A journey to KAOS: tackling "wicked" infrastructure

C. M. Blom[1,2]
[1]*Department of Engineering, Cambridge University, UK*
[2]*Anguillid Consulting Engineers and Scientists Ltd., New Zealand*

Abstract

Infrastructure exists in a complex environment within the context of society. It supports the well-being of our communities and enables (or constrains) development. It is currently estimated that in the short-term more than US$53 trillion needs to be invested globally in new infrastructure.

It is no surprise then that there is a drive to make better use of existing infrastructure and that there is a growing awareness that a key part of the equation is the untimely erosion of asset 'value' (in its broadest sense) and of functional outcomes. Intertwined with this is an industry realisation that some project level 'sustainability' initiatives have performed poorly or do not work well within current engineering and organisational conventions. It makes little sense then to seek an improvement in such initiatives when the system itself does not support them. This is particularly so where there is an inherent inability to transfer knowledge across the life cycle of an asset or system.

This paper advances several of the author's concepts from infrastructure practice in New Zealand. Industry examples are used to explore whether the interface of engineering process and the organisational frameworks that 'cocoon' this presents an infrastructure opportunity. In doing so, it sets out the *a priori* constructs for a research programme that will enquire into how decision making processes affect infrastructure fitness.

Keywords: infrastructure management, land transport, value innovation, systemic sustainability, adaptive capacity, resilience, fitness, complex systems, decision making.

WIT Transactions on Ecology and The Environment, Vol 191, © 2014 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SC140772

1 Introduction

This article aims to bridge a practitioner/academic transition by presenting an industry perspective and overviewing some of the *a priori* constructs to be developed through further research. To this end, the article briefly traverses the concepts of sustainability and some of the issues facing infrastructure management in the New Zealand context, before providing an overview of approaches that have been developed by this author and are concurrently being developed by industry to address the issues before it. The paper does not seek to present a complete picture, but rather to canvas a few select matters that have led to the development of, and provide the background to, a research programme (which is briefly outlined). The subsequent research will explore how decision making contributes to the fitness of outcomes (adaptation, resilience, and values retention) within infrastructure 'systems' with the aim of improving performance and thence the sustainability of outcomes.

2 Sustainability and infrastructure

Sustainability is a well-established concept and has been in common usage at least since the "Brundtland Report" in the late 1980s [1]. In the New Zealand context, sustainability is embedded within the purpose of the principal environmental legislation, the Resource Management Act (RMA [2]). Sustainability is not a state of stasis however, and this introduces both complexity and uncertainty [3, 4]. Consequently, adaptive management is an oft adopted approach in New Zealand [5–7]. Sustainability as a principle is therefore an intrinsic part of infrastructure projects in New Zealand.

The presence of legislative or other drivers does not preclude the opportunity for innovation and improvement within the infrastructure setting (e.g. [7–9]). Similarly this also does not preclude implementation issues, which range from the uptake of principles [10], implementation of consent conditions [6], through to functionality and performance in operations [11, 12]), amongst others.

Some of the implementation issues being experienced at the practical or applied level appear to stem from a dichotomy that arises from the inherently systemic nature of sustainability [13, 14] and the reductionist or project oriented nature of business and engineering [15, 16]. This is perhaps underscored (at least in the New Zealand context) by the RMA and the legislative focus in the consenting of capital works and can be seen in infrastructure within (for example) strategic documents and sustainability statements.

Whilst such initiatives are invaluable, experience has shown that despite best intents at this level, sustainability led initiatives are not well catered to at a system level. Consequently they are frequently not delivering the outcomes sought over the longer term [6, 12]. This is further exacerbated by value discontinuities that emerge, most noticeably, between capital projects and operations [11]. To effect sustainable outcomes then, this dichotomy needs to be further reconciled and a way found to apply the "action lessons" to the social-technical system itself [18].

