DECISION SUPPORT FRAMEWORK FOR INFRASTRUCTURE STRATEGIES

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ABSTRACT

The national economy is supported by environmental, economic and social infrastructure networks. These infrastructure networks are highly interdependent due to linkages between the networks. Often these infrastructures are managed independently of each other. Changes in one sector of the economy will affect other sectors through linkages between sectors of the economy and together reach a new equilibrium. Interdependence between infrastructures indicates that national objectives will not be achievable through strategies focussing on one sector at a time or one infrastructure at a time. Policy makers need a methodology to guide them through a series of interrelated policy and investment interventions over time to improve the national operating capabilities embedded in interdependent environmental, economic and social infrastructures. This paper presents an integrated decision support framework which allows policy and investment options related to the operating capabilities of the economy to be evaluated holistically in terms of three sustainability measures: welfare of the people, environment and economy.

The approach in this paper is to present the results of a literature review of related frameworks and models and to present an integrated framework and model which is able to express the impact of policy and investment interventions in infrastructure networks in terms of the three sustainability measures.

We conclude that the objective may be achieved through a decision support system (DSS) supported by hybrid model consisting of an integrative macro economy model and sector specific infrastructure model with sufficient technological explicitness to evaluate the impact of policy and investment interventions. This hybrid model should reflect the interdependence between infrastructures.

The integrated decision support framework will enable policy makers to evaluate the trajectory of national operating capabilities over time with and without specific policy and investment interventions within the context of a hybrid model of the integrated economy that reflects the infrastructures of sectors of the economy.

This paper is relevant to economic and social impact of technology, to national and regional technology policies and infrastructure, and supports the theme of technological planning, foresight and forecasting.

Key words: DPSIR Framework, Decision Support, National Infrastructure, Multi-sector, Economy, Social, Environment.

P039

INTRODUCTION

Economic and social infrastructure networks

Sustainable development in practice needs to achieve a balance among economic, environmental and social objectives for both present and future generations. Depending on the national imperatives, one of these aspects may dominate to the neglect of others. National strategies need to develop the ability to consider and make trade-offs among economic, environmental and social objectives in policy making. (OECD, 2006)

Social, economic and environmental health of a nation depends on the efficient and reliable operation of environmental, economic and social infrastructures. Economic infrastructure networks such as transport, electricity and water networks support economic activity, while social infrastructure networks such as health, education and security infrastructures and services impact on the welfare of people. Environmental infrastructure networks such as water treatment and waste processing impact on the quality of the environment and its capacity to sustain life. The environmental, economic and social networks are interdependent, dynamic and complex.

These infrastructures evolve over time in response to policy and investment interventions to adapt to changing demand. Ideally, decision makers should make decisions to improve the welfare of the people while also ensuring a sustainable future. These conflicting objectives are more difficult to achieve where multiple stakeholders participate in the decision making process.

Infrastructure governance limitations

The organisational structure tasked with governance and strategic interventions into national infrastructures is typically bureaucratic and infrastructure types are allocated to different departments matching sectors of the economy. This organisational structure may recognise the interdependence of infrastructures, but typically manages the infrastructures independently. (Peters, Kumar, Zheng, Agrawal and Peeta, 2014) This effectively results in a reductionist management approach that ignores the behaviour of a complex system of interdependent infrastructures. (Anderson, 1971) The behaviour of complex systems requires a form of management and tools and practices that are able to respond to unpredictable behaviour emerging from the integration of multiple distributed infrastructures that serves multiple stakeholders. The Cynefin framework proposed by Snowdon (2002) distinguishes between order and disorder, and uses this distinction to match a system management problem and its context to a suitable management approach. It follows that managing individual infrastructures separately may not fully achieve the national objectives, because the management approach is not appropriate to the problem space as indicated in Figure 1.

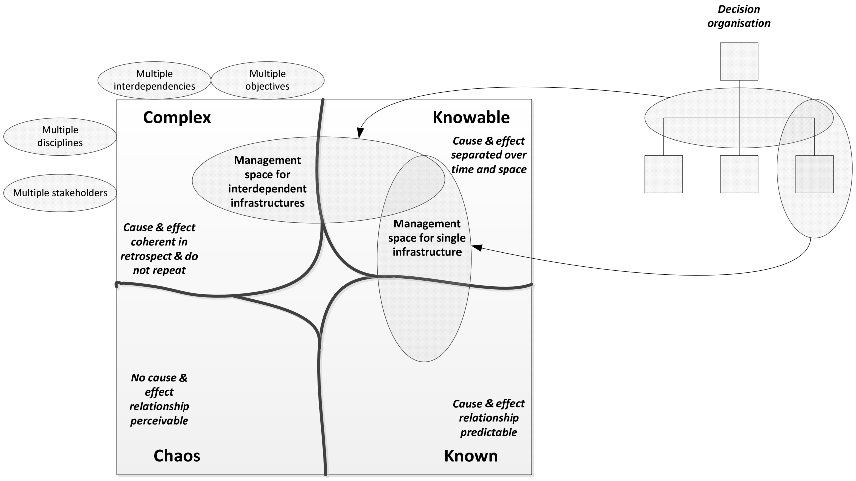

Figure 1: Problem Statement in context of the Cynefin framework adapted from Snowdon (2002)

Multiple interdependent infrastructures each introduce their stakeholders to the problem space. It follows that there is a need for a problem structuring method that will enable multiple stakeholders of environmental, social and economic infrastructures to participate in the decision-making process to achieve an informed, joint solution which is inclusive and sustainable. The problem structuring method should provide a mechanism to cast a complex problem into a structure that allows multiple decision makers to gain the required insight into the complexity of interdependence to develop acceptable solutions that enjoy the support of stakeholders.

The decisions that effect policy and investment interventions into national infrastructures are made under uncertainty. It is common that the current state is not fully known and the future evolution of the system is influenced by drivers, some of which are uncertain and outside of the control of the decision makers. Examples of these drivers are global economic growth, population growth and cost of energy over time. Scenario planning has emerged as a suitable approach to create coherent and plausible future evolutions of these external drivers as context for evaluation of intervention options. Prospective intervention options should be evaluated under multiple scenarios to assess their impact on social, economic and environmental measures to select and plot an evolutionary development path for infrastructures.

