Engineering Asset Management Review 1

Joe E. Amadi-Echendu · Kerry Brown
Roger Willett · Joseph Mathew *Editors*

Definitions, Concepts and Scope of Engineering Asset Management

Springer

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Foreword

Engineering Asset Management is emerging as a major concept under which well established principles and innovative practices are being assembled, coalesced and developed towards advancing the management of engineered physical assets.

This inaugural issue of *Engineering Asset Management Review* Series is timely and pertinent. It is timely because of the ongoing efforts to develop and adopt standards that will not only direct the prevailing ambiguities in the academic subject matter, but also minimize the perplexities experienced by organizations attempting to implement their own asset management policies, strategies, tactics and practices. It is pertinent as economies seek to recover from the latest world-wide recession caused by the recent debilitating global financial crisis. The importance of cost containment, value creation based on 'real' assets, and sustainability of global financial systems demands innovative ways of managing both engineered physical and natural assets.

The International Society of Engineering Asset Management (ISEAM) (www.iseam.org) has initiated the publication of the *Engineering Asset Management Review* Series through Springer-Verlag as a global quality journal that appeals to academia, as well as the public sector and private industry. The Review Series arises from ISEAM's successful annual World Congress on Engineering Asset Management (WCEAM) (www.wceam.com) which began in Australia in 2006 and has since been held in UK in 2007, China in 2008 and Greece in 2009. The formation of both ISEAM and WCEAM has been influenced through the efforts of the Cooperative Research Centre for Integrated Engineering Asset Management (CIEAM), Australia.

I commend this first issue of the *Engineering Asset Management Review* to you as we embark on establishing a coherent body of knowledge to guide further education, training, certification, research, policy, strategy, tactics and practice in the management of engineered physical assets upon which real value creation is based.

Australia, August 2010

Professor Joseph Mathew
Chair, Board of Directors
The International Society
of Engineering Asset Management

Preface

Engineering Asset Management Review (*EAMR*) Series is a publication of the International Society for Engineering Asset Management (ISEAM) dedicated to the dissemination of research by academics, professionals and practitioners in engineering asset management. *EAMR* complements other emerging publications and standards that embrace the wide ranging issues concerning the management of engineered physical assets.

The theme of Volume 1, as befits the inaugural issue of EAMR Series, is dedicated to the Definitions, Concepts and Scope of engineering asset management (EAM). The term "engineering" in the title of the *Review* indicates that it focuses on the management of engineered physical assets used in the "real" economy. EAM is a multidisciplinary endeavor involving traditional science, engineering and technology disciplines, logistics and operational research; business management disciplines including risk, economics and financial accounting; and psychology disciplines such as human and organizational behavior.

The articles published in this volume are but a small number that reflect the multidisciplinary nature of EAM. Whilst a plethora of definitions exist, the first article, comprising Section 1, reviews the common threads from a wider pedagogical viewpoint. The following section on Concepts includes articles illustrating the typical industry approach, where the tendency is to apply frameworks and simplified models in a highly dedicated manner. Section three comprises a number of articles that illustrate the wide ranging scope of EAM, while section four includes articles on the vexatious issue of condition monitoring, asset data, information and decision making. Section five contains articles on the challenging issues of sustainability and safety confronting every organization and often treated with high trepidation. The vital issue of human dimensions in EAM is discussed in the final two articles of this volume.

The Editors wish to thank all the contributors for their effort and patience through the review process. To all readers, we invite your comments and further critique, so that we all may benefit from the ongoing debate that should provide a useful body of knowledge relevant to the management of engineered physical assets.

Australia, New Zealand, August 2010

Joe E. Amadi-Echendu, Editor-in-Chief
Kerry Brown, Senior Editor
Roger Willet, Senior Editor
Joseph Mathew, Senior Editor

Introduction to Engineering Asset Management Review Series

Engineering Asset Management Review (EAMR) is published by Springer-Verlag under the auspices of the International Society of Engineering Asset Management (ISEAM). Engineering asset management (EAM) focuses on life-cycle management of the physical assets required by a private or public firm, for the purpose of making products, and/or for providing services in a manner that satisfies various business performance rationales. In exploring the wide ranging issues involved in the management of engineered assets constituting our built environment, EAMR takes a broad view of the inter- and multi-disciplinary approach which combines science, engineering, and technology principles with human behavior and business practice.

The purpose of EAMR is to publish research and opinions which explore strategic and tactical issues, as well as technical data, and information involved in the creation (formulation and design), acquisition (procurement, installation and commissioning), maintenance, operation, decommissioning, disposal and/or rehabilitation of physical assets. The range of articles covers all industry sectors and physical asset types (infrastructure, plant, equipment and facilities).

The aim of EAMR is to provide a forum for:

- the assembly of a body of knowledge in this emerging field of EAM;
- knowledge transfer between researchers and practitioners;
- cross-disciplinary interaction between engineers, technologists, economists, environmental practitioners, behavioural scientists and business managers;
- the presentation of a wide spectrum of viewpoints and approaches from designers, developers, project managers, owners, operators, users and vendors.