Sustainability assessments often draw upon triple or quadruple bottom line tools (e.g. [19, 20], and present the approach as nested or overlapping 'well-beings' (inferring a balancing exercise; refer to Figure 1). One of the issues with this approach is that whilst it encourages discourse and seeks balance, it does not reference why an action is being taken (and whether the right choice is being made). This might seem self-evident, yet project context can be obscured or even lost in the engineering, the detail of a business case, or other process hurdles (which may focus on the ability to 'tick boxes'). That 'sustainability' can, despite the statutory drivers, sometimes be treated as an adjunct can further cloud matters.

A simple modification of the quadruple bottom line approach has been developed and used in the infrastructure arena. This introduces a fifth element: function (refer to Figure 2). The approach has been found to provide an effective focus (what problem are we solving/what is the question/purpose?). It also seeks to integrate sustainability conversations earlier within decision making processes, and also serves as a reminder that function is not solely about the asset itself [21, 22].

Figure 1: Quadruple bottom line approach to sustainability [19, 23].

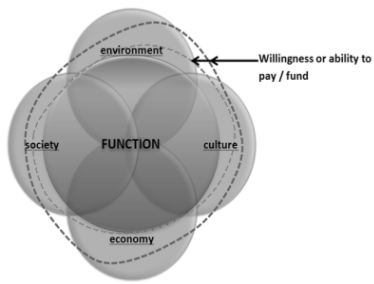

Figure 2: Fifth element sustainability approach.

The 'fifth element approach' also seeks to clearly distinguish between the basic functions required for long-term performance, and additional features that might be modified by a willingness or ability to fund. Note too that the fifth element may not necessarily be centred in all instances and this is where the willingness or ability to fund factors can assist in addressing trade-offs that may arise. This then, provides a counterpoint tension to the classic time-cost-quality triangle [24] by providing the opportunity to focus on and pursue:

- Community aspirations or priorities;
- Constraints;
- Performance and outcomes (as distinct from quality or efficacy);
- Timeliness (rather than speed); and
- Additional resilience, robustness, and adaptive capacity.

3 Infrastructure sustainability

Infrastructure exists in a complex environment within the realm of society; it does not exist in its own right but rather it supports the well-being of our communities and enables (or constrains) development. Indeed the current vision for infrastructure in New Zealand has inherently sustainable ambitions in that *"By 2030 New Zealand's infrastructure is resilient and coordinated and contributes to economic growth and increased quality of life."* [25].

It is currently estimated that more than US$53 trillion needs to be invested globally in infrastructure in the short-term to bring it up to an 'acceptable level' [26]. New Zealand's public asset base alone is valued at approximately NZ$115 billion dollars, and approximately NZ$17 billion is planned in capital works to 2015 [25]. The operations, maintenance and renewals budget for Auckland's transport assets alone is over NZ$5 billion dollars over the next decade [17].

It is no surprise then that there is a drive to make better use of existing infrastructure [17, 25]. This reflects not only a desire to improve efficiency and efficacy in the face of constrained economic conditions, but reflects a growing awareness [27] that infrastructure assets lose value before their time and that knowledge, equity, and even matters such as statutory compliance status are also lost over the asset life cycle [6, 11, 12].

3.1 The linear nature of life-cycles

Despite terminologies that suggest otherwise, infrastructure delivery and management processes are founded in management conventions that are inherently linear (refer to Figure 3), and follow a command and control or production line tradition emanating from the industrial revolution [15, 16]. Significant attention has been given to process efficiency [14] and this is reinforced from the macro level right through to the individual components within the asset life cycle process. This may be seen by the use of asset management tools that deconstruct the asset to its constituent parts but rarely capture matters of context or "place".

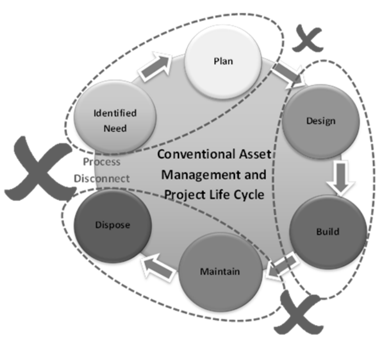

Figure 3: Asset management life cycle with common organisational and project divisions (modified from [12]).