Decision making which affect national infrastructure networks involves multiple stakeholders with multiple domain specific objectives, some of which may not be mutually supportive and even conflicting. Examples are the objective to achieve economic growth and the objective to improve the health of the environment. Multiple stakeholders that pursue multiple objectives in a common problem space indicates the need to apply multi-criteria decision analysis (MCDA) to support these complex decisions.

This paper proposes a framework for problem structuring and decision support for decisions relating to policy and investment interventions in national infrastructure networks. It proposes a method for multiple stakeholders to make informed decisions on a sequence of interrelated interventions in national infrastructures by understanding the combined impact of these interventions on the welfare of people and the environment. Figure 1 indicates that the problem space spans the complex and knowable domains of the Cynefin framework and thus the methods which should be applied should be appropriate to these domains. The relationship between hierarchical governance structures and potential loss of consideration for emergent properties of interdependence is also indicated.

The rest of the paper is structured as indicated in Figure 2. First we provide an overview of problem structuring methods appropriate for complex interdependent national operating capabilities. We then provide an overview of modelling approaches applied to interdependent national operating capabilities that reflect social, environmental and economic objectives. This is followed by an overview of MCDA methodologies used in decision support of multiple diverse stakeholders. We then propose a model based multi-methodology approach that integrates methodologies which have successfully been used in complex domains and that is appropriate for joint decision making across organisational boundaries.

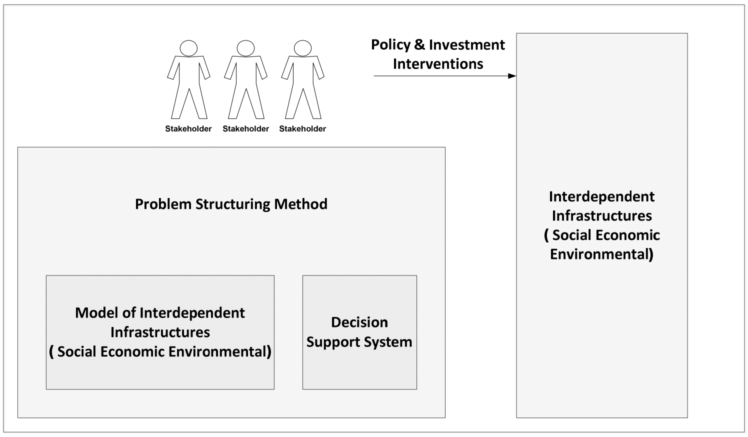

Figure 2: Methodology review

METHODOLOGY REVIEW

Problem structuring methods for multi-criteria and multi-stakeholder decision making

Problem structuring methods (PSM) represent a group of techniques employed to address complex problems with multiple stakeholders who have conflicting interests. PSMs are employed to enable understanding of the problem and increase engagement of multiple stakeholders into a participative process towards an inclusive solution. PSMs do not directly present a solution to problems, but are useful in structuring problems. (Rosenhead, 2013)

There is a considerable range of PSMs reported in literature applied to a vast range of problems. Three methodologies are prominent in literature: Soft Systems Methodology (SSM), Strategic Choice Approach (SCA) and Strategic Options Development and Analysis (SODA).

The SSM was developed by Peter Checkland as a modelling tool to structure problems and thinking around real world systems and problems. The SSM approach develops an ideal model for the system as objective and then compares the ideal model with stakeholder views of the current system. This objective of the approach is to propose improvements to the current system that meets the needs of stakeholders through engagement with the various perceptions that exist with stakeholders of a current system. (Checkland and Scholes, 1991 and Checkland, 1999)

The SCA is a methodology used for strategy development and planning. SCA is described as a planning methodology that accommodates uncertainty in problems and decisions. SCA is used in the context of a group of decision-makers to assist on decisions on strategic options. SCA uses a structuring of the problem and relationships between components of the problem space to discuss solutions through workshops. It is therefore an inclusive and participatory process. (Friend and Hickling, 2005)

SODA is a technique applied in groups to construct cognitive maps of how people perceive and think about a problem and is used to structure the problem using the views of the stakeholders in a work session context. Group consensus is negotiated via this process based on the structured problem. Consensus and engagement are the contributions of the process. (Dyson and O'Brien, 1998)

The PSMs discussed above are general in nature and may be applied to a large range of problems which involve multiple stakeholders. The Drivers Pressures State impact Response (DPSIR) framework is an example of a PSM which was developed in a narrowly defined problem space and then generalised to be applied on other problem areas. Yuting and Fan (2013), motivates the use of the DPSIR framework as PSM for a strategic innovation tool to be used by domain specialists to inform policy intervention. Bell (2012) also reports the application of the DPSIR framework in a multi-methodology approach for management of coastal management projects around the Mediterranean. He demonstrates that DPSIR is a useful and practical PSM when applied in a participatory and systemic multi-methodology process.

Models for Interdependent infrastructure

Engineering and economic approaches

Social and economic infrastructures and their interdependencies have been the subject of research by both the engineering and the economics community. The economic approach views interdependencies as exchange of monetary value between networks, while the engineering approach views interdependencies as functional exchange of commodities and services. There is a need to combine the two approaches.

In the engineering community significant research focus is placed on how infrastructure is interconnected and what functional cascading effects in interconnected infrastructures may result from failure in one infrastructure. (Rinaldi, Peerenboom and Kelly, 2001), Pederson, Dudenhoeffer, Hartley and. Permann, 2006).

Peters et al (2014) notes that an approach which neglects to include economic and industry response to the emergent effects of interdependent infrastructures does not capture the economy-wide implications relevant to policy analysis. They also note that models and theories are often limited to selected infrastructures and their interdependencies without consideration for interdependencies in the wider economy.

In the economic community the computable general equilibrium (CGE) models are used to capture interdependencies between infrastructures that are then expressed as market dependencies. A make-use table is one artefact in economic modelling that indicates the value of commodities used as input from other sectors to produce a unit of value output in the sector. In this context CGE models do not treat infrastructures different from a sector of the economy. It therefore does not explicitly capture physical characteristics of infrastructure networks such as capacity and throughput, which are critical design parameters in the engineering domain.

There is a need to combine the strengths of the engineering and the economic perspectives in a single hybrid framework which may inform policy and investment interventions relating to economic and social infrastructure networks. (Peters et al, 2014). This need is recognised and in response, engineering models attempt to integrate economic perspectives and economic models attempt to express technological explicitness.