The content of EAMR is structured within a scope that includes the following generic areas of interest/expertise and themes:

Scope

- Investment Issues:
  - Funding/financing
  - Public private partnerships
  - Due diligence
  - Valuation
  - Technology transfer
  - Innovation
- Technical:
  - Project management
  - Risk management
  - Operations
  - Maintenance
  - Procurement
  - Decommissioning
  - Rehabilitation
  - Human dimensions
- Decision Support:
  - Data warehousing
  - Modelling
  - Standards
  - Prognostics
  - Life-cycle assessments
  - Benchmarking
- Education:
  - Curriculum development
  - Accreditation
  - Training
- Technologies:
  - ICT
  - Sensors/condition monitoring
  - ERP/transactional
  - Component technologies

Generic Themes

- Concepts and theory covering any of the headings above: A key requirement is that the contribution provides an extensive review and critique of existing literature plus the formulation of unambiguous new knowledge or insight. Theory building.
- Applications: A key requirement is that the contribution provides a considerable review of existing literature plus empirical data that demonstrates the application of theory. Theory testing.
- Case Studies: A key requirement is that the contribution provides empirical data that validates a concept, theory or model in practical industry or public situations. Reflexive in-practice.

Electronic Editorial Procedure

EAMR maintains an open call for papers in addition to pre-selecting papers from accredited conferences (*e.g.*, World Congresses on Engineering Asset Management). Guest Editor(s) may propose special issues on approval from the Editor-in-Chief before sending a call for papers.

Manuscripts submitted in accordance to the submission guidelines at Springer-Verlag website (see www.editorialmanager.com/eamr) shall receive a minimum double-blind review. Manuscripts for revision and re-submission may be subjected to further refereeing.

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Part IV Scope (Asset Data and Condition Monitoring)

Part I
Definitions

What Is Engineering Asset Management?

Joe E. Amadi-Echendu, Roger Willett, Kerry Brown, Tony Hope, Jay Lee, Joseph Mathew, Nalinaksh Vyas and Bo-Suk Yang

Abstract Definitions of asset management tend to be broad in scope, covering a wide variety of areas including general management, operations and production arenas and, financial and human capital aspects. While the broader conceptualisation allows a multifaceted investigation of physical assets, the arenas

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constitute a multiplicity of spheres of activity. We define engineering asset management in this paper as the total management of physical, as opposed to financial, assets. However, engineering assets have a financial dimension that reflects their economic value and the management of this value is an important part of overall engineering asset management. We also define more specifically what we mean by an "engineering asset" and what the management of such an asset entails. Our approach takes as its starting point the conceptualisation of asset management that posits it as an interdisciplinary field of endeavour and we include notions from commerce and business as well as engineering. The framework is also broad, emphasising the life-cycle of the asset. The paper provides a basis for analysing the general problem of physical asset management, relating engineering capability to economic cost and value in a highly integrated way.

Keywords Engineering asset management, Definitions, Frameworks, Challenges

1 Introduction

Shaping an emergent field of endeavour requires understanding the boundaries of the specific activities contained within that field. However, acknowledging the associated activities and functions from closely related fields may also provide new insights and analytic tools. As such it may also involve learning from other related fields. In developing a definition of engineering asset management (EAM), we have drawn from the general field of asset management, but also from associated asset management sectors.

Since the 1990s however, it has been argued that the field of asset management requires an interdisciplinary approach in order to ensure that an appropriate mix of skills can be brought to bear on resolving the vexed issue of asset management. The new orientation has been on developing a range of strategic responses to safeguard the large public and private investments in assets. In this context, however, definitions of what is asset management, engineering or otherwise, tend to be broad in scope. In this paper, we propose to define EAM as the management of physical, as opposed to financial, assets. Moreover, it is contended that while the management and maintenance of the asset is a critical task, engineering assets also have a financial dimension that reflects their economic value. The management of this value is an important part of overall EAM.

Following from this previous research, our approach is interdisciplinary and we include notions from commerce and business as well as engineering. The framework also draws on a broader set of considerations, emphasising the life-cycle of the asset rather than just focusing on the maintenance aspects. The paper starts by briefly and selectively reviewing what the literature considers asset management to be and outlining the various conceptualisations of asset management, examining the appropriateness of these. The next section of the paper develops a detailed characterisation of the basic concepts of EAM that is needed to support a broader understanding of EAM. Lastly, the paper draws out the implications of the characterisation of EAM to highlight the most commonly cited problem confronting asset management, that is, data quality.

2 Viewpoints in the Literature About Engineering Asset Management

Until quite recently, definitions of EAM focussed on two distinct but important aspects of the management of assets. The first concentrated on the information and communication technology required in the management of data relating to assets. The second focused on the way in which EAM systems can be integrated and managed to inform decision-making about those assets. However, in the last five years or so, there has been an increasing emphasis on the overall dimensions of what constitutes EAM. The arena of the constitution of the *total* asset management is suggested as an important consideration for advancing the field of EAM.