This focus on efficiency has not served to address the ultimately linear nature of infrastructure delivery and management. Nor does it address the handover gaps that exist between project phases and organisational divisions which tend to align with project phasing and funding milestones (Figure 3).

The lack of feedback between phases and particularly so between operations and strategy is critical both in theory and in practice. This accords with Busby [28], and also the views of Lenferink *et al*. [29] who opine that "*although conceptually promising, a full backward integration linking all the different planning stages, has not yet been applied in practice*." This very aspect (along with matters of operational complexity) was the subject of a body of work undertaken between 2008 and 2011 for North Shore City Council and thereafter Auckland Transport (excluding the State highway network, Auckland Transport is accountable for transportation assets and operations across the Auckland region of New Zealand). The project considered a regional asset that transcended organisational boundaries and asset functions [11, 12]. Whilst the concepts developed had benefits, these have since evolved further and are discussed below.

3.2 Context and complexity

The significance of the systemic breakdown has been particularly highlighted with the emergence of complex, multimodal or multifunctional (i.e. 'wicked') infrastructure and an increased focus on customer outcomes. Whilst infrastructure is perhaps wicked in its complexity, processes either ignore or overly simplify this. However because the system is ultimately complex, this will not necessarily read as holistic or systemic failure [16] as is reflected by long standing engineering practice and processes. This systemic 'breakdown' is however starting to bring a realisation within industry that there needs to be thinking beyond a single project strand and that complex infrastructure may be better served by revisiting current engineering and organisational conventions.

One of the crucial concepts to be derived from the above referenced body of work to address this point was the concept of Community Orientated Results and Co-ordinated Operating Requirements (CORe^{TM}; refer to Figure 4).

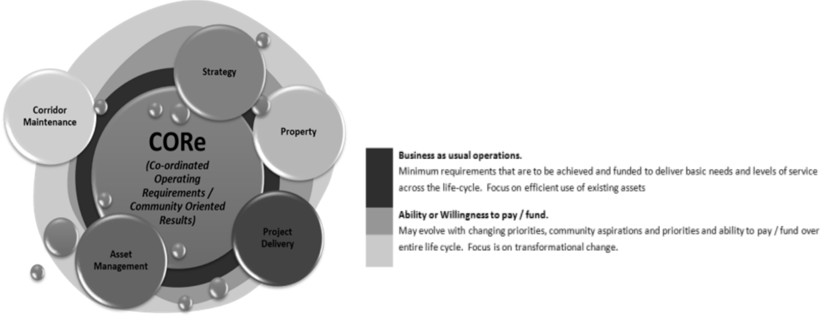

Figure 4: CORe^{TM} [12]. Note: positions and functions indicative and illustrative only and case specific.

This concept proposed refocusing (not restructuring) the hierarchical organisational structure on the functional outcomes and fully integrating project requirements across all phases of the life cycle. This was undertaken not for the individual assets, but the infrastructure that was associated with the establishment the sense of place and its subsequent functioning. This concept was embodied within operational documents and started to lead to changes across the organisation before being overtaken by local government re-structuring. The concept was subsequently developed further at an operational level for a tranche of regional infrastructure operations. As can be seen this integrates the demarcation between 'business as usual' and a willingness/ability to fund additional performance outcomes as first described in Figure 2.

The vision of this concept was the creation of co-ordinated collaborative units; best described as mimicking neural synapses when replicated at the system level; whereby each unit (and not unlike a complex adaptive system in its own right) might interface with other parts of the organisation and exist at different scales, facilities/projects, or functions. Because the concept does not require restructuring, each unit or functional team may co-exist within one or multiple units at any one time. This in turn gives rise to the concept of functional ascendancy in which a particular discipline or team may have overall accountability or priority over others depending on the stage in the life cycle or nature of the outcomes being delivered. The point however is that performance of the physical infrastructure (at whatever scale), and the associated services is externally focused and outcome oriented (at the system level).

