Defining and evaluating 'science for sustainability'

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1. Summary

If science and engineering efforts in support of sustainable development are to be made more effective we need to be able to evaluate the effectiveness of innovative research programmes and the transferability of good practice. In turn, this depends on establishing an externally-specified reference standard by which to evaluate programme performance. This paper sets out to define the challenge that sustainability poses to science and engineering by drawing out key differences from usual scientific practice. These differences are used as a basis for developing a preliminary methodology for evaluating science and engineering efforts in support of sustainable development. Our initial hypotheses are that: the contribution that a research project makes to sustainable development is related to a set of generic product- and process- related research outcomes, which can be evaluated on the basis of normative (externally-specified) sustainability criteria; research management procedures, research designs and research processes that conform strongly with the principles of sustainable development are likely to contribute to strong research outcomes; and, both research designs and research outcomes are likely to be influenced by the external research context, especially by the existing status of scientific and social capital and capacities and by how well these are aligned to meet the challenges to science and society posed by sustainable development. A fourth hypothesis is that contextual conditions, research designs and research outcomes are dynamically interconnected through a feedback loop. The paper describes the AIRP-SD study of the EC STRATA programme that tested these hypotheses.[1] It draws lessons from the study about the nature of successful science and engineering efforts in support of sustainable development and suggests that well-designed programmes could leverage the effectiveness of future RTD activities by improving the quality of research contexts.

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2. Introduction

A priority need as we enter the 21^{st} Century is for future development to be sustainable and for future products, processes and services to be produced with much higher eco-efficiency. Just as labour productivity improvement has been the guiding theme of past growth-oriented development, resource productivity improvement will be the dominant theme that drives and co-ordinates innovation in the 21^{st} Century, which will be concerned increasingly with the qualitative aspects of how economic output and wealth are produced. The pressure of a growing world population and a growing world economy as citizens everywhere seek to secure a decent standard of living on a planet with limited resources and limited capacity to absorb and process wastes ensures that this will be the case. In turn, the high levels of eco-efficiency and resource productivity improvement that will be needed in the coming decades - improvements of an order of magnitude at least - will require "systems level" changes in the way that needs are met, jobs are created, income is earned and export sales are generated. In their turn, these will depend upon changes in the institutions that support development and that provide the contextual framework for innovation and decision making.

Given the lead times involved in achieving resource productivity improvements of this magnitude, work on strategic long-term restructuring of our economies and societies needs to be underway already if the sustainability challenge is to be met. This is why sustainable development is so great a challenge to societies and to science. It defines a wholly new development paradigm. It calls for innovation across a broad set of fronts: structural, social and technological. Perhaps most importantly, it calls for innovation in the innovation system itself in order to re-orient innovation efforts toward new goals, to make these efforts more efficient and to accelerate the pace of progress on resource productivity improvement so that this overtakes and runs increasingly ahead of economic growth. Only then - and only if achieved eco-efficiency gains are used to reduce environmental pressure and secure poverty reduction - will the stress on the planetary system that underpins our economies, our societies and our welfare be reduced.

Sustainable development implies a new industrial revolution that will see new concepts of "wellbeing" and new models of "competitiveness" emerge. Living standards and life quality within countries will increasingly depend upon the resource efficiency with which vital needs are met. In the richer countries with ageing populations, a backlog of environmental problems and a need to restructure physical infrastructures to fit the new context, there will be many claims on increasingly scarce capital. Reducing the resource cost of comfortable living will be an imperative for the future wellbeing of societies with large numbers of non-working citizens, while in the productive economy increasing resource productivity will be an imperative for securing the highest possible marginal productivity of labour and capital, as well as of natural resources. Competitiveness and what determines it will be redefined. Economic leadership in the 21^{st} Century will lie with those nations that seize the opportunity of responding to the sustainability challenge. They will make their own economies more robust and resilient in a world characterised by high resource prices, high waste disposal costs and increasing threats to conventional energy and materials supply chains. They will also lead in the technologies and associated know-how of the new 'resource productivity' development paradigm. History shows that leadership processes are dominated by positive feedback and that an early lead in meeting an innovation challenge often brings long-lasting competitive advantage. First movers will have best chance of becoming long-term front-runners.

This paper looks in greater depth at the innovation challenges that sustainable development poses for science and engineering. Precisely what are the challenges? What have been the responses to date? How effectively have these challenges been met by the first set of pioneering innovation programmes that have set out to support sustainable development? Are there transferable lessons to be learned?

3. Sustainability challenges to science and society

Prevailing systems of innovation and the prevailing development pathway are mutually supportive and re-enforcing. The institutions involved in the generation, commercialisation and diffusion of new products, processes and services - including the institutions of science, government, business and finance, as well as the systems for determining research and technology development priorities - are all part-and-parcel of the same prevailing development paradigm. In effect, today's national innovation systems and the current development paradigm have co-evolved. By contrast, sustainable development implies paradigmatic change - innovation for a new development paradigm. At issue is whether it is possible to initiate new innovation trajectories from within the context of prevailing institutional and organisational arrangements that have been developed over generations and are arranged specifically to support business-as-usual. A first concern is to develop a typology of the specific challenges that sustainable development poses for science and society as a basis for suggesting what forms of restructuring and reorientation of innovation systems are required and what kinds of new scientific, social and governance capacities and capital need to be built or strengthened to support sustainable development.