Investigations relating asset management to issues of data capture and information technology focus on the ways in which the condition of assets can be monitored more effectively to prevent premature deterioration of an asset. Madu (2000) suggests maintenance, reliability and cross-organization analysis are key issues in managing equipment asset use, arguing that 'asset management' is facilitated by IT software. Madu refers to asset management as being dependent upon on enterprise resource systems (ERS) that collect data and contends that firm competitive advantage can be gained through the effective use of these.

Asset management has also been defined in a range of different contexts including transport (US Federal Highways Authority, 1999; McElroy, 1999), construction (Vanier, 2001), electricity (Morton, 1999) chemical engineering (Chopey and Fisher-Rosemount, 1999) and irrigation (Malano *et al.*, 1999). A US study in transport by the Federal Highways Authority (FHA, 1999) was an early and systematic attempt to understand the critical elements of asset management. The FHA developed an asset management primer to guide thinking and activities in this area.

McElroy (1999) in outlining the approach of the US Department of Transport to asset management, defines asset management as a 'systematic process of maintaining, operating and upgrading physical assets cost-effectively'. The focus on effective asset management is argued to require an asset decision making framework that incorporates organizational structures and information technology aligned with financial and budgetary considerations.

Malano *et al.* (1999) elucidate general principles and functions of asset management from their research interest in irrigation and drainage infrastructure. They contend that key principles of asset management comprise a set of pre-asset acquisition strategies for planning and initiating assets, asset operation and maintenance, performance monitoring, together with allied asset accounting and economics, and audit and renewal analysis.

Vanier (2001) lists among the challenges for asset management, seamless data integration, a standardisation framework and life cycle analysis. The attention to asset life cycles, especially in infrastructure research and practice flags a growing interest in generalising asset management away from the traditional areas of asset maintenance. An upsurge of publishing activity around 2000 focused on the design and formulation of asset management systems. By the early 2000s, a broader conceptualisation emerged recognising more than the ICT and systems approaches to asset management. In the area of maintenance management, Tsang (2002) adds human dimensions as a key issue for the successful management of engineering assets. Complex interactions of skills and resources, physical asset specificity and the way these assets are managed are discussed in Reed *et al.* (1990).

In the context of the built environment, Amadi-Echendu (2006) relates a number of themes including the application of a scientific approach to whole of life asset management ("terotechnology"), the importance of considering the asset as being part of a "value chain" and the need to take a holistic approach to asset management by analyzing problems across the traditional boundaries of the business, information technology and engineering disciplines. He notes a number of key developments in asset management. First, there is a demand for the development of improved financial metrics to inform asset managers about the performance of their assets. Second, the value of assets has to be considered in the light of capital funding and expenditure options. Third, the value of assets have to be assessed as part of a larger program of projects and not just in isolation. Fourth, asset management takes place in an organizational setting that is becoming more fluid, so that greater flexibility in management scenarios (*e.g.* outsourcing) is becoming more important. Fifth, innovation in engineering and communication technologies is rapidly changing the opportunity set facing the asset manager. Sixth, regulation and increasing quality standards are making it essential that asset managers are professionally trained and adopt increasingly sophisticated best practices. Finally, seventh, for all of the above reasons the approach of the asset manager requires to change to accommodate a broader style of thinking about the elements of and approaches to their profession.

The main theme of the Amadi-Echendu paper, that asset management is much broader and has many more dimensions than asset maintenance, traditionally conceived, is echoed in Woodhouse's (2001) conception of asset management. Woodhouse sees the asset manager as a translator of ideas, an interface between business objectives and engineering reality, effecting economic outcomes from physical assets in a complex environment of changing technologies and ideas, numerous regulations and differing social values. Woodhouse also sees the same threats to good asset management as does Amadi-Echendu: a silo mentality based upon adherence to traditional paradigms and a myopic, disciplinary focus; short termism concentrating on immediate profit at the expense of asset longevity and engineers and accountants who do not speak to each other. He also identifies some other key areas of concern where practice has not kept pace with theory: dysfunctional incentive systems, reliable and objective risk quantification, a fire fighting mentality and poor data quality. Woodhouse sees the greatest danger, however, in the shortfall of human capital educated to adapt to the more sophisticated needs of modern asset management. In a sense, he believes the techniques and know-how already exist, and only need to be adapted to produce the systems needed for effective asset management. It is the human factor that is the weak link in the chain.

Mathew (2005) gives an account of how the Centre for Integrated Engineering Asset Management (CIEAM), an Australian collaborative research centre funded by the Australian federal government, is addressing the issues highlighted by Amadi-Echendu and Woodhouse, including the problem of training a new generation of assets managers with what would traditionally be seen as multi-disciplinary skills. The focus of CIEAM is on integrating the human dimensions and decision modelling aspects of EAM with technology (advanced sensors and intelligent diagnostics) through systems integration.

