can be labeled the first loop). Also, indications of impact can be defined in terms of new roles and the creation new markets, the rate and spread of change (this can be labeled the second loop). Larger/different markets may emerge and so other impacts. Evaluating the socio-economic impacts with innovation processes following this pathway has to take this non-linearity into account.

### ***Embedding Pathway D: Widespread uptake with low performance requirements in multiple domains***

This embedding pathway relates to a business model of low performance requirements and large markets. An example for nanosensors is in clothing, where patches worn on the body become part of the clothes. Sensors for salt (in sweat), heart rate and temperature and others are in development (Yu 2006, Tomasik 2008). In this application of nanosensors, there is less of a need for high accuracy (in contrast with medical diagnostics). Their use can be in the health sector, but in the sports sector, where specific activities require dedicated clothing, for example in fitness centers (Ren 2006). Low performance nanosensors can also play a role in clothing for comfort and status, where demand for these product applications stem from cultural trends such as wealth demonstration and the new importance of lifestyle and the economy of experience. Here, knowledge from a new field of technology is exploited early on, for relatively simple technological applications, where the added value of the new technology is visible and where high performance is not a requirement.

What this discussion of four embedding pathways sketches is only the beginning of the construction of impact pathways that can identify indications of socio-economic impacts. In the literature there are quite some attempts to discuss socio-economic impacts, including “soft” impacts (for the latter, see Van der Burg and Swierstra 2013), but as uncontrolled speculation – the ‘what if’ scenarios. To control the speculation, we focused on embedding pathways in the short term. This is as far as we could come in this paper. The next step is to consider potential impacts, based on the story told in the relevant embedding pathway.

## **In conclusion**

We opened the paper with recognition of the need for impact assessment, both in real-time and prospectively for technology developers as well as policy makers, government agencies and other actors involved in technology development and societal embedment. We claimed that simple indicators of impact are an illusion, and offered an alternative: indications of impacts based on qualitative analysis of emerging technologies and their embedding in society. We introduced the notion of exploratory pathways (section 2) and embedding pathways (section 3) to do justice to the patterns in such developments without falling back into a deterministic perspective. These pathways emphasize ongoing developments, which allows one to identify where to expect what kind of effects impacts. Methodologically, it is not itself an indication of impact, but specifies the world in which impacts are co-produced. In our process approach, there is no strong distinction between process, and impacts-as-outcomes-of-a-process.

How does one get from impact pathways to indications? Constructing impact pathways is a major effort, drawing on insights from science, technology and innovation studies, but also more general insights into how things go in our late-industrial societies. Socio-technical scenarios are particularly helpful. Indications of impact are not stipulated beforehand, but derived from the picture sketched in the impact pathway for the particular domain or domains. Thus, indications will always be bespoke indications, developed for the particular case and context. Some of them may be generally applicable indications, but these are often not very interesting.<sup>14</sup>

In the same vein, it is important to highlight that applying these tools will be more or less interesting depending on the socio-technical context. For example, it is less interesting for novel drugs technologies, where there is a clear pathway of development and assessment. However, for new enabling technologies the approaches described in sections 2 and 3 would be very useful, because potential contexts of embedment would be less well articulated and quite varied.

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<sup>14</sup> Compare the situation of R&D indicators, where one can have standardized input and activity indicators, but runs into complexities once output (other than publications) and impact (other than citations and other reputational measures) are addressed.

Once indications are identified, there is the practical challenge of operationalizing them. There are no general specifications how to “do” indications of socio-economic impact, other than the tension between exploration and exploitation (March 1991).

Impact pathways and bespoke indicators have different functions for different actors: the immediate development and societal embedding actors use them to anticipate and inform their strategic thinking and action. For administrators, and sometimes also policy makers and politicians, indicators support monitoring and sometimes also steering at a distance. Further specification and operationalization may well be different for the two different types of audiences/users.<sup>15</sup>

In these last considerations, the issue of productive reduction of complexity is visible again. Scholars of Science and Technology Studies have an important role to play here, with their strengths in case studies and in the conceptualization (and contributing to the construction) of the co-evolution of science, technology and society. On the one hand, they have to contribute to keeping complexity visible; on the other hand they have to collaborate in productive reductions. Mobilizing STS understandings for prospective analysis already is an intellectual challenge and one taken up in the S.NET community.

STS scholars are playing a role in the development of nanotechnologies by stimulating reflexivity in the design and development processes (cf. Constructive Technology Assessment) and in providing tools and approaches for research and innovation evaluation. Such activities create a tension in STS, one must become part of the worlds of research, product development and policy making whilst not being absorbed by them<sup>16</sup>. This tension is a challenge that the S.NET community should take up.

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<sup>15</sup> Embedding pathways can be further developed into scenarios to interact with experts who then further detail Impact Profiles. Once impact profiles are made clearer, bespoke indicators could be developed.

<sup>16</sup> This is the old challenge of going native, as discussed and experienced in anthropology. Here, there is further challenge because of the difference in the power landscapes: the director of a nanotechnology center can hire a sociologist in residence (for example Robert Doubleday in Cambridge). Rip and Robinson (2013) have described a methodology of insertion as an approach to handling this tension.

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