This approach is aimed at changing the nature of 'conversations' from depreciation, audit requirements, and reporting timeframes to matters such as customer service, sense of place, enabling of business, and environmental outcomes (for example). This does not imply that depreciation and other management considerations are set aside, but rather that process is 'reclaimed' by the outcomes being sought, not the means of managing and controlling them. This is also why this has been couched as a conversation; this requires a move beyond tick boxes or linear lists, and requires a shift in culture [3, 16, 18, 30].

The approach also seeks to address overlapping interest and sometimes overlapping function, which in turn posed the risk of embedding organisational siloes. The risk of insular processes and practices establishing was found to have the potential to result in (amongst other things):

- Highly partitioned and independent operations/activities (opportunity loss);
- Duplicate or counterproductive effort (inefficiency);
- Omissions or degraded community outcomes; and
- Friction or eroded team morale.

3.3 The infrastructure ecosystem

Stapledon [31] adopts a sustainable infrastructure definition that identifies sustainable infrastructure as being that which is 'fit for purpose', and "*where fitness is a function of an asset's capacity to be:*

- *Continually useful over its entire life;*

- *Resilient and adaptable to changing external circumstances;*
- *An integral and consistent part of the wider infrastructure 'jigsaw'; and*
- *Fulfilling community expectations by helping to solve sustainability challenges.*"

Fitness could therefore perhaps be summarised as resilience, adaptive capacity, and the ability to retain values. This articulates a broader range of considerations than the more usual meaning of fit for purpose, which "*has a specific legal derivation where it is recognised that every commodity has a function to serve and in identifying and prescribing that function (or objective), the commodity is said to be 'fit-for-purpose' when that function/objective is fulfilled*" [32].

However other than matters of climate change and an emergent focus on resilience arising largely from the effect of natural disasters (e.g. [33]), infrastructure sustainability is still largely focused (in research and in practice) on the impacts of infrastructure as a system on its wider environs [31, 34] or on its constituent parts. The function of the wider infrastructure system itself does not appear to have been widely explored. The next of the key concepts was aimed at addressing this and in so doing takes the previously described CORe™ and relates this to the operational life cycle of the infrastructure network.

Before presenting the concept, it should be noted that for simplicity, the concept takes the functional ascendancy/zones of influence illustrated in Figure 4 and instead presents these as 'orbitals'. The approach is however the same – the closer to the nucleus, the higher the priority or influence.

The abovementioned system view was the basis for developing a more integrated framework from which regional scale infrastructure decision making and operations could be made. It sought to provide for not only context and complexity, but in terms of network or system function and its need to evolve over time (and therefore both its resilience and its adaptive capacity). It does so again without getting into organisational restructuring – and it considers the accountabilities relative to operational function rather than organisation structure. It also seeks to shift the focus away from the capital works pipeline to infrastructure performance relative to community (inclusive of business/economic and environmental) outcomes.

Figure 5 then, provides a more holistic approach and a (purposefully) operations centric life cycle. The strategy was developed to improve the management of the Auckland region's public transport infrastructure assets (a cross-organisational function). It merges life cycle processes with the notion of a co-ordinated (co-)operational unit and that of functional influence and associative ascendancy. This provides for change and a dynamic system that is oriented to its context and the role infrastructure plays in society.

As with the CORe™ concept, supporting functions and "interested" departments (i.e. those which may have a longer term accountability for an asset or outcome) can therefore be involved and influence a particular stage in the process but not necessarily control it (as the accountability may lie elsewhere given the underlying organisational structure, which does not change). Similarly, third parties (such as community groups, adjacent landowners, utility providers) can also be embedded within the associative and collaborative framework.