Top down and bottom up approaches

The need for a hybrid approach is reinforced by Hourcade, Jaccard, Bataille and Ghersi (2010) in a review of top-down and bottom-up modelling approaches in the energy-economy decision space.

Bottom-up models in the energy sector describe the competing energy technologies and are useful in exploring possible technology futures with their respective environmental impacts. However, they do not sufficiently support macro-economic decisions related to different energy pathways such as impact on economic growth.

In contrast, top-down (TD) models, describe impact of policies on public finance, employment and economic growth, but are not flexible enough to incorporate impact of technological change beyond current state of practice. This is an inherent characteristic of CGE models the dominant economic model in use for policy analysis.

Hourcade et al (2010) illustrate the desirable features and shortcomings of the two approaches in three dimensions: Technological explicitness, Micro-economic realism and macro-economic completeness. Figure 3 implies that there is the possibility of an ideal model that satisfies all three requirements, at the rear right hand corner of the cube. To build the ideal model would be a huge undertaking, but a hybrid model which incorporates desirable features of bottom-up and top-down models will approach this ideal model objective. They conclude that hybrid modelling will face challenges in theoretical consistency between BU and TD approaches and will uncover limits in data required for empirical validation.

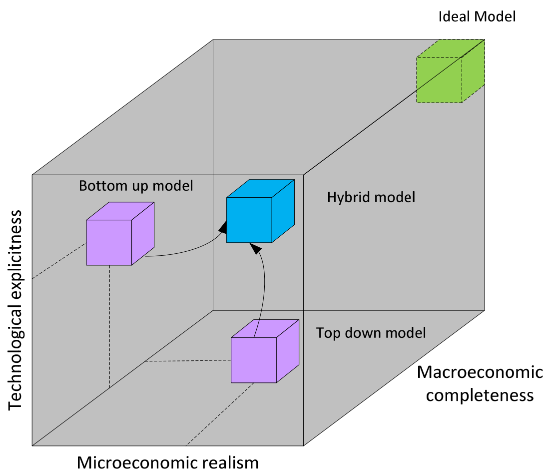

Figure 3: The case for a Hybrid Model (Hourcade et al,2010)

Developing a hybrid model requires a multi-disciplinary approach and a number of research projects typically focussed on energy and transport domains have reported advances towards this objective.

There are a number of examples of integrated models employed in the transport and energy domains that estimate the economic impact of infrastructure investments. The linkage between investment into infrastructure and economic impact estimated through economic modelling using CGE models and combined with traditional transport modelling. Transport models are used to estimate the change in flow capacity and cost advantages of the improved infrastructure. These research projects confirm the observations from Hourcade et al (2010) that the engineering and economic domains express their problems in vastly different levels of resolution and units of measure. Bridging this chasm has proven difficult and few practical models are in use. A number of frameworks provide insight into interdependence between infrastructures and we provide a summary of promising frameworks below.

Infrastructure computable general equilibrium (ICGE) Framework

Peters et al (2014) describe an integrated framework to capture the interdependencies between the transportation and energy sectors. They argue that the current approach to manage the transportation and energy sectors independently of one another will not achieve the national objectives because the approach does not take into account the emergence due to interdependence between the sectors. They present a system of systems based framework to evaluate interventions through policy and investment. Their infrastructure computable general equilibrium (ICGE) framework is based on the spatial computable general equilibrium (SCGE) model of the economy described in Shoven and Whally (1992) and integrates a transport formulation into the SCGE model. The study recommends that the interdependence between the transportation and energy sectors need to be reflected in an integrated framework. Also that policy interventions need to be evaluated by taking into consideration the wider economic implications and impact on national strategic objectives. The SCGE model is an appropriate foundation to incorporate wider economic impacts into the decision making process as the SCGE model is widely used for economic modelling. However, this study considers only interdependencies between the transport and energy sectors and achieves the integration via an economic model.

Complex, Large-scale, Inter-connected, Open and Socio-technical (CLIOS) Process

Sussman and Mostashari, (2008) describe the Complex, Large-scale, Inter-connected, Open and Socio-technical (CLIOS) process that uses a systems of systems approach to create and evaluate alternative design options to improve the performance of complex integrated infrastructures. The CLIOS process was conceived as a process to represent the characteristics of complex engineering systems with a range of social, economic, political and environmental impacts as an integrated whole consisting of physical systems and institutional structures. (Sussman and Mostashari, 2007) The CLOIS process is used to analyse the behaviour of the integrated and interdependent physical systems and to create strategic alternatives to improve performance. The process also identifies strategic alternatives to improve performance of the institutional system and potential linkages with implementation of improvements in the physical systems. The process then brings the physical and institutional alternatives together in a feasible strategy for implementation. (Chikhale, Mansouri, Mostashari and Efatmaneshnik, 2012) The value of the CLIOS process is the focus it places on an integrated socio technical system and participation of the stakeholders in identification of relevant alternatives. The institution is also treated as an integral part of the complex system. The CLIOS process has been applied to improve of the social, economic, political and environmental performance of cities.

Drivers Pressures State Impact Response (DPSIR) framework

The DPSIR framework was developed to structure environmental reporting and is widely used in this role in the Organisation for Economic Co-operation and Development (OECD) countries. Giupponi, Mysiak, Fassio, and Cogan (2002) applied the DPSIR framework to a decision support system (DSS) for water resource policy analysis at the catchment scale. They apply the framework to analyse causal chains to environmental impact in order to conceptualise and decompose the problem. This is followed by identification of implementation options that may improve the state of the environment. These options are then evaluated in turn through a modelling process that reconstructs the problem and applies the treatment options in the model to estimate the impact in the problem space. They add a DSS to the framework to assist decision makers in the selection of a suitable implementation option based on multiple stakeholder criteria. The options are assessed using MCDA evaluation techniques that expresses the preference of stakeholders. The DPSIR and DSS has potential to support decision makers in analysis of alternative policy alternatives to manage environmental impact on water resources in the European Union. The benefit of using the DPSIR framework to develop a DSS for water catchment management was the already wide adoption of the framework in environmental reporting.