<u>Orientation and ambition</u>

A fundamental starting point is that sustainable development - with its requirement for improvements in eco-efficiency of an order-of-magnitude or more - implies the need for new system-level solutions to production-consumption questions. The need is for path-breaking solutions conceived in terms of fundamentally different sets of technologies, institutions and social arrangements than those we have today. Whereas innovators working to improve existing solutions can take the paradigmatic framework conditions for granted, those working on sustainable solutions must base their work on the belief that these will change. Moreover, they must actively work toward changing them if new solutions are to be implemented. This means that innovation for sustainability cannot be restricted to designing and evaluating solutions, but must also engage with the *process* of designing and implementing paradigmatic change. This is a strategic management challenge that requires special ways of working and a special toolkit to deal with the issues entailed, such as creating visions of sustainable futures, handling the dynamics of co-evolutionary change on several innovation fronts, handling uncertainty that is inherent when shifting into realms not previously experienced and communicating with stakeholders and decision makers about options and their implications. The challenge of managing change and transition is a multi-level one, since different spatial levels of the development system (local, national, regional, global) are interdependent. This means that sustainability research may be targeted on technical development problems or transition-management problems that are manifest on any scale, but that ‘solutions’ will always need to be designed and evaluated to take into account the links with other scales.

The normative nature of sustainability implies that the challenge is prescriptive, rather than predictive. The challenge is not to forecast the future, but rather to envision a desirable socio-economic future that meets macro-sustainability constraints and conforms with society-agreed concepts of what constitutes a good quality of life, to set this as a target state and to work toward its realisation. The design task is multi-dimensional because societies' needs are multi-faceted. Sustainable development implies the need to consider a broad set of economic, social, environmental and political criteria. This implies that these same criteria are integrated into every step and stage in the process of finding, evaluating and implementing solutions. It implies the need for multi-objective, multi-criteria methods and tools for analysis. And it implies widening the boundary of analysis to encompass all significant cross-over impacts so that these are internalised into analysis and impact assessment. The requirement to take many disparate criteria into account complicates the search process, since it engages non-market values and implies the need for decisions to be made over the relative importance of different criteria and for compromise and trade-off among objectives. The selection of criteria and the relative weighting of each cannot be established by reference to markets or by scientific supposition, but can only be determined and legitimated by stakeholders and their representatives. Moreover, the criteria and weightings are likely to change as stakeholders' understandings change and, with it, their values and attitudes. In turn, this implies that scientists cannot search for solutions alone, but are engaged as one of several agents in a dynamic process of social problem-solving.

Complexity and uncertainty

In sustainable development the focus is no longer just the techno-economic system that delivers economic growth, but the whole socio-ecological system embracing the natural world, the cultural world and interactions between the two. Over recent years there has been stunning advance in our understanding of the planet, its history of transformations and its present dynamics (Holling 1990). We now know that the natural world is a complex, hierarchically-structured system characterised by non-linear dynamics. It belongs in the class of evolving, self-organising, “dissipative systems”, which are far from thermodynamic equilibrium, which have multiple stable states, which are characterised by the potential for irreversible change and where discontinuous behaviour and structural change is the norm. By implication, the understanding needed for environmental change covers processes that operate over an enormous range of scales, interactions that operate with wide-ranging time lags and impacts that depend on threshold effects. The inherent complexity of the natural world leads to indeterminacy and uncertainty. It is intrinsically impossible to understand perfectly and completely so complex a system whose behaviours may be, in any event, intrinsically chaotic.

This is all the more important when interactions between mankind and nature are increasingly mediated through more powerful technologies. The combination of uncertainty, powerful technological interventions, the potential for irreversible ecological change and the limited capacity of humanity to adapt or respond when ecological change undermines the very basis of human survival or life quality constitutes a powerful case for a precautionary approach. This is certainly the case when planetary stability is at stake and may also apply when the livelihoods and quality of life of large numbers of vulnerable people are threatened by a technology or a development whose impacts cannot be known in advance. To exercise precaution demands considered judgement of potential benefits and risks of development choices, as well as concern for the distribution of these across society and generations in relation to the vulnerabilities of stakeholders in the event of problems.

There are comparable difficulties in dealing with the human and institutional systems, science included, that are integral to the process of development and the search for sustainable development. In sustainable development, we are dealing with a decentralised and distributed innovation system with many individual but interdependent actors and many stakeholders. As the stakes involved in a shift to sustainable development are high, there is need to reckon with the interests and strategies of the various stakeholders and also with the uneven distribution of power in human and institutional systems. Human decisions and actions are frequently based upon what effectively amount to gaming strategies, where the purpose is to pre-empt the behaviour of another actor or provoke a particular response. Thus, the social systems that interact with the natural world are, in their own ways, just as complex, unpredictable and unfathomable as the natural system. Social systems are complex. Indeed, as Funtowicz and Ravetz point out, they are reflexively complex (Funtowicz and Ravetz 2002).

As there are no “cure-all” solutions in sustainable development, there is a need to ensure that understanding of the sustainability threat and appreciation of the objectives and principles of sustainable development are widely diffused into all spheres of development decision making within society, politics, business and science.

Scientific culture and organisation

One consequence of complexity is that no single scientific discipline or field of expert knowledge will be able to capture all that is relevant to the analysis of development problems. Furthermore, each field of expertise, while bringing to bear important insights to the problem, will necessarily introduce its own subjectivity relating to the artificial boundaries used to frame the problem and to the theories and methods used to analyse the problem. The assumptions introduced to enable a complex real world system to be analysed in parts, as if each existed in isolation, and to enable each part to be treated as if it were a simple or merely complicated system,[2] rather than something elementally or functionally embedded within a complex system, effectively ensure that each system subjected to disciplinary scrutiny is, in effect, artificial. The system analysed by each discipline and the image each discipline holds of the world and its phenomena reflect its own cognitive understanding. Each is, at best, partial, distorted and subjective. It follows that no single discipline or approach can capture all that is relevant, that it takes a plurality of approaches to obtain the best possible image of reality or to gain the best possible diagnosis of problems or solutions and that no one discipline or perspective is privileged with a more “valid” insight than others.