These holistic views of asset management reflect the general movement in engineering circles to emphasize the importance of asset management rather than just asset maintenance, to focus on the bigger picture of life cycle asset assessment, including strategy, risk measurement, safety and environment, and human factors. These themes are common to Townsend (1998), Mitchell (2006), Schuman and Brent (2005) and sources such as the Organization for Economic Cooperation and Development's (OECD's) definition of asset management (OECD, 2001). In the UK a Publicly Available Specification has been released by the British Standards Institution (PAS 55 1&2, 2004) embodying the same principles of life cycle analysis, systematic risk assessment and sustainability.

The tendency to generalise and broaden the conceptualization of asset management is clear and presently seems to form an unwritten consensus among practitioners and academics alike. The commonalities are focusing on the life-cycle of an asset as a whole, paying attention to economic as well as physical performance and risk measures, appreciating the broader strategic and human dimensions of the asset management environment, with the objective of improving both efficiency and effectiveness of resources. In the next section we develop these characteristics in a discussion of the basic concepts of EAM.

3 Basic Concepts in Engineering Asset Management

In this section we discuss, much more precisely than is usually done, what are the key concepts that must underpin the broader frameworks for EAM that have been proposed in the literature. Our aim is to characterise the subject matter of EAM more specifically and clearly. We want our characterisation to be as general as possible so as not to exclude useful and interesting work in this area. For this reason the definition should be flexible, to accommodate new areas as they become relevant. However, we also want the definition to provide focus to our research.

Any characterisation of EAM in the broadly conceived form must have two main parts: (i) an object, *i.e.* the 'engineering asset' and (ii) a process of managing that asset. We will discuss these parts of the definition separately, then combine them together.

3.1 What Is an 'Engineering' Asset?

The definition of an asset given in the Oxford English Dictionary (OED) is:

> *"All the property of a person or company which may be made liable for his or their debts." (OED, 2007)*

The importance of considering this ordinary meaning of the word 'asset' is that we want our concept of an engineering asset to be consistent with basic, everyday ideas. The main points to note about the dictionary definition are that there is (a) an object ('property') to which (b) a legal entity ('person or company') attributes (c) a value ('debt'). Thus an asset is more than just a physical thing. It is part of a relationship between an object and an entity and a value is attached to the object by the entity. We consider these three aspects of an asset in turn.

a. Engineering Asset Objects. First we need to differentiate 'engineering' asset objects from 'financial' asset objects. All asset objects fall into one of these two categories of objects. Financial objects, such as securities traded on stock exchanges, patent rights and derivative securities of various sorts exist *only* as contracts between legal entities. Legal rights, either in engineering objects or in other financial objects are transferred between legal entities by contracts. Engineering objects, the things that are managed by engineering asset managers, such as inventories, equipment, land and buildings, in contrast, exist independently of any contract, although rights in them can be included in contracts creating financial assets (*e.g.* commodity futures). Financial assets exist and have value only as derivatives of engineering assets.

Engineering asset objects can therefore be likened to the base of a pyramid structure on which all other asset objects rest, as visualized in Figure 1. Above the base of the pyramid are various levels of financial asset objects that can, in principle, be created at will. Everything above the base of the pyramid is a financial asset object that we exclude from the definition of an engineering asset. Only the objects at the base of the pyramid (the 'real' assets) are the subject matter of EAM.

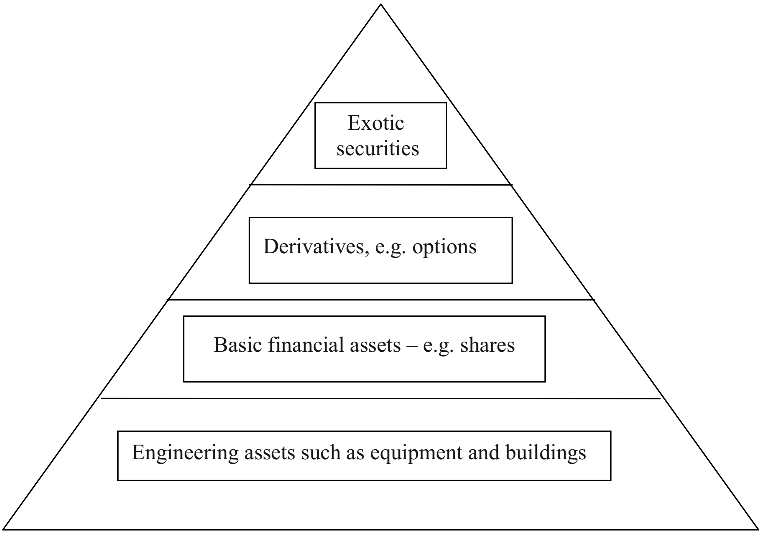

Figure 1 The fundamental nature of engineering assets

b. Legal entities. Legal entities are natural individuals or other entities such as companies created by a legal agreement. An object becomes an asset when a legal entity has legal rights in the object. Consequently the notion of an asset is defined as being an object with respect to a legal entity or some collection of legal entities. The reference to 'collections of legal entities' allows us to logically refer to the assets of, say, a Mining Corp's group of companies (which are not legal entities as such). Assets, therefore, do not exist as objects in limbo, without specifying the entity to which they relate, whether they are engineering or financial assets. Consequently, EAM must always have an organizational context in mind, such as managing the earthmoving equipment owned or leased by a Mining Corp or the naval vessels of the government.