Multidimensional Hierarchically Integrated Framework (MHIF) framework

Alabdulkareem, Alfaris, Sakhrani, Alsaati, and de Weck (2014) describe systems such as water and electricity networks as critical systems because of their impact on the social, environmental and economic health of society. They describe the system complexity in terms of functional complexity due to linkages between systems, spatial complexity due to the distributed nature of these systems and temporal complexity due to the evolution of system states as a result of investment and policy interventions over time. They present a Multidimensional Hierarchically Integrated Framework (MHIF) for modelling this class of complex engineering systems. The MHIF provides a generic mathematical formulation which allows multiple interconnected infrastructures to be represented as a series of states to represent temporal complexity. The framework represents functional complexity through decomposition of systems into layers, while the spatial complexity of each layer such as water and electricity is represented as coupled supply and demand components. The framework decomposes the complex system into interconnected building blocks that are modelled separately. The hierarchical decomposition allows modelling the system at various scales depending of required granularity. Building blocks are modelled as a combination of agent based modelling (ABM) and system dynamics (SD). SD describes agent internal behaviour. Possible future states of the system are modelled to evaluate different interventions in the system based on a set of decision variables. The system future states are modelled within a range of scenarios that are controlled by general driver variables. The system state is expressed as a set of key performance indicators. The MHIF provides a mathematical formulation to describe demand-supply flow through complex interconnected systems.

Multilayer infrastructure network (MIN) concept

Motivated by studies into vulnerabilities of integrated infrastructure systems and the need for integrated planning for infrastructure expansion to meet the demands of urbanisation, Zang and Peeta (2011) propose a multilayer infrastructure network (MIN) concept. They propose a generalised modelling framework to integrate a multilayer network representing various spatial infrastructures represented as layers. They use a market-based economic approach to reflect the linkages between the various infrastructure systems. The MIN concept models the various individual infrastructure networks independently and integrates the infrastructure networks through links that reflect the market interactions as demand-supply functions. The MIN concept uses the computable general equilibrium (CGE) theory, and its spatial extension SCGE, to model market interaction between sectors of the economy. Each individual infrastructure network represents a sector of the economy and a node in the infrastructure layer is a producer or consumer of commodities (such as electricity and fuel) that flow between nodes in an infrastructure layer. Flows between infrastructure layers are dependencies between infrastructure layers. The interdependencies are modelled in the CGE model via a production function whose parameters reflect the magnitude of the dependency. Network flow capacity, capacity constraints and cost of flow in an infrastructure is modelled in the production function. Investment interventions may be modelled through a change in a cost function or a change in capacity constraint. The use of CGE modelling to inform economic decisions in an economy is well established. The MIN concept proposes a generalised modelling framework to capture the interdependencies of physical infrastructures and provides a link between the engineering and economic disciplines in a single modelling framework that builds on the CGE model.

Robust Decision Making and Exploratory Modelling and Analysis

Robust Decision Making (RDM) is a decision-making framework that seeks robustness in policy or investment interventions. (Lempert and Popper, 2003) RDM creates a large ensemble of plausible future scenarios to challenge candidate policy or investment interventions. The outcomes of candidate policies are then evaluated against criteria to select robust rather than optimal strategies. Candidate strategies are preferred when they are able to adapt and perform reasonably well and fail in the least number of plausible future scenarios. RDM is computationally intensive as it requires evaluation of strategies under a large number of plausible scenarios. RDM engages the decision makers in an interactive process of discovery to select robust strategies under uncertainty.

Exploratory Modelling and Analysis (EMA) is an approach that uses computational methods to analyse complex and uncertain issues. (Kwaggel and Pruyt, 2013) EMA extends model based decision support methods where uncertainty in models and scenarios reduce the value of predictive modelling to support decision-making. EMA is useful where limited information does not allow a single model to be specified that adequately describes the system behaviour. In such cases more than one model may be specified that fits the available information. EMA allows computational experiments with a set of plausible models resulting from variations in uncertain information. EMA may be used to determine the extent to which uncertain information influences the outcome of the model of system behaviour. The decision-makers may then debate which policies will produce satisficing results across the alternative sets of uncertain information that determine system behaviour or future scenarios.

Assessment of current approaches for decision support in complex environments

The research literature indicates that there is a range of analytical methods for the estimation of the wider economic impacts that follow from policy and investment interventions into national infrastructures with varying degrees of complexity. Approaching the problem from the bottom up with an engineering focus, or from the top down with an economic focus or a hybrid approach that combines the two approaches, addresses only part of the problem space, as the social and environmental aspects are not adequately addressed.

The tendency to manage sectors of the economy independently, one infrastructure at a time has its origin in the hierarchical governance structure. The result is a reductionist management approach which is inadequate to respond to the emergent effects of interdependence between social and economic infrastructures. A review of research in infrastructure modelling that informs policy and investment interventions indicates that a decision support framework is required that allows the multiple stakeholders of social and economic infrastructures to participate in joint decision making process towards a common objective. This decision making process requires support from a multidisciplinary model of the problem space in which stakeholders recognise that their objectives are addressed.

Figure 4 indicates that the majority of reviewed frameworks address the complexity of interdependence with methods that are appropriate to the domain. The CLIOS and DPSIR frameworks are suited to incorporate multiple stakeholders of environmental, social and economic infrastructures, while the MHIF framework provides a detailed mathematical formulation of system states. RDM and EMS are suited to decision-making under uncertainty.

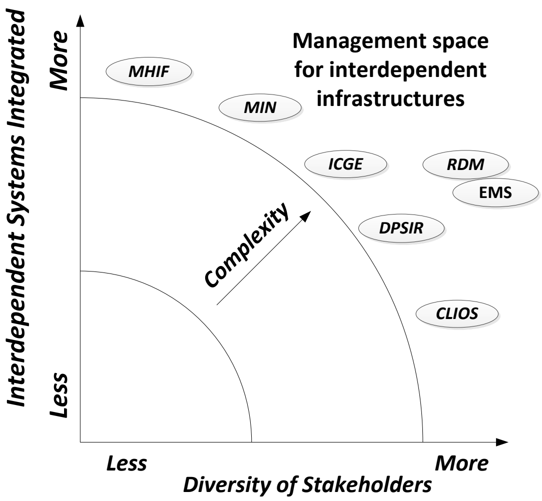

Figure 4: Mapping of Frameworks in terms of characteristics of the problem domains

Decision support methods for multi-criteria and multi-stakeholder decision making

Decision making that affects economic and social infrastructure networks involves multiple stakeholders with multiple domain specific objectives, some of which may not be mutually supportive and even conflicting. Decision makers are also plagued by cognitive biases that affect the quality of their decisions. The negative impact of cognitive biases on the quality of decision making has been reported by a number of academics (Kahneman, Slovic, and Tversky, 1982, Kahneman, 2011, Tversky and Kahneman, 1981). Stanway, Hart and Taylor (2013) note that the impact of cognitive biases are more pronounced within sectors of the economy where supply and demand cycles are slow, capital investments are large and benefits of capital investments manifest over longer periods. These conditions are present in decisions relating to national infrastructures.