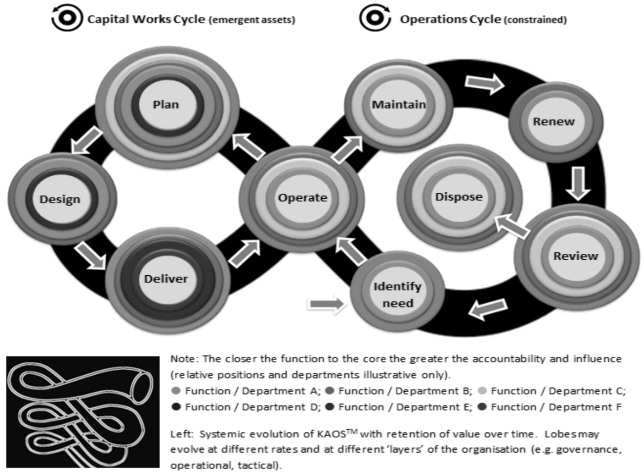

Figure 5: Kinetic Asset Operating Strategy (KAOS™]).

The terms "emergent assets" are purposefully used to describe the capital works and project delivery processes, and "constrained" to describe existing assets:

- 'Emergent asset' is used to seek a mind-set shift away from project delivery administration and the works process to a greater awareness that those projects deliver assets that need to be operated within the public realm. Ideally then, it would generate different processes and interactions.
- 'Existing assets' are considered "constrained" as they must operate within defined level of service or performance indicators, community expectations, statutory, or other processes. The aim is to stimulate added awareness that decisions need to be made relative to all applicable confining parameters.

Willingness or ability to fund factors can be provided for and the framework also provides the opportunity to build fitness (i.e. incorporating the attributes of resilience, adaptive capacity and values retention). As such this provides for the retention and development of matters such as knowledge 'equity', or to enables the entropy inherent in conventional processes to be addressed. It seeks to enable an organisation to do so across the operational life cycle of the *system* (rather than just an asset) and because it embeds contextual matters more fully addresses the feedback shortcomings identified in Lenferink *et al*. [29] and Blom *et al*. [12]. The creation and enhancement of fitness should then enable the system to evolve and adapt as conceptualised in the inset to Figure 5.

This development of fitness is not only important to the management of infrastructure and the business processes of those organisations managing it (many of which in New Zealand are accountable to ratepayers), but it is also important to the wider community and environment. By retaining the fitness of the system the community is also able to realise the benefits of the infrastructure as consented, designed, or even constructed. In theory this should be at no additional cost if the life cycle costs are well understood and apportioned in the project development phase. It might also create a long-term cost saving if infrastructure function is able to be sustained across the original design life. Either of these scenarios would improve broader societal and environmental outcomes, both of these are however matters that require further research.

Whilst not necessarily constrained by this, fitness can be retained and enhanced primarily across two key milestone or handover points:

- Operation of existing assets: By ensuring operational information is captured in a way that is relevant, accessible and addresses all organisational requirements (and not just the interests of one department). Operational requirements feed into the operational and maintenance cycle and in turn information arising from that process re-inform operational decision making. This evolution of information could be considerable over a 10–50 year design life and so is crucial to capture rather than allowing this to dissipate over time. Decommissioning or reinvestment decisions in the longer term should be better informed (i.e. this enables thinking and strategies to extend beyond shorter often mandated horizons).
- New assets: By ensuring operational information informs strategy and planning processes and similarly all relevant design and construction information is fed back into operations. Whilst this cross over depends on the frequency of new projects, it is perhaps the one with the greatest potential to add value, and to create incremental and step change within the system; particularly if it has built a substantial and informed knowledge base over the life cycle of an asset. This is where operational performance matters can and should inform design and where design intent can be communicated and the decisions captured so that the "system" evolves.

Whilst these two key milestones are the most vital, the system also relies upon fitness (including aspects such as knowledge) transfer occurring at every stage. Consequently organisational culture of co-operation is equally as important as the framework. As with the preceding concept, we note that each one of these adaptive life cycles can co-exist at different scales and co-exist at the facility, mode, and function scale.