Thus, the tasks inherent in sustainable development are totally different from those for which western science and modern innovation systems were conceived. Funtowicz and Ravetz argue

[2] Indeed, uncertainty is not just a feature of complex systems, it is the defining feature that distinguishes complex systems from those that are simple or just complicated. A simple system can be captured in theory and practice by a deterministic, linear causal analysis. Complicated systems require more variables for explanation or for control than can be neatly managed in its theory. With complexity, we are dealing with phenomena of a different sort. In a complex system, elements and subsystems are defined by their relation within hierarchies of inclusion and function. A complicated system can be modelled reliably despite the large number of elements and relationships involved. A complex system, by contrast, is characterised by multiple potential equilibria and cannot be accurately or reliably modelled. Systems that are complex are not merely complicated, by their very nature they imply deep uncertainties and a plurality of legitimate perspectives.

that, conceptually and organisationally, modern science has been constructed around a model of the relationship between mankind and nature as one of conquest and control rather than one of respecting ecological limits, managing problems, expecting surprises and adapting to these (Funtowicz and Ravetz 2002). Furthermore, the power and influence of modern science are derived from its facility to tackle problems that can be neatly bounded. Modern science is based upon two complementary traditions: a tradition of breaking down complex real world systems of interest into parts and a complementary, although less well developed, integration science for combining the understanding obtained through disciplinary study of the separated parts. This structure and organisation of science was developed and institutionalised long before the problems of complexity, uncertainty and chaotic behaviour were recognised. The result is that conventional science is well equipped to deal with the large number of problems and questions that are manageable within fairly narrowly-defined system boundaries (problems that concern simple or complicated systems), but ill equipped to deal with complex systems and complex developmental problems.

The strength of conventional science is that it provides for elegant theory and for a high level of certainty and reproducibility of scientific findings, especially when experimentation is conducted under controlled conditions where all variables other than those under investigation are held constant or are externalised. However, this strength is offset by several weaknesses. The initial splitting of real world phenomena into discrete sub-systems of interest and the initial matching of phenomena with study approaches are based upon cognitive understandings about what is and what is not important, about what should and what should not be studied and about how phenomena of assumed interest should be studied. An inevitable subjectivity surrounds the initial compartmentalisation and choice of analytical method. In addition, the artificial simplification introduced by delineating system boundaries may also restrict the applicability of findings to real world problems or lead to unintended and unforeseen consequences when knowledge is applied, since only those impacts that fall within the system boundary will have been analysed. Furthermore, each discipline has its own terminology and conventions and makes its own set of simplifying assumptions. These are often mutually inconsistent, making the theory, methods, data and knowledge from different fields of study incompatible and reducing the possibilities for building the composite picture through integration science.

The major concern from the perspective of sustainable development, however, is that phenomena that arise through system interactions and which lie in the 'grey areas' between disciplines may fall out of consideration altogether. In the process of breaking down real world systems into parts, most of the links and relationships that are the central concerns of sustainable development – the links between the natural and social systems or between levels in hierarchical structures or between time periods – are severed and are not studied by the specialised disciplines. Relatively new academic fields such as resilience and complex systems theory seek to address these issues by integrating the social and natural sciences. Due to the complexity and non-lineararity of complex natural and human systems, scientists, economists, and engineers all have to make assumptions when constructing their mathematical models. In sustainable development our very concern is for relationships, phenomena and problems that lie at the interfaces between different scientific fields. Moreover, the very fact that these are today's major societal problems in part reflects their past neglect by the prevailing scientific paradigm which, consistent with the prevailing development paradigm to which science is recursively related, has tended to externalise them.

Another facet of scientific culture that arises from analysing bounded systems along the tradition of experimental science is the image of science as neutral and objective with a purpose to establish hard facts and truths. The “science of parts” places importance on scientific certainty. Whilst there are notable exceptions, overall a narrow enough focus is usually chosen in order to develop data and tests that can be used to reject invalid hypotheses. A major hindrance to progressive research is the pressure to narrow uncertainty to the point where acceptance of an argument among scientific peers is essentially unanimous. Thus a culture is developed where scientists are reluctant to present findings or recommendations until there is a strong basis of scientific evidence that puts these beyond doubt. The approach is conservative and unambiguous at the price of being incomplete. But the danger of this approach is that in being so focused it will miss critical areas and is not appropriate for sustainability.

One response has been to distinguish different types of uncertainty. Nonetheless, the insights of chaos theory, behavioural psychology and resilience theory mean that whichever approach to modeling is taken there will always be some irreducible uncertainty about the behaviour of our systems of interest and therefore also about the outcomes of management interventions in those systems. Given the intrinsic limit to our capacity to model the behaviour of our systems of interest, the issue switches to one of how best to manage such systems. The challenge is to develop a different *management approach* based upon regarding uncertainty less as an obstacle to action and more as a source of creativity and inspiration for the development of intrinsically safe interventions. The challenge to science in support of such a management approach is to shift toward a 'whole system' / 'design for sustainability' approach.[3] A focus on whole system design for sustainability can at least deliver relative certainty over what can be done to reduce our ecological footprint and can be used, at the same time, to integrate environmental, economic and social criteria into solution designs.

Communication with policy makers and stakeholders

Even though the specifics of sustainability problems are relatively new, an established body of theory and methods has been developed in relation to analogous complex problems. This body of theory and experience suggests that problems characterised by a large number of potentially conflicting objectives, high degrees of uncertainty and risk, potential irreversibilities, large numbers of stakeholders, high stakes, unavoidable subjectivity and context specificity, cannot be handled satisfactorily by centralised decision making structures and processes. Instead, they are best analysed and resolved in decentralised fashion through participatory processes that engage the relevant actors and stakeholders in a constructive social process of mutual learning and decision making. Thus, innovation for sustainability calls not only for interdisciplinary working, but also for transdisciplinarity, interagency working and stakeholder engagement. Innovation for sustainability must integrate knowledge, values and actions from different domains, both formal and informal.