The basic organizational concept that underpins the notion of an asset, the relationship between the asset object and a set of legal entities, is summarized in Figure 2.

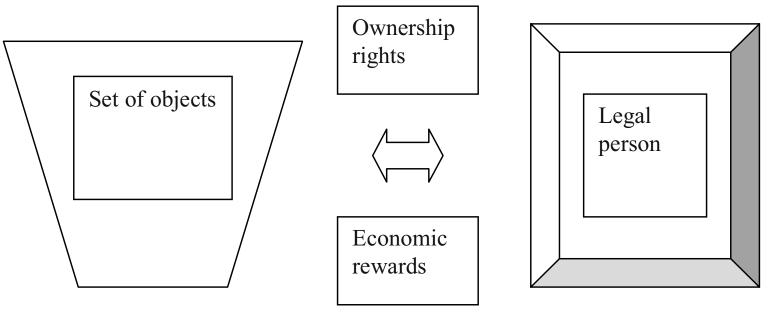

Figure 2 The basic components of an asset

c. Value. Engineering assets can have two basic types of value: *capability* value and *financial* value. Both types of value have the common feature that they depend upon the purpose for which the asset is being used. Capability value is the value traditionally of interest to engineers and is mainly of relevance to engineering assets rather than financial assets. It is measured on a physical, not a financial, scale. The capability of naval vessels, for instance, depending upon purpose, might be measured by the probability of the vessels requiring maintenance during an operation. The capability of a machine might be measured by the number of products that it can process per second, *etc.* Physical measures are heterogenous, measured by many different scales, such as units, length, weight, *etc.*

Financial value can also take many forms, depending upon the purpose for which the asset is used. The original cost of an asset is appropriate, for example, if the aim of the valuation is to identify how funds have been expended. If 'valuation in use' for the purpose of determining if an asset should be retained or replaced is the aim of the measurement, present values of estimated future cash flows and the expected value from disposing of the asset are relevant to the decision. Financial value is measured on a monetary scale. In single currency this means that all assets can be compared in one measurement dimension, which can sometimes be useful in decision making. Different measurement scales exist because the financial scale can be measured in different currencies. At any point in time the different currency units can be converted by a linear transformation. However the currency conversion rate can change significantly and quickly, which can cause difficulties in using financial measures for international comparisons.

Capability value and financial value of engineering assets are related in some manner, otherwise we could not know, for example, how much it costs to own and

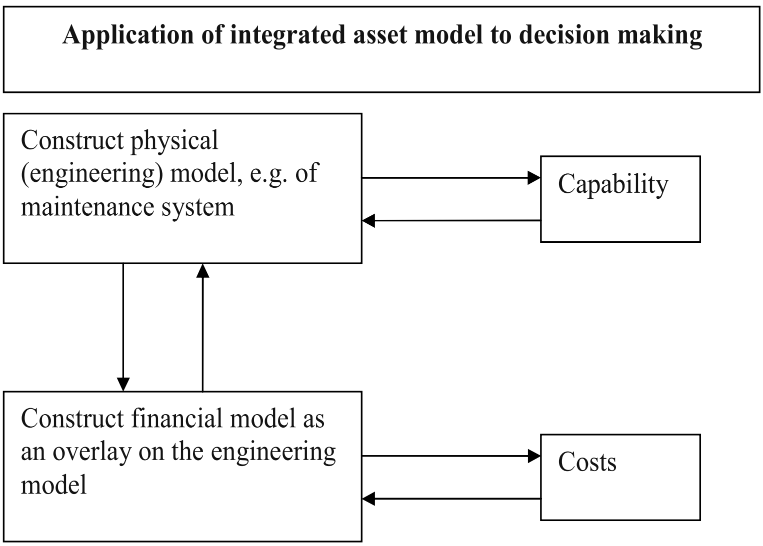

Figure 3 The relationship between capability and financial values of engineering assets

use an asset or how much more expenditure is needed to raise the capability of the asset to satisfy a change in service delivery requirements. This fact is important in any analysis of an engineering asset. The nature of the relationship between capability value and financial value is shown in Figure 3.

This Figure provides a basis for understanding the problems faced by engineering asset managers in pursuing the main function of asset management, *i.e.* the optimisation of performance against a profile of value requirements.

3.2 Engineering Asset Management

Management is defined in the OED as follows:

> *"Organization, supervision, or direction; the application of skill or care in the manipulation, use, treatment, or control (of a thing or person), or in the conduct of something." (OED, 2007)*

The OED more specifically defines asset management, perhaps significantly citing quotation from quite recent US sources, as:

> *"... the active management of the financial and other assets of a company, etc., esp. in order to optimize the return on investment." (OED, 2007)*

Management is goal-directed towards some purpose. In the case of EAM, purpose takes many forms which can be thought as differing views of the basic questions implied by Figure 3, *i.e.* how can an intervention in the processes relating capability and financial values be effective in achieving a particular goal, such as increasing the level of capability or reducing costs?