In this context decision makers should benefit from a DSS that provides a formal structure to the decision making process, incorporates multiple criteria and allows multiple stakeholders to participate in the decision making process. MCDA is a collection of formal approaches that specifically include multiple criteria to assist individual or group decision making. Huang, Keisler and Linkov (2011) performed a survey of MCDA methods and their use in decision making in environmental applications and find that there has been significant growth MCDA tool integration into formal implementations of DSSs. They also find that where multiple MCDA tools have been applied to the same problem, the recommended course of action was similar.

Mendoza and Martins (2006) perform a critical review of MCDA methods applied to natural resource management and describe new MCDA approaches aimed at addressing the complexity of managing ecosystems, with respect to multiple criteria and multi- stakeholders. They find that effective decision support requires a participatory approach during all stages of the modelling process. Stakeholders or decision makers must be able to contribute to modelling through identification of model components, formulation of relationships, and the decision-making process. This implies that along with problem solving methods such as MCDA there is a need for participatory problem structuring methods.

MCDM methodologies may be classified as single objective decision making (SODM) methods, multi criteria decision making (MCDM) methods, and decision support systems (DSS) as indicated in Figure 5. (Zhou, Ang and Poh, 2006) DSS includes decision aiding tools that assist decision makers to overcome their limitations in judgement and is useful when confronted with complex and unstructured decision problems. DSS may include decision analysis methods appropriate to the problem domain.

SODM refers to methods for evaluating the available alternatives with uncertain outcomes under a single objective and methods applied include decision trees (DT) and influence diagrams (ID). MCDM allows decision makers to rank alternatives on the basis of trade-offs between a number of often conflicting criteria. (Colson and Bruyn,1989) The two groups of techniques under MCDM are multiple objective decision making (MODM) and multiple attribute decision making (MADM). (Yoon and Hwang, 1995) MODM methods choose the best among a set of conflicting objectives subject to constraints of the problem. MADM methods select preferred solutions from a set of alternatives through evaluation of multiple conflicting criteria. As indicated in Figure 5, there are a range of practical MADM methods in use.

Multiple attribute utility theory (MAUT) enables decision makers to express preferences as multiple attribute utility functions. (Keeney and Raiffa, 1976) The analytic hierarchy process (AHP) is a group decision methodology to structure the problem as a hierarchy of sub problems and to evaluate alternative solutions in relation to objectives. (Saaty,1990) The elimination and choice translating reality (ELECTRE) methods, is a family of outranking methods (Yoon and Hwang, 1995), as is preference ranking organization methods for enrichment evaluation (PROMETHEE). (Brans, Vincke and Mareschal, 1986)

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a method that selects a solution from a set of alternatives based on the shortest geometric distance from the ideal solution and the longest geometric distance from the worst solution. (Hwang; Lai and Liu, 1993).

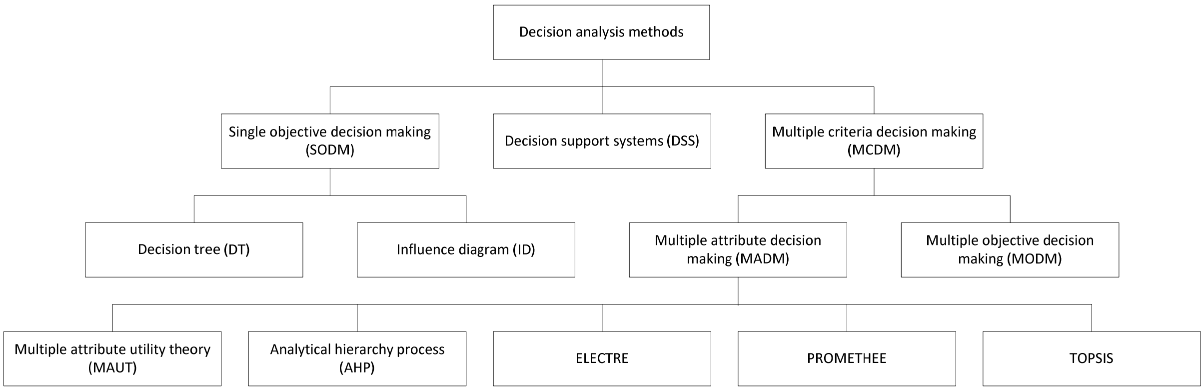

Figure 5: Classification of Decision Analysis Methods (Zhou, Ang and Poh, 2006)

MULTI-METHODOLOGY FOR INTEGRATED PLANNING

DPSIR framework as problem structuring method

The DPSIR framework describes the links between human activity and the resulting impact on the environment. The *drivers* in the underlying human processes lead to environmental *pressures*. Examples are growth in human population, growth in economic activity and changes in land use. The drivers in the underlying processes lead to pressures on the environment such as non-sustainable use of natural resources (forests, water and minerals) and pollution of water, air and land. These pressures on the environment impacts on the *state* of the environment and limits its capacity to support life and economic activity. Change in the state of the environment has an *impact* on human welfare and economic activity and ecosystem functions. The level of impact on the environment may be expressed as the extent to which value of economic activity and human health and welfare is impaired. The *response* represents the interventions by decision makers to reduce the adverse impact on human welfare and economic activity and ecosystem functions through policy and investments. These responses may be directed at a combination of changing drivers, reducing pressures and changing states. The DPSIR framework describes an environmental management process as an iterative cycle of reactive responses as shown in Figure 6.