Since uncertainty is high, the analysis of uncertainty becomes a topic for analysis in itself. Moreover, through the connection between science and implementation an opportunity is created to learn about the systems under management, since every policy and management action will

[3] Such a shift can be seen in the traditionally reductionist field of chemistry. Originally, environmental chemistry was concerned simply to measure levels of pollutants in the environment. But, since the early 1990s, chemists are increasingly seeking to design chemicals for dissipative uses so that these are intrinsically benign. They are beginning to 'design-out' toxic chemicals. Such shifts will greatly assist policy makers looking for solutions-oriented approaches to sustainable development.

necessarily be taken on the basis of incomplete science and will represent a test of the underlying hypotheses upon which the policy or management action is predicated. This essentially describes an “adaptive management” approach (Holling 1978, Walters 1986) that is sometimes used in the management of renewable resources, but which could form a useful general model for sustainability-oriented innovation. The essential point here is that in the case of sustainability there is a special need for continuous learning and adaptation, since the system of interest is not only incompletely understood, but it is also a moving target, evolving in part because of the impacts of management actions. Under these circumstances, management actions need to achieve not only the social goals desired, but also ever changing understanding of the system under management. Policy and management actions can be designed specifically to test hypotheses, probe the system and, so, reduce uncertainty. This puts premium on the quality of the science-policy interface and, also, on the levels of societal trust in policy makers and scientists.

The foregoing comments also help to throw light on the links between risk, uncertainty, experimentation and learning, which is useful for operationalising the precautionary principle. Clearly, risk cannot be avoided in situations of uncertainty. Moreover, a balance has to be struck between the risk inherent in inaction and the risks of acting on the basis of incomplete knowledge. When issues and the responses are local, or even regional, actions can be designed as management and scientific experiments whose purpose is to generate both understanding and solutions at the same time. But when problems are global, such as in the case of climatic change, a very different approach is needed.[4] Good experiments are meant to fail, but the experimenters should live to learn from their experiment. Holling proposes the general rule here that risk taking is appropriate only when errors are affordable. Put differently: "We should not take risks with elements and qualities that underpin societies, economies or nature, especially when these are inherently planetary in scale, since these are the very foundations upon which sustainability with opportunity is based. Such elements and properties should be protected and preserved" (Holling 1990).

This raises the more general issue of communication at the science-policy interface. In principle, science is needed to supply the underpinnings of informed action while policy and management responses are needed to create an enabling framework for sustainable development. However, the two communities - scientists and policy makers - frequently suffer from a communications gap (Myers 1990). The issue is complicated, because the quality of communication at this interface is a function not only of how science is organised, but also of the organisation of policy making. Just as the disciplinary division of science externalises important factors from scientific consideration, so the division into governmental agencies, departments and ministries can lead to neglect of factors that fall outside agency or departmental responsibilities. The divisions may mean that the institutions of government find difficulty in developing integrative responses to systems-level solutions even when these are proposed by science. One implication is that the capacity of government to develop integrated policy responses may be a contextual factor in the success of innovation. Another may be that building this capacity is potentially an important element in adapting our national innovation systems to fit them better to support sustainable development.

[4] Thus, Holling argues that in this case, “the observed and anticipated changes in carbon dioxide concentration alone are so unambiguous, so great and world-wide that we dare not continue as we are. We cannot predict confidently what impacts will flow from these changes, but we cannot continue to play out such a huge experiment on the whole planet” (Holling 1990).

New roles for scientists and engineers

In sum, the requirements of sustainable development imply the need to reorient innovation efforts toward new thematic priorities and new process challenges. They specify new roles for scientists within the process of sustainable development as initiators, facilitators, co-ordinators and mediators in societal processes of complex problem solving and decision making. These roles are additional to the traditional roles of science and technology in providing information and technical means. They specify new tasks in relation to the handling of risk and uncertainty, and pose special requirements for communicating with a wide range of non-scientific actors and stakeholders as well as with policy makers. They imply new ways of working, focused on inclusive and interactive approaches. They also specify a wider set of goals and outcomes for science and technology, which in turn holds implications for research management, research funding and research evaluation. New funding models are needed to enable innovation challenges to be re-conceptualised from first principles, to translate these into research proposals, to build transdisciplinary research networks and to cover the additional costs that are implied for stakeholder participation and communication.

4. The AIRP-SD Project

At issue is the potential contradiction that sustainability research, which by definition is aimed at changing development trajectories and paradigms, is today dependent on prevailing national innovation systems for recognition, resources and steering. This situation is hardly likely to liberate innovation for sustainability unless special provisions are made at the outset expressly for this purpose. In some countries, this fact has been explicitly recognised and efforts have been made to establish pioneering programmes of research and technology development (RTD) with mandates not only for exploring radical new ways of meeting needs in the long-term future, but also for strengthening the innovation system in its capacity to support sustainable development, for example by developing and testing research methods and innovation management processes appropriate for supporting sustainable development.

In order to learn from the experience of these innovative sustainability-oriented programmes, a specific research project was established within the framework of the EC STRATA Programme. Its mandate was to make consistent evaluations of some of the first wave of innovative sustainability-oriented RTD programmes. The AIRP-SD project screened over 100 RTD programmes and projects and made detailed evaluations of nine, which were chosen, *inter alia*, because of their specific sustainability orientation, their long-term outlook, their innovative approaches to research definition, finance, management and design and the availability of detailed information about the programme. The nine RTD programmes chosen for detailed evaluation included, among others, the Socio-Ecological Programme (Germany), the Programme on Technologies for Sustainable Development (Austria), the Ecocycle Programme (Sweden), the Zero Emission Research Initiative (Japan) and the Sustainable Technology Development Programme (the Netherlands).

The AIRP-SD project objective was to find how best to design and administer innovation programmes in support of sustainable development. An answer to this question clearly depends upon using a consistent evaluation methodology based upon external reference standards for judging programme completeness and quality. But, whereas evaluators usually have an established reference standard to structure their evaluations, in regard to innovation efforts in support of sustainable development there is no established reference model for how science efforts should be designed and no firm basis of experience over which research designs have worked well in the past or have worked better than others. Indeed, to find answers to these questions was the purpose of the AIRP-SD research. Thus, an ancillary objective of the AIRP-SD project was to design an appropriate method for evaluating sustainability-oriented research programmes.