Management takes place at different levels of an organization and this also affects the views of service delivery capability and value profile that concern asset managers. An engineer engaged in condition monitoring very close to the basic engineering process may look at a specific point in a complex process, which might impact on the values connected as in Figure 3 in only a small part. An information manager may be concerned with providing the data that supports measurements of the relationships. An accountant might be interested in how the costs are caused by operating the assets and a human resource manager might be concerned with the safety and health issues arising from the process. Senior management may be concerned with overall profitability, longer term, life-cycle strategies for the asset and its relationship to organizational policy. The differing views of the capability-value profile management, relating to different levels of the organization are thus governed by the fundamental decision categories in respective strategic, tactical and operational contexts.

The recent tendency has been to define EAM in an all-encompassing manner, embracing the various dimensions of asset management implied in Amadi-Echendu

(2006), Mathew (2005) and Woodhouse (2001). The characterisation of EAM in this section is consistent with that tendency and provides a structure within which the different concerns expressed about asset management can be related together. The major challenges facing EAM are discussed in this context in the next section.

4 Requirements and Challenges for Broad Based EAM

The literature and our characterisation of EAM highlight a number of key requirements of the broader consensus interpretation that has recently begun to emerge:

1. Spatial generality: EAM extends across all types of physical asset, including human resources, in any industry.
2. Time generality: EAM extends over time to include short term (*e.g.* utilisation) and long term (*e.g.* lifecycle) aspects of physical assets.
3. Measurement generality: Real and financial measurement dimensions: measurement data includes measurements of the economic value the (financial dimension), social as well as the physical (the capability dimension) attributes of assets.
4. Statistical generality: Risk and other higher moment estimates of measures are important in EAM as well as the basic, first moment return measure of asset performance.
5. Organizational generality: EAM takes place at all levels of the organization, from direct contact with the asset to the strategic interactions that take place in the boardroom.

These five requirements of EAM generality have at least three implications. First, EAM is multi-disciplinary since it requires input of skills from virtually any discipline source, such as traditional engineering areas, information technology, economics and management. Second, decisions in EAM extend from operational and tactical aspects of asset management to strategic aspects, such as life-cycle modelling. Third, the human dimension of EAM requires the use of qualitative modes of analysis as well as the more traditional quantitative modes typically considered to be central to EAM.

Broadly based EAM consequently demands an information system that captures data supporting decision making across the areas suggested by the requirements and implications just described. Ideally an information system is needed that provides continuous data on the physical and financial conditions and changes in condition of a set of assets that is being managed for some purpose. The purpose for which the asset set is managed is defined by reference to the organization that controls the assets. This may be maximizing profits in a private company or providing satisfactory safety and environmental outcomes in a government agency, for example. It is evident, however, that in the vast majority of organizations, the opinion of many engineers is that poor data quality is probably the most significant single factor impeding improvements in EAM (*e.g.* Woodhouse, 2001).

Amadi-Echendu (2006) discusses an accounting system as the basis of an EAM information system in this context. Figure 4 reproduces the structure discussed in that paper. An advantage of using an accounting system as a starting point for an information system that would support the kind of comprehensive style of EAM envisaged in this paper and elsewhere is the generality of its coverage of organizational assets and its use in organizational decision making, especially at high levels. All of what we have defined in this paper as the engineering assets of an organization are recorded in an accounting system. Further, the accounting systems and assets of organizations are defined in such a way that those of one organization can be aggregated to provide asset analyses of arbitrarily defined organizations of any size (by a process of what accountants call ‘consolidation’).

The engineering asset manager focuses on what accountants and economists refer to as the ‘real assets’, *i.e.* everything except the trade marks, licenses and patents shown in Figure 4. The main strength of accounting systems in terms of the measurements they provide for decision making lie in the financial dimension referred to earlier and in the fact that they are routinely used for decision making at the most senior level of organizations and for reporting to stakeholders. The information accounting systems produce therefore has significant real world impact.

However, accounting systems as such are often deficient in relating financial measures to physical measures used for traditional engineering decisions. Engineers tend to rely on plant maintenance and inventory systems for such data. These engineering focused systems, although easily capable of integration with financial