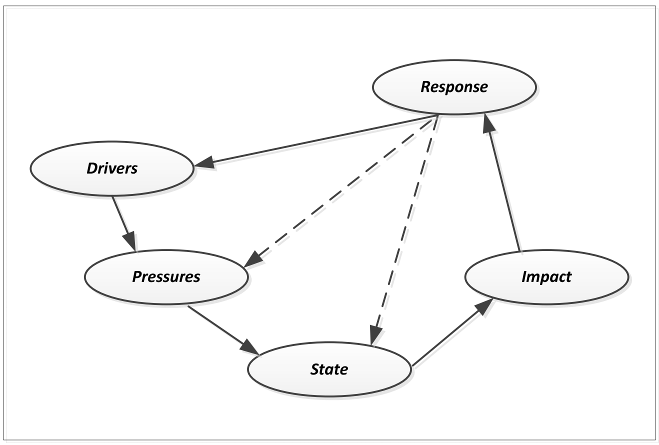

Figure 6: DPSIR framework

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Although the DPSIR framework was originally developed for environmental reporting, Guipponni et al (2002) added to the framework a DSS for management of water catchment areas and Bell (2012) reports the use of DPSIR in a multi-methodology DSS for coastal projects.

The DPSIR framework is expanded here to a general framework to inform decision makers responsible for governance across all sectors of the economy to aid decision making on interventions in interdependent national operating capabilities. This larger scope of application expands the original of terminology used in the DPSIR for environmental reporting as follows: The interest is in *drivers* that lead to *pressures* in the social and economic infrastructures, production and manufacturing and the environment, while the *state* describes the social and economic infrastructures and the environment. *Impact* is expressed in terms of social welfare, economic health and environmental health. In *response* to the expanded scope of drivers, pressures, state and impact, the interventions are aimed at a sustainable trajectory for the environment and socio-economic welfare of the nation. An example of the expanded scope of the DPSIR framework is shown in Figure 7.

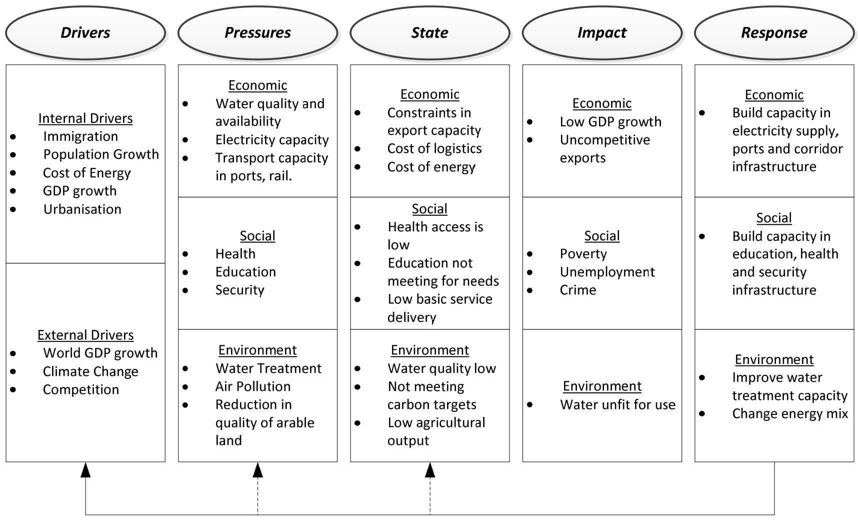

Figure 7: Example of DPSIR applied to national imperatives

DPSIR as decision support methodology for integrated planning

The DPS elements of the DPSIR framework is captured in a hybrid model that reflects the operating capabilities of the economic, social and environmental infrastructures at a resolution that is sufficient to evaluate impact of policy and investment interventions. The hybrid model estimates a measure of effectiveness for the operating capabilities of the economic, social and environmental infrastructures expressed in terms of criteria determined by stakeholders in the infrastructure and their capabilities. Acceptance of the model based measure of effectiveness is critical to the planning process. The model based measure of effectiveness criteria span the economic, social and environmental domains and should reflect the current state of the system and project an evolutionary trend for the next 30 years as a base case.

The IR elements of the DPSIR framework are implemented as an iterative experimentation by stakeholders with potential alternative interventions. For each alternative intervention option (and the base case), an evolutionary trend for the next 30 years is projected and evaluated in the MCDM (using TOPSIS in this example). The evaluation is recorded in the *analysis matrix* over the projected period. This analysis matrix reflects the state of the system as evaluated in terms of criteria determined by stakeholders over the projected period. The *evaluation matrix* represents the *impact* in the DPSIR matrix and is the consolidated value expression of the stakeholders combined. The evaluation matrix reflects the impact on the state of the system over the projected period expressed as the stakeholder value function for the base case and each intervention option over the projected period. An agreed stakeholder decision rule can then be used to select the appropriate intervention option, that is then implemented and incorporated as part of the base case. This process is shown in Figure 8 and in Figure 9.