The lack of an established body of theory and practice at the start of the AIRP-SD project suggested the need to develop one through an iterative, heuristic procedure, beginning with tentative hypotheses about the nature of the research processes that might support sustainable development and then testing, refining and validating the hypotheses through the evaluation process itself (Weaver 2002a). The first set of working hypotheses was based upon what can be deduced about innovation for sustainability from the concept of sustainable development itself or from the nature of the socio-ecological system of interest or from experience in handling analogous complex problems.

The AIRP-SD project identified three connected objects for evaluation: the outcomes of research programmes; the quality of research design, process and management and the innovation context. In addition, using the normative-deductive approach described above, the project specified a set of goal-oriented and process-oriented sustainability principles. These include: the maintenance of ecosystem function and diversity; intergenerational equity; intragenerational equity; broad participation; promoting actions to face vulnerability and build resilience; precautionary action; knowledge sharing and mutual learning; transparency and justification of decision making; global and systemic approaches (which include spill-over impacts); and, the use of appropriate issue-scale boundaries (space-time boundaries) in problem analysis. Again, using a normative-deductive approach and reflecting upon the challenges that sustainable development poses for innovation, the project set out a broad set of generic outcomes that innovation for sustainability could target including: visions and indicators of desirable socio-economic futures; new solutions to development problems consistent with such visions (e.g., new production-consumption systems or elements thereof); models and information in support of transition processes; new supporting scientific capital and capacities; and, new supporting social capital and capacities.

The approach of AIRP-SD was that research programmes could be evaluated on the basis of the strength of their contribution to these outcomes, that the quality of the research design and process could be evaluated on its degree of conformity with sustainability principles, and that the context for innovation could be evaluated on the basis of the status of the national innovation system in relation to how well this facilitates meeting the sustainability challenges faced. As working hypotheses, the project was developed from the propositions that: contextual conditions influence both innovation efforts (level, design quality, orientation; etc.) and innovation outcomes; research design and management quality influences the nature and quality of innovation outcomes; and, contextual conditions, research design and process characteristics and programme outcomes are interconnected dynamically through a feedback loop (Weaver 2002a, Weaver 2002b).

To test these hypotheses evidence was collected for each of the nine programmes to enable judgements to be made about programme contexts, designs and outcomes. Judgements were made about the strength (strong, weak, neutral) and direction (positive, negative) in relation to how well contextual conditions facilitate innovation for sustainable development, in relation to how well programme management and design conform with sustainability principles, and to how well programme outcomes contribute to sustainability goals. Different relevant features of programme contexts, research designs and outcomes were first evaluated separately and then the links between the evaluation objects were analysed. In this second step, it was possible to evaluate the influence of each feature of a programme design on programme outcomes, the influence of each feature of a programme design on all other design features (to explore synergies), the influence of context on programme design (to explore context dependency and transferability of innovative design features) and to evaluate any programme-induced changes in context.

Clearly, good practice may be context specific in some instances, but may also be in the form of generalisable lessons. There was certainly a good deal of conformity across programmes about the importance of adopting liberating financial and administrative models, reconceptualising the innovation challenge, setting ambitious targets, adopting a systems approach, adopting a co-evolutionary approach, practising transdisciplinarity, using iterative and participatory procedures, using multi-purpose and multi-functional tools/methods, etc. It also seems to help to have an influential, respected and charismatic person to make the initial breakthrough by taking the fight to the funding agencies to win backing for a sustainability-oriented RTD programme and/or to have a creative administrator in a funding agency who is willing to risk some percentage of a research budget on efforts aimed at supporting long-term sustainable development and scientific renewal.

5. Good practice in science for sustainable development

Findings from the AIRP-SD project support the hypothesis that research programmes that are designed, administered and implemented in conformity with sustainability principles and goals and which practice the principles of sustainability deliver outcomes that support sustainable development. Furthermore, there are clear synergies among design features of successful programmes. By way of example, broad participation and transdisciplinary working is an important design feature for sustainability-oriented innovation. So is an iterative research procedure. But the presence of both in the research design is what provides opportunity for mutual learning and enables assumptions and positions to be revisited in the course of a programme, paving the way for a dynamic adjustment in the research process, which is needed to build compromises and to handle risks and uncertainties. Just as sustainable development represents a coherent, integrated, systems approach to finding solutions to development problems, innovation in support of sustainable development needs to adopt a compatible systems approach. This requires that the approaches taken to research management and design integrate sustainability principles and objectives into each and every aspect of process.

Recommendations for sustainability-oriented research programme design and conduct are summarised in Table 1 (Jansen *et al* 2003) and in the following paragraphs. Detailed results and examples of good practice are reported elsewhere (Funtowicz *et al* 2003). Summary conclusions cover appropriate financial models, organisational models and research models for sustainability-oriented RTD programmes together with suggestions for managing cross-cutting aspects of programmes, including knowledge management, communication and dissemination, and the handling of risk and uncertainty.