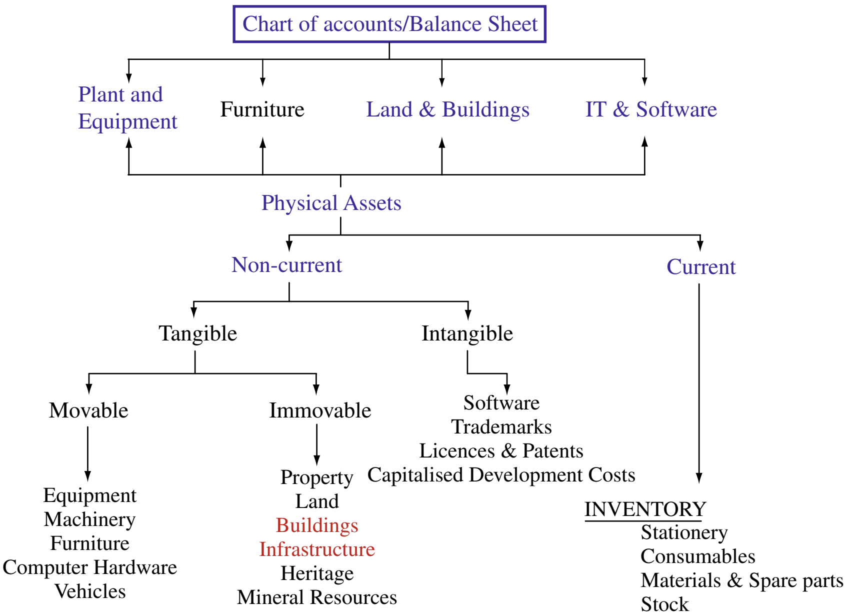

Figure 4 Asset structures in accounting systems

accounting systems in theory, and for which well tested and reliable software exists in practice, are often not well linked in practice. Data is frequently entered incorrectly or not at all into many fields and systems generally fail to deliver data of sufficient quality to provide the kind of support envisaged above for EAM.

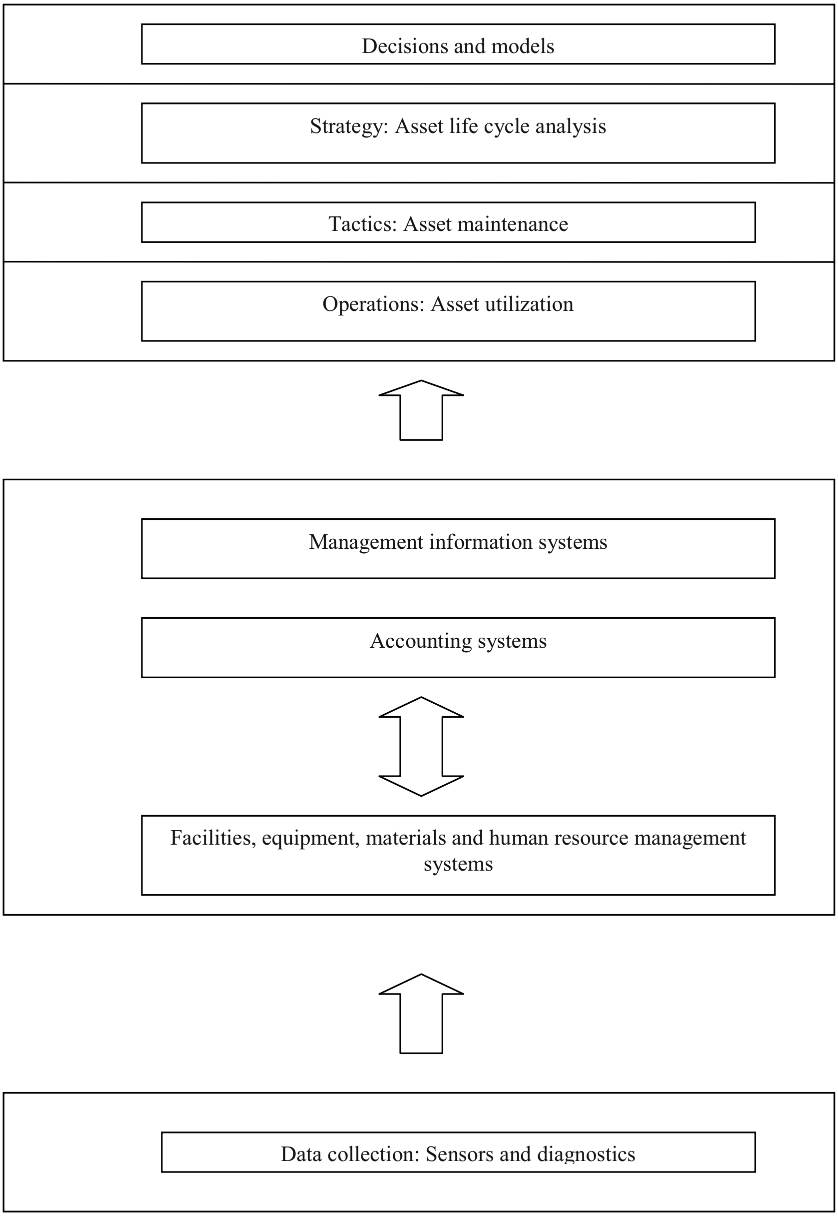

Figure 5 Areas, features and challenges of EAM

The general challenge faced by information systems in effectively supporting EAM is shown in Figure 5. Figure 5 is a composite of the basic elements of diagrams characterising EAM in the literature. If EAM is to be as comprehensive in its reach as we and others have argued, the data requirements for the decision models are very great. As Woodhouse (2001) notes, the greatest challenges for EAM often do not lie in the technical aspects of implementation of the EAM framework described in Figure 5, such as developing new sensors and diagnostic tests or better decision models. Rather they lie in the human element in data collection, entry and analysis. As reported in many studies of various types of enterprise resource management systems, failures of implementation are most often caused by insufficient resources being devoted to training and indoctrination of staff. This leads to the proliferation of legacy systems and incompatible, missing or inconsistent data.