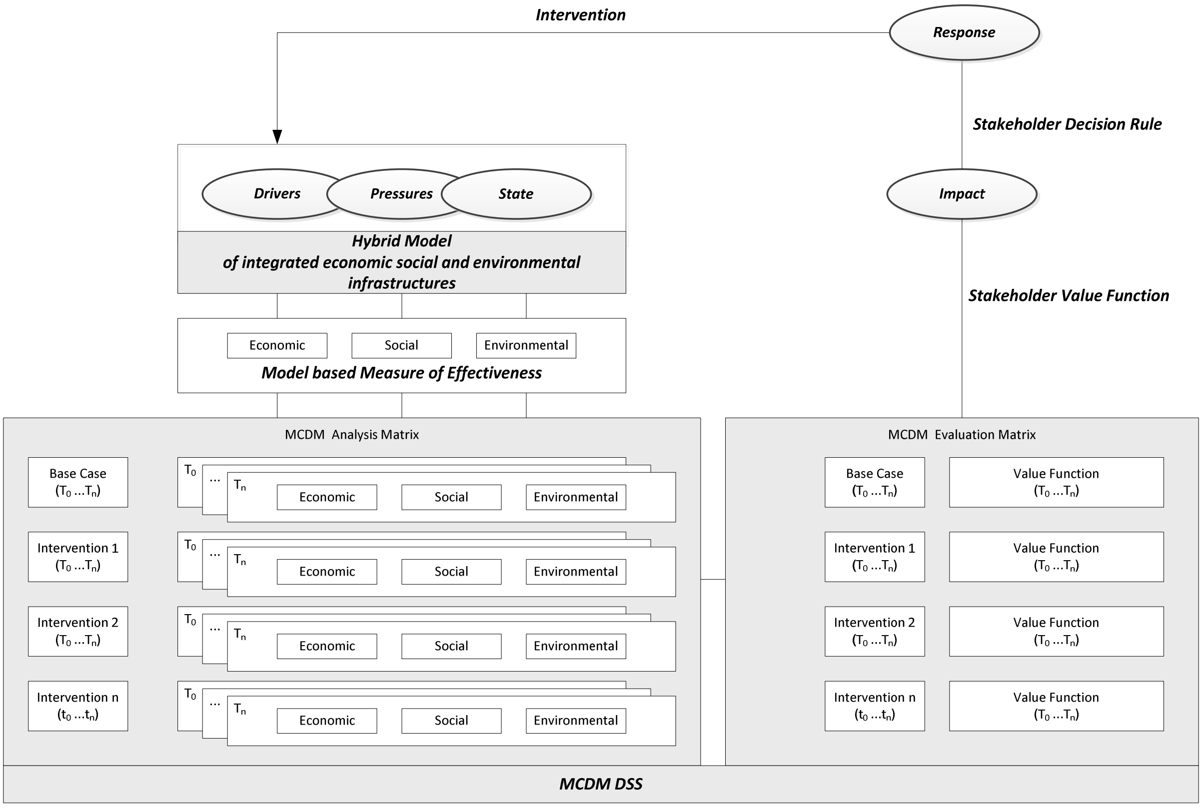

Figure 8: Integrated planning for interdependent systems based on DPSIR DSS

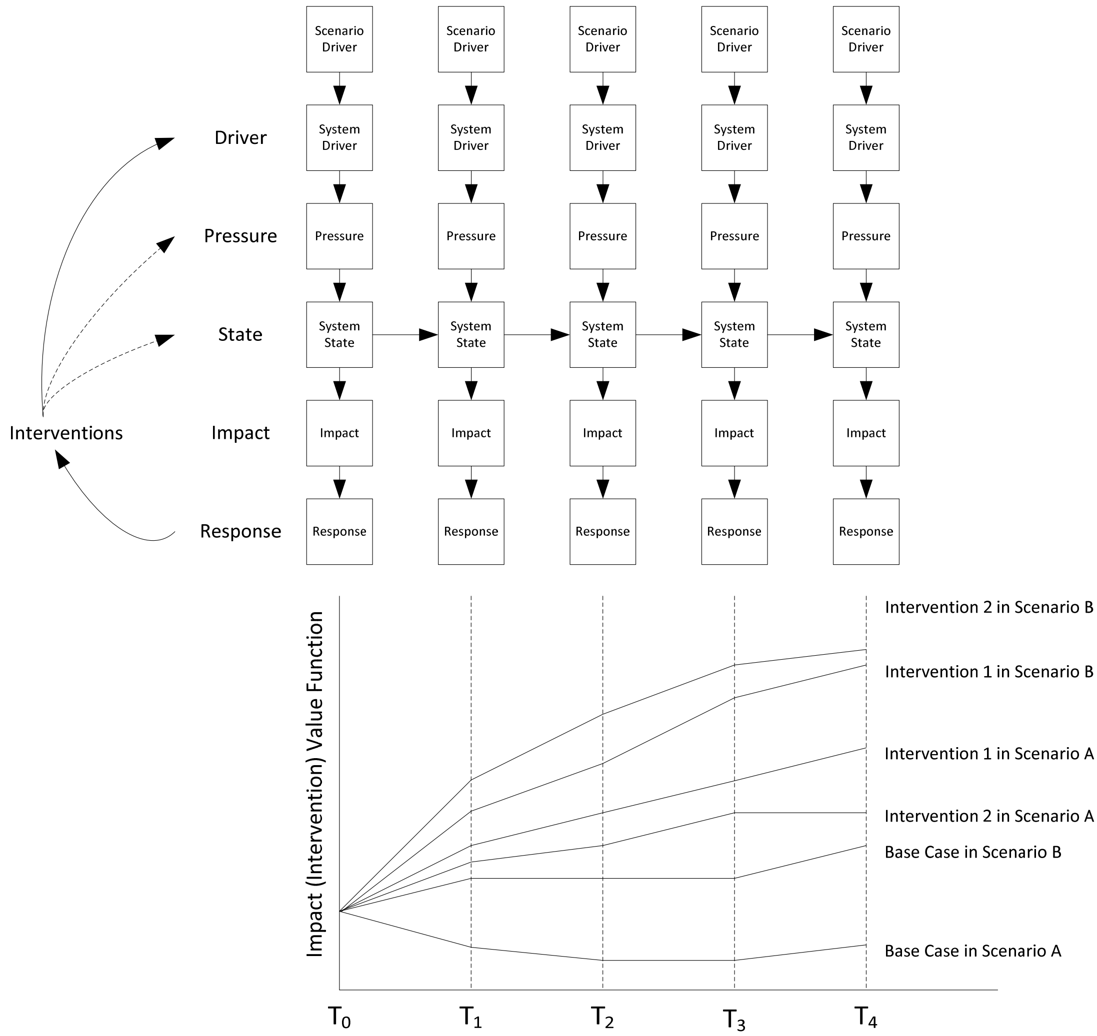

Figure 9: Example of evolution of system state due to interventions

CONCLUSION

Integrated planning for interdependent systems is a complex problem domain for which model based decision support methodologies are appropriate.

We review literature of decision support methodologies for interdependent systems and propose a multi-methodology approach which is model based and integrates methodologies that have successfully been used in complex domains. The proposed approach is based on the DPSIR framework and integrates (1) a problem structuring method with (2) an integrated model of interdependent systems and (3) a MCDM based DSS. The purpose of the framework is to support an integrated management approach that is able to respond to the emergent effects of interdependence between national infrastructures. The result is a multi-methodology DSS for integrated planning of interdependent sociotechnical systems that integrates multiple stakeholders and multiple criteria in joint decision making across organisational boundaries. The method may be extended incorporate features of RDM or EMS to evaluate policies under uncertainty.

REFERENCES

Alabdulkareem, A., Alfaris, A., Sakhrani, V., Alsaati, A. and de Weck, O., (2014), The Multidimensional Hierarchically Integrated Framework (MHIF) for Modeling Complex Engineering Systems, Complex Systems Design & Management 2014, pp 301-313.