Financial model: Given the multiplicity of objectives that sustainable solutions are asked to meet and the trade-offs between these that are implied, a diversity of funding sources (co-funding arrangements) together with flexible funding mechanisms that are oriented to problem-solving (phased funding arrangements with in-built decision moments) are best suited to provide for the independence and integrity of researchers and research results. Such financial models also enable innovative 'checks and brakes' mechanisms to be incorporated. Because learning and sharing knowledge are key components of the sustainable development process, funding should cover the creation of knowledge partnerships, training activities and quality assurance procedures. Dedicated funding is specifically required for promoting internal cross-learning among programme projects or components and for promoting external knowledge sharing with stakeholders and the general public. Owing to the long-term nature and inherent uncertainty and complexity of sustainability-oriented research a balance is required in financial management between traditional approaches and openness. Schemes and criteria for programme evaluation are needed that allow for uncertainty and risk

Organisational model: Considering the high degree of complexity and uncertainty surrounding the objects and modes of sustainability-oriented research, flexible management and decision making patterns (adaptive management) embedding change as a structural factor and oriented toward participatory problem-solving are needed. Openness, transparency and accountability of management are important guiding principles for the good governance of programmes. Continuous quality assurance procedures by processes that engage an extended research community and mechanisms for extended consultation/participation with stakeholders across societal sectors are needed. Because socially robust (shared) decisions are highly desirable, there is a need to re-define success factors for management away from simply financial factors so that these include the guiding principles just listed: participation, openness and transparency. Managers' profiles and selection criteria might be modified accordingly and enhanced via on-going learning. Equally, because sustainability research transcends natural and social sciences, management and research teams should engage multi-disciplinary capacities to enable new forms of problem conceptualisation and new pathways for solving problems to emerge.

Research model: Quality checks are needed at the exploratory and initiation phases of research programme set-up to ensure all required aspects and stakeholders are duly considered and to ensure internal consistency. There is a need to ensure complementarity and coherence among components of research design and process. The programme design should preferably be inter- and trans- disciplinary, long-term oriented, implementation oriented, vision led, and system based including global concerns. Broad participation mechanisms from exploration and initiation phases are needed with repeated moments of participation throughout the research programme in order to build a basis of shared knowledge and supporting 'language' to allow interchange of knowledge and information as well as to promote discussion and bargaining of values. The selection of activities for funding should be open to scrutiny via transparent criteria. Accountable evaluation methods are required based on transparency and upon input from representatives of multiple interests. Multi-functional approaches and tools should be used in the research to develop and to evaluate developmental options and these should be justified in terms of legitimacy, fitness for purpose, reliability, etc. Quality assurance procedures are needed at each outcome level.

Knowledge management, communication and dissemination: Science for sustainable development implies a paradigm shift in research, development and innovation. The main issues for knowledge management relate to sustainability awareness raising, knowledge sharing, mutual learning and quality assurance to assure legitimacy of both research and practice. Essentially, these call for a new model of science for policy based on a co-production of knowledge. In turn, this calls for a democratisation of the research process, which requires extended participation across societal sectors and accountability of different perspectives. This requires mediation structures, spaces and processes to be created within RTD programmes to enable different types of knowledge to be exchanged and mediated into useful input for sustainability research, especially in relation to problem-framing, the creation of shared visions and the evaluation of research processes and products. Inter- and trans-disciplinary research implies a "mixed" community of researchers and research users, so knowledge has to be prepared for many different audiences if sharing is to be successful. Time must be invested in developing and clarifying meanings and a common language. Equally, when dealing with external audiences, training and dissemination efforts should be tailored for specific target groups. The range of such groups necessarily extends in sustainability-oriented research well beyond the usual scientific peer groups of normal science. In essence, sustainability research can be considered as a platform for multiple languages, perspectives and scales; this needs to be operationalised through methods that create contexts of dialogue among diversity and plurality. Quality checks by peer reviewers and by users (extended peer reviews) are needed at all stages in the research in order to attain socially robust research processes and products.

Uncertainty and risk: The management of uncertainty and risk must be considered explicitly in the research design, not only because sustainability problematiques are inherently prone to uncertainties, but also because programme outcomes may be further sources of uncertainty and risk when RTD programmes are highly innovative and are concerned with innovation in situations characterised by vulnerability. Management of risk and uncertainty in such cases depends upon establishing assessment activities and on creating resilience conditions for adaptation, such as strategies for coping with unintended effects. Risk and uncertainty management activities therefore need to be transversally integrated into programmes in a recursive and reflexive way. Equally, special efforts are needed to communicate uncertainty and risk. Essentially, uncertainty, lack of knowledge and potential risk are drivers for more inclusive and accountable governance agendas. Hence the communication of uncertainty and risk - as ever, tailored to the needs of specific target audiences - is an essential step in attaining shared decisions and policies.

6. Conclusion

In sum, there is an urgent need to adapt national systems of innovation to meet the challenges and opportunities of sustainable development.

In designing research programmes that are intended to support sustainable development there is a special need to consider programme structure and process alongside programme content since these are important features of design that have been found to impinge strongly on the success of programmes, especially in the extent to which they enable a research programme to practice the principles of sustainable development and, through this, to build new capacities, competencies, processes and structures that are intrinsic components of sustainable development.

Just as important for our national innovation systems is that results from the AIRP-SD project support the possibility of establishing a positive feedback loop through which successful sustainability-oriented research programmes might leverage the effectiveness and sustainability impact potential of future efforts in support of sustainable development, including future sustainability-oriented programmes, by inducing changes in innovation contexts, in innovation policy and in innovation capabilities and capacities.[5]

The way to strengthen our national innovation systems so that these target and support sustainable development is, therefore, to integrate the principles of sustainable development thoroughly throughout a set of pioneering RTD programmes. By practising sustainability principles in innovation processes, we change the processes of innovation and, over time, the structures that characterise and define our national systems of innovation and their application contexts, making these increasingly more open to and supportive of development that will be more sustainable. As in many other areas, the applicable adage here is that "practice makes perfect".

7. References

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[5] A good example is the Dutch Sustainable Technology Development Programme (Weaver *et al* 2000), which has had an important influence on thinking within the Netherlands about the role of technology in sustainable development, on the need to work simultaneously on innovation tracks with different time horizons and the importance of reflecting this at a national policy planning level by having two national environmental policy plans running concurrently, one for the short/medium terms and the other for the long term. Substantial funding has been made available within the Netherlands for sustainability-oriented research by hypothecating part of the natural gas revenues to this purpose. When the Dutch take over the Presidency of the European Union later this year, the Dutch government will promote eco-efficiency as the way for the Union to achieve its sustainability and competitiveness goals.