4 Future research focus

As noted, although infrastructure is often physically linear, as is the traditional engineering process and asset life cycle, it is in fact a wickedly complex adaptive system. The broader context, function, and use by or interaction with society – the humanity of infrastructure engineering as it were – is being lost [21]. This is exacerbated by organisational siloes within infrastructure organisations as well as the organisation's capacity to manage integrated infrastructure systems with multiple trans-disciplinary objectives.

There will be an array of innovations that might improve the sustainability of new projects – however it is clear from experience and preliminary research that unless the engineering process itself is addressed along with the organisational and business frameworks that support it, it is unlikely that those innovations would affect the systemic change being sought [18]. Indeed, it makes little sense then to try and improve the sustainability of infrastructure when the system itself does not support it and is 'entropic'.

Consequently it is proposed that by tackling the very nature of engineering process itself and the organisational frameworks that 'cocoon' this, a step change in infrastructure management (and perhaps broader sustainability practice) might be instigated. Several concepts have been developed with this aim and this is the basis for future research. The focus of the research will be the organisational and operational interface of infrastructure systems, and the associated 'questions' as they are currently framed ask:

- How does the decision making process lead to an outcome that delivers fitness?
- What sense making or decision making framework might better enable fitness?
- What might change as a consequence?

The aim of this research is to provide a framework for and capture the outputs from a series of active learning and case studies so that it can assist infrastructure managers (and thence funders and policy makers) to improve the efficacy and overall sustainability of infrastructure as a complete but wicked system.

Acknowledgements

This paper has been prepared with the assistance of Anguillid Consulting Engineers Ltd (Anguillid), Professor Peter Guthrie (Cambridge University), A Finch (Auckland Transport), and R Fairclough (National Infrastructure Unit, New Zealand Government Treasury). CORe™ and KAOS™ are Trade Marks of this author and Anguillid. Permissions have been obtained from Anguillid for the use and reproduction of protected intellectual property herein and shall not be reproduced without the written permission of a Director of Anguillid.

References

[1] UNWCED, *Our Common Future*. Oxford University Press, 1987.

[2] *Resource Management Act*, Pub. L. No. 1991 No 69, 1991.

[3] Gunderson, L. H., & Holling, C. S. Panarchy: *Understanding Transformations in Human and Natural Systems*. Washington, D. C.: Island Press, 2002.

[4] Newig, J., Schulz, D., Fischer, D., Hetze, K., Laws, N., Lüdecke, G., & Rieckmann, M. Communication regarding sustainability: Conceptual perspectives and exploration of societal subsystems. *Sustainability*, 5, 2976–2990, 2013.

[5] Allen, W. J. *Working together for environmental management: The role of information sharing and collaborative learning*. Ph.D. Thesis, Massey University, 2001.

[6] Brown, M. A., Clarkson, B. D., Barton, B. J., & Joshi, C. Ecological compensation: An evaluation of regulatory compliance in New Zealand. *Journal of Impact Assessment and Project Appraisal*, 31(1), 34–44, 2013.