Anderson, P.W., (1972), More Is Different, Science, New Series, Vol. 177, No. 4047. (Aug. 4, 1972), pp. 393-396.

Bell, S., (2012), DPSIR = A Problem Structuring Method? An exploration from the “Imagine” approach, European Journal of Operational Research, Volume 222, Issue 2, 16 October 2012, Pages 350–360.

Brans, J.P., Vincke, P.H. and Mareschal, B. (1986), How to select and how to rank projects: the PROMETHEE method. Eur J Oper Res 1986;24:228–38.

Checkland, P (1999), Systems Thinking, Systems Practice: a 30 year retrospective.

Checkland, P. and Scholes, J. (1991), Soft systems methodology in action.

Chikhale,M.M, Mansouri, M., Mostashari, A., and Efatmaneshnik, M. (2012), Intelligent Governance of Large-Scale Engineering Systems: A Sub-Systemic Approach.

Colson, G. and Bruyn, C.D. (1989), Models and methods in multiple objectives decision making. Math. Comput. Modelling 1989;12:1201–11.

Dyson, R.G. and O’Brien, F.A. (1998): Strategic Development Methods and Models. John Wiley & Sons, Chichester.

Friend, J. and Hickling, A. (2005): Planning Under Pressure. The Strategic Choice Approach. Elsevier Butterworth-Heinemann, Oxford.

Giupponi, C., Mysiak, J., Fassio, A., Cogan, V., (2002). Towards a spatial decision support system for water resource management: MULINO-DSS 1st release. Proceedings from AGILE 2002 Conference on Geographic Information Science. Palma de Mallorca, (Spain), April 25–27, 2002.

Hourcade, J., Jaccard, M., Bataille, C. and Ghersi, F. (2010), Hybrid Modelling: New Answers to Old Challenges. The Energy Journal 2, Special Issue (2006) 1-12.

Huang, I.B, Keisler, J., and Linkov, I. (2011), Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends, Science of The Total Environment, Volume 409, Issue 19, 1 September 2011, Pages 3578–3594.

Hwang, C.L.; Lai, Y.J.; Liu, T.Y. (1993). A new approach for multiple objective decision making. Computers and Operational Research 20: 889–899.

Kahneman, D. (2011), Thinking, Fast and Slow, New York: Farrar, Straus and Giroux.

Kahneman, D., Slovic, P. and A. Tversky, A., (1982) Judgment Under Uncertainty: Heuristics and Biases, New York: Cambridge University Press.

Keeney, R.L. and Raiffa, H. (1976), Decisions with multiple objectives: preference and value tradeoffs. New York: Wiley; 1976.

Kwaggel, J.H. and Pruyt, E. (2013), Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty.. Technological Forecasting & Social Change 80: 419-431.

Lempert, R.J. and Popper, S.W.C.B.S., (2003), Shaping the Next One Hundred years: New Methods for Quantitative, Long-Term Policy Analysis. RAND Corporation, Santa Monica, CA.

Mendoza ,G.A. and Martins, H., (2006), Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms, Forest Ecology and Management 230 (2006) 1–22.

Mostashari, A., Sussman, J., (2008), A Framework for Analysis, Design and Management of Complex Large-Scale Interconnected Open Socio-technological Systems.

OECD (2006), Good practices in the national sustainable development strategies of OECD countries.

OECD (Organisation for Economic Co-operation and Development), (1994), Environmental indicators - OECD Core Set, OECD, Paris.

Pederson, P., Dudenhoeffer, D., Hartley, S. Permann, M. (2006). Critical Infrastructure Interdependency Modeling: A Survey of U.S. and International Research. Prepared for the Technical Support Working Group, Idaho National Laboratory, Idaho Falls, ID, August 2006.

Peters, J.C., Kumar, A., Zheng, H., Agrawal, S. and Peeta, S., (2014), Integrated Framework to Capture the Interdependencies between Transportation and energy Sectors due to Policy Decisions, Nextrans Project No 079PY04, May 2014.

Rinaldi, S.M., Peerenboom, J.P., Kelly, T.K. (2001) Identifying, understanding, and analyzing critical infrastructure interdependencies. Control Systems, IEEE, Volume 21, Issue 6, (Dec., 2001) pp. 11-25.

Rosenhead, J., (2013), Problem Structuring Methods, Encyclopedia of Operations Research and Management Science 2013, 1162-1172

Saaty, T.L. (1990), How to make a decision: the analytic hierarchy process. Eur J Oper Res 1990;48:9–26.

Shoven, J., Whalley, J. (1992), Applying General Equilibrium. Cambridge University Press. 1992.

Snowden, D. (2002), Complex Acts of Knowing: Paradox and Descriptive Self-Awareness, Journal of Knowledge Management, vol. 6, no. 2.

Sørensen, L. and Vidal, R.V.V., Evaluating Six Soft Approaches, Economic Analysis Working Papers. 7th Volume – Number 9.

Stanway, G., Hart, W. and Taylor, C., (2013), Overcoming Biases in Strategy Formulation, Virtual Consulting International.

Sussman, J. and Mostashari, A., (2007), CLIOS Users Guide.

Tversky, A. and Kahneman, D., (1981), The Framing of Decisions and the Phycology of Choice, Science, 211/ 4481 (January 1981): 453-458.

Van Zeijl-Rozema, A., Cörvers, R. and Kemp, R., (2007), Governance for sustainable development: a framework, Conference on Earth System Governance: theories and strategies for sustainability, Amsterdam, 24-26 May 2007.

Yoon, K.P. and Hwang, C.L., (1995), Multiple attribute decision making: an introduction. Thousand Oaks, CA: Sage; 1995.

Yuting Qiu, Y. and Fan, Y., A, (2013), Problem Structuring Method for Innovation Strategy: A Tentative DPSIR Approach, iBusiness, 2013, 5, 80-83 http: //dx.doi.org/10.4236/ib.2013.53B017 Published Online September 2013 (http://www.scirp.org/journal/ib).

Zhang, P. and Peeta, P., (2011), A generalized modeling framework to analyze interdependencies among infrastructure systems, Transportation Research Part B 45 (2011) 553–579

Zhou, P., Ang, B.W. and Poh, K.L., (2006), Decision analysis in energy and environmental modeling: An update, Energy 31 (2006) 2604–2622.