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Table 1: RTD programmes for Sustainable Development - from start to finish

(Adapted from Jansen *et al* 2003)

Many reference manuals and guidelines on RTD programme design and management exist already, describing principles and methods which are often applicable also to sustainability-oriented RTD programmes. For this reason, we concentrate here on those special recommendations for RTD programme management and design that are specific to – or especially important for – sustainability-oriented RTD. Clearly, since contexts vary markedly between countries, flexibility is needed in setting up sustainability-oriented RTD programmes. In effect, there are few hard-and-fast rules that can be articulated for the design and management of sustainability-oriented programmes, but rather a framework of broad principles which needs to be interpreted flexibly according to the application context. This table focuses on issues that will need to be resolved in the course of programme set up and gives some practical hints, especially about potential pitfalls in programme set up and ways of avoiding these.

Phase or element	Practices	Pitfalls
Contextual conditions	Context influences: o the possibility to set up sustainability-oriented RTD o the design characteristics of the RTD activities There needs to be a sense of urgency in science, policy and society for the sustainability challenge to be taken up through RTD.	There is seldom consensus within science, politics and society on the urgency of the SD challenge. Framing the issue solely in terms of SD is unlikely to be helpful in gaining broad support for tackling SD problems. More useful is to transform the SD problem into a challenge that has *a broad base of potential support*; i.e. one that appeals to many parties to work on and that may even be perceived by "SD-non-believers" as holding potential benefits.
Initiation	Given the urgency of many SD problems, there may be a wide range of potential research initiators from among the set of affected parties and stakeholders. To be effective, initiators should be in a position (or hold a role) that gives them access to the major actors implicated in the problem and its potential solution. Initiators will be inspired and / or supported by different actors, including NGOs, industry, academics, civil service etc.	Timing is critical. A good proposal at the wrong moment may lose the opportunity for years to come. Therefore, the ground needs to be prepared by the initiator and supporting parties before launching the proposal to ensure a receptive context.

Exploration	The initiator(s) prepare a rough sketch of the programme, its basic principles and its goals in relation to the problem it seeks to address. This is the first opportunity to embed sustainability principles into the programme design and objectives. On the basis of this rough sketch, individuals and organisations potentially important for the problem solution need to be identified and invited to explore the outline programme to see whether the challenge is recognised, whether there is sufficient support for the programme, whether and how changes might be made to the programme that would broaden the appeal, to allocate roles in the programme, and to determine which networks are essential for the ultimate success of the programme*, i.e., which parties may in the end be interested to implement the results, so that they might be involved from the beginning.* During this process of exploration the circle of involved parties may be widened on the basis of suggestions and support from the parties already engaged. The exploration results in a programme draft.	Not spending enough time or care during the exploration phase risks problems later, including loss of time in later phases of a programme. This is a real and big risk, which has beset many programmes. Exploration is not an open bottom-up exercise. The initiator should have a clear vision on the challenge and be able to explain and defend it, but the vision should not be so detailed that it is closed to modification, to filling in or to re-interpretation from the position of the stakeholders party to its discussion. In a final plenary meeting with the various parties involved in the exploration phase, the parties will need to recognise themselves and their contributions in the draft programme and its vision.
Process Monitoring	Usually sustainability-oriented RTD programmes are not stand alone programmes but rather are part of a learning process towards a transformation of society. To make the experiences and "lessons" of one programme or project available for new programmes and projects (and for educational purposes more generally) monitoring and reporting processes need to be established already from the very beginning. This covers, also, the need for comprehensive descriptive materials about programmes and projects, including relevant policy documents, descriptions of management structures and principles, decision making processes, involved parties, financing and organisational aspects, etc.	For many national programmes, monitoring is a condition for approval; however, monitoring is often perceived as a burden, which should be reduced to the bare minimum. Adopting such an attitude risks losing many chances to learn *even in the programme itself*. It is strongly recommended therefore to set up a monitoring plan with elements to be monitored and with a clear responsibility for its implementation and maintenance right from the beginning.
(Provisionary) Principles and Mission	The programme draft should contain the objectives of the programme, its mission and its provisionary principles. These should be in line with SD principles and reflect aspects such as how risk, transparency, participation and communication will be handled.	Constituting a programme draft is not an administrative operation. It is an essential element in the processes through which both creativity and support are to be gained. The operation should be iterative. In iterative processes, creativity may be developed in small groups or by individuals, but the results have to be checked and amended in larger supporting groups of potential partners and stakeholders.

Preparation	From the initial exploration phase, the programme draft has to be transformed into a full proposal that fulfils the requirements of research investors and others who will play decisive roles in the execution of the programme. The programme draft must also win their trust. The efforts to be delivered and the process of research to be undertaken should be clearly described. The proposal should be ready for start-up including the availability of main staff and the commitment of relevant institutions and organisations.	There is a tension between the inherent flexibility needed in SD-oriented research and the unpredictability as regards programme outcomes on the one hand and the need for certainty of RTD investors about the work to be undertaken and the products to be delivered on the other. A compromise can be achieved by building GO/ NO-GO decision moments into the funding arrangement with judgements about programme continuation based upon the monitoring of interim results, especially interim process-related outcomes.
Profiles of people	The nature of sustainability-oriented research and RTD programmes justifies additional requirements on the part of the engaged scientists and staff that go beyond the “normal” requirements on employees merely fulfilling their routine functions. In particular every researcher, research manager or member of a steering body should have a sense of the meaning of sustainable development and its implications for the conduct of the research (e.g. transdisciplinary attitudes and skills, participatory research processes, etc.). A “champion” who leads by example is needed. Members of steering bodies should preferably act on the basis of their authority in the field rather than as representatives of interested parties (i.e. genuinely be willing to provide *independent* judgement and advice). In the spirit of working toward alternative futures, those who will live in those futures and have a vested interest in them, should be engaged in the work. Young scientists should be encouraged to be active in sustainability-oriented RTD programmes.	It would not be the first time that for understandable reasons (lobbies, time pressure, lack of availability), risks are taken in the appointment of the personnel who will perform crucial functions in the research. Time spent searching for appropriate personnel will be well spent.