[7] Winter, R., & Blom, C. *Undertaking Earthworks During Winter in Auckland – Can it be achieved successfully?* 3rd South Pacific Conference: Comprehensive Stormwater and Aquatic Ecosystems Management/10th Conference of the Australasian Chapter of the International Erosion Control Association, Auckland, 2003.
[8] Blom, C. *A 'DEVICES' approach to environmental management*. New Zealand Water and Wastes Association Conference, Rotorua, New Zealand, 1997.
[9] Blom, C., & Drury, L. *Environmental sustainability in action – innovation and outreach at Grafton Gully*. New Zealand Water and Wastes Association Conference, Auckland, New Zealand, 2005.
[10] Blom, C. *Application of stormwater quality tools in roading*. Road Controlling Authorities Forum, New Zealand Water and Wastes Association, and Ministry of Transport Roading and Stormwater Technical Workshop, Wellington, New Zealand, 2002.
[11] Blom, C., & Irwin, A. *Piloting a new approach to asset management: The stormwater story*. Water New Zealand 7th South Pacific Stormwater Conference, Auckland, New Zealand, 2011.
[12] Blom, C., Irwin, A., & Rangamuwa, S. *A new model for asset management: Albany Lakes precinct.* European Transport Conference, Glasgow, United Kingdom, 2011.
[13] Gaziulusoy, A. İ., Boyle, C., & McDowall, R. A conceptual systemic framework proposal for sustainable technology development: Incorporating future studies with a co-evolutionary approach. *Civil Engineering and Environmental Systems* 25(4), 301–311, 2008.
[14] Guthrie, P., & Konaris, T. *State of the World Report 2012*: Sustainable Infrastructure. International Federation of Consulting Engineers (FIDIC), 2012.
[15] Handy, C. *Understanding Organizations* (4th ed.). London: Penguin, 1993.
[16] Uhl-Bien, M., & Marion, R. *Complexity Leadership Part 1: Conceptual Foundation*. Information Age Publishing, 2008.
[17] Auckland Transport. *2012–2041 Integrated Transport Programme*. 2013.
[18] Harris, G. *Seeking Sustainability in an Age of Complexity*. Cambridge University Press, 2007.
[19] Hawkes, J. The fourth pillar of sustainability: Culture's essential role. In *Public Planning: Common Ground,* 2001.
[20] Vanclay, F. The triple bottom line and impact assessment: How do TBL, EIA, SIA, SEA and EMS relate to each other? *Journal of Environmental Assessment Policy and Management*, 6(03), 265–288, 2004.
[21] Jowitt, P. Now is the time. *Proceedings of ICE, Civil Engineering*, 2010.
[22] Star, S. L. The Ethnography of Infrastructure. *American Behavioral Scientist*, 43(3), 377–391, 1999.
[23] Mihelcic, J. R., Crittenden, J. C., Small, M. J., Shonnard, D. R., Hokanson, D. R., Zhang, Q., Sutherland, J. W. Sustainability science and engineering: the emergence of a new metadiscipline. *Environmental Science & Technology*, 37(23), 5314–5324, 2003.

[24] Marques, G., Gourc, D., & Lauras, M. Multi-criteria performance analysis for decision making in project management. *International Journal of Project Management*, 29(8), 1057–1069, 2011.

[25] New Zealand Government. *National Infrastructure Plan 2011*. Retrieved from http://www.infrastructure.govt.nz/plan, 2011.

[26] OECD. *Strategic Infrastructure Needs to 2030: Main Findings*. Organisation for Economic Co-Operation and Development, 2012.

[27] Frangopol, D. M., Kallen, M. J., & Noortwijk, J. M. v. Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. *Progress in Structural Engineering and Materials*, 6(4), 197–212, 2004.

[28] Busby, J. The neglect of feedback in engineering design organisations. *Design Studies*, 19(1), 103–117, 1998.

[29] Lenferink, S., Tillema, T., & Arts, J. *The potential of a life-cycle approach for improving road infrastructure planning in the Netherlands*. Bijdrage aan het Colloquium Vervoersplanologisch Speurwerk, Santpoort, 2008.

[30] Schein, E. H. Three cultures of management: The key to organizational learning. *Global working*. Living and working across the world with cultural intelligence, 37, 2010.

[31] Stapledon, T. *Why Infrastructure Sustainability is Good for your Business*. Co-operative Research Centre for Infrastructure and Engineering Asset Management, Australia, 2012.

[32] Cox, A., & Thompson, I. 'Fit for purpose' contractual relations: determining a theoretical framework for construction projects. *European Journal of Purchasing & Supply Management*, 3(3), 127–135, 1997.

[33] Wise, C. Organizing for Homeland Security after Katrina: Is Adaptive Management What's Missing? Public Administration Review 66 (3), 302–318, 2006.

[34] Jeon, C., & Amekudzi, A. Addressing Sustainability in Transportation Systems: Definitions, Indicators, and Metrics. *Journal of Infrastructure Systems*, 11 (Special Issue: Sustainability of Transportation and Other Infrastructure Systems), 31–50, 2005.