Organizing Support and Commitment	Organizing support for and commitment to a programme among partners (actors and stakeholders) is essential for the conduct and success of a programme and is a central objective of its communication activities. Mutuality and interaction are in turn characteristics of the communication strategy. Effective communication in support of commitment- building depends on integrating basic SD principles into the communications strategy (which will enhance almost all aspects of the programme) and on developing an awareness of the needs, sensitivities and interests of specific partners with whom communication and dialogue needs to take place. Already in the very first phases of establishing a programme, an inventory should be made of organisations and individuals likely to play a role in the success of the programme and the take-up of its results. This inventory seeks to establish the interests and positions of organizations and individuals (their currency) in their playing field (their arena). An inventory may serve to help make potential benefits of the programme explicit to potential partners or to add value to the work of the programme and its outcomes from the perspectives of partners and so help enlist their involvement and support. It may deliver a basis for negotiations on funding or on the active participation of potential partners. Continuous updating of this inventory is advantageous during the whole life of the programme.	Creating false or inaccurate expectations about results is to be avoided since even if this helps win early support for and commitment to a programme from partners, disillusionment in later phases is counterproductive and can lead to a potentially damaging loss of trust and credibility in the programme. Co-funding by industry offers multiple potential benefits beyond the research investment itself; it may strengthen industry commitment, increase the chances that results will be implemented in practice and provide opportunities to reach out to other partners through industry networks. The other side of the coin is the risk of focusing too strongly on the interests of the co-funder and thereby of under-representing the interests of other stakeholders. This puts adherence to SD principles at risk.
Communication Model	Communication is a continuous activity from the beginning to the end of a programme with a fluent change over from internal communication to external communication and vice versa. Provisions have to be made to disseminate the knowledge gained in the programme adequately and to assure its effective use.	Communication is frequently considered as a side issue to which not too much time and money should be spent. In sustainability-oriented programmes, the contrary is the case; communication is an essential responsibility and one of the most important. The whole palette of communication means, from bilateral to public, internal and external, has to be used. Communication principles have to be established from the start, corresponding to SD principles on participation and transparency. Within this frame, however, different forms and attitudes are possible and are necessary in order for communication efforts to be tailored to the needs of specific stakeholders.

Organization Model

Continuity, credibility and trust are requirements for any organization. In SD-oriented research, which requires flexibility, confronts uncertainty, and must work with stakeholders having a range of often-conflicting interests, credibility and trust are even more important. A constitutional document establishing the programme and describing the roles, tasks, rights and responsibilities of the various parties may be the basis of commitments to it by various organisations, institutions and individuals. The programme constitution is likely to include a programme steering group to which the programme management is responsible and a broadly- based expert consulting or sounding board whose members have authority in their own personal capacity. A specific organisational problem has to be solved when the programme is carried by a bureaucratic organisation, such as a ministry or large scientific institute. A positive characteristic of such organisations is that they create and maintain certainties (for public, politics, clients), which tends to make them trustworthy. However, sustainability-oriented research is intrinsically engaged in a search for systems-level and paradigmatic change that takes us beyond the realm of past experience. By definition, it implies uncertainty. To be involved in such research implies a risk of loss-of-trust for the organisations concerned.

Insufficient distance (figuratively and literally) of the programme to its commissioner may lead to continuous tensions within the programme and attempts to interfere in it by the commissioners (e.g. for economic or political reasons). This intrinsic tension requires some distance to be created between the programme and its commissioner.

Financing

Especially when public money is at stake an optimum has to be found between the need for independence of the research and the need to give account for expenses. This means that the research efforts, the administration, the research process (principles, domain of research), a rough time schedule, a beginning and an end in time, all have to be established and assigned. In this balance, trust in the programme leader and in the programme management capacities plays a key role.

The best way to ascertain real interest in the programme and the commitment to it of private parties is through their participation, be it in “cash” or “in kind” . Substantial financial contributions should not be expected: within prevailing socio-economic structures, private investment in long-term research with high risks and great uncertainties (and with the objective to change production systems) is unlikely. Strategic considerations relating to the future survival and role of a company in new markets constitutes the most likely argument or driver for private parties to participate in sustainability-oriented programmes.

To reduce the risk of non application of research results, the participation of stakeholders (more specifically those with potential to play a decisive implementation role) is essential. However this holds the danger of biasing research toward the production of potential private benefits. Societal aspects like inter- and intra- generational equity tend to be under-developed. The use of a "factor concept", such as an ambitious eco-efficiency target grounded in the wish to meet the (basic) needs of whole future generations may be one of the countervailing means.

Programme management	SD principles should be applied not only in the research execution but also in the research management. This is an extra requirement over and above the usual norms of sound programme management. In view of the characteristics of SD research (complexity, uncertainty, many stakeholders, high stakes, contested facts, etc), programme management has to pay specific attention to striking pragmatic balances within an overall systems approach (e.g., balancing tensions over the means, capacities and timings of contributions by various parties, bridging tensions between the development of creativity and of broad support, shaping forms for participation and transparency, etc). A repeated, iterative approach is needed throughout the research process from problem definition and goal setting to implementation, through which outcomes at each stage might be shaped in a creative setting and checked and amended in a supportive setting with relevant stakeholders (social process). Synergies between projects within the programme should be sought to strengthen opportunities for new perspectives on solutions to emerge and to help inter- and trans-disciplinary working.	Sticking to existing paradigms and/or focusing on disciplinary contributions may block creativity in finding breakthroughs. Nonetheless, there is need early on to establish clear definitions, understandings and ground-rules for the research process among participants in order to avoid problems in later phases.