Nevertheless, other challenges remain to be overcome in the implementation of a broad based EAM framework. The ability to integrate data and decision making across organizational levels in a consistent and behavioural non-dysfunctional manner is as yet largely unsolved. Also the objective assessment of asset risk is in its infancy, whether in the capability or the financial dimension.

5 Conclusions

EAM concerns the productive use of those assets that provide the value supporting all assets in the economy. It is thus essential to all that it is carried through as effectively as possible. This paper has emphasised a broad based characterisation of EAM that has come increasingly to represent a consensus view in the literature. The implications of that viewpoint have been examined through consideration of the key basic concepts that such a broad based EAM must encompass. Our analysis suggests that the human dimension of EAM has to be handled competently, both in terms of training and in terms of managing processes, if EAM is to be effective. Organizational structures delineated along traditional disciplines often fail to provide an asset-centric focus. This exacerbates and amplifies divergent views on what should constitute asset management in an organizational setting. The important thing to note is that the asset is oblivious to such dogmatic divisions, hence synergistic integration at the organizational level intuitively points to better collection, collation and analyses of the wide range of data required for effective EAM.

With divergent, non asset-centric organizational structures, current practice in most information systems has only evolved so far as to data collection still geared to fulfilling a traditional maintenance cost control philosophy rather than a full asset value management functionality. Financial and engineering information systems are typically insufficiently integrated such that concurrent measurement of both technical and financial risk is undeveloped. Furthermore, data and decision systems are generally not well integrated across different organizational levels and do not yet provide the same level of reliability for strategic decision making that they do for operational decision making. Consequently, the true nature of the important relationship between asset capability and associated value profile is rarely well understood.

Organizational synergy with its implied cognitive dispensation, coupled with integrated data quality are the primus-requisites for consistent EAM outcomes. Developments in sensors and diagnostics, improved information systems and decision models are all factors that can contribute to improvements in EAM. However the biggest challenges for asset managers, due to the need to change traditional conceptions of EAM, are most likely the various aspects of its human dimension as manifest on organizational settings and associated cognitive dispensations. Thus, the need to develop a consistent knowledge base, coupled with organizational refocus on the asset, plus commitment to re-aligning education and training towards effective human resource development are probably the most pressing challenges facing EAM in the short to medium term.

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Part II
Concepts

Identifying Core Functions of Asset Management

Vladimir Frolov, Lin Ma, Yong Sun and Wasana Bandara

Abstract It is widely acknowledged that effective asset management requires an interdisciplinary approach, in which synergies should exist between traditional disciplines such as: accounting, engineering, finance, humanities, logistics, and information systems technologies. Asset management is also an important, yet complex business practice. Business process modelling is proposed as an approach to manage the complexity of asset management through the modelling of asset management processes. A sound foundation for the systematic application and analysis of business process modelling in asset management is, however, yet to be developed. Fundamentally, a business process consists of activities (termed *functions*), events/states, and control flow logic. As both events/states and control flow logic are somewhat dependent on the functions themselves, it is a logical step to

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first identify the functions within a process. This research addresses the current gap in knowledge by developing a method to identify functions common to various industry types (termed *core* functions). This lays the foundation to extract such functions, so as to identify both commonalities and variation points in asset management processes. This method describes the use of a manual text mining and a taxonomy approach. An example is presented.

Keywords Asset management, Functions, Processes, Complexity, Business Process Modelling

1 Introduction

In many organisations, physical assets are the foundation for success and future growth. The effective management of these assets (hereon referred to as *asset management*) is essential to the overall success of such organisations [1]. Around the world, hundreds of billions of dollars are spent on managing assets. However, along with monetary significance, the rising importance of asset management is being fuelled by other factors, such as: the general ageing of assets; changing stakeholder and service level requirements; augmented emphasis on public health and safety; and increasingly stringent requirements set by regulating bodies [2, 3]. Organisations are acknowledging such factors as being significant to their operations and are thus looking to continually improve their asset management practices. In turn, this has led to an increase in research on asset management in both the academic and practitioner arenas, evident in the amounts of literature being published by both fields.

Asset management (in the context of physical assets, rather than financial assets) is a systematic, structured process covering the whole life of physical assets, whereby the underlying assumption is that assets exist to support the organisation's delivery strategies, and requires a certain level of management insight and expertise from diverse organisational disciplines [4]. In support of this definition, it has been acknowledged in the literature that effective and optimal management of physical assets requires an interdisciplinary approach [5, 6]. Thus, it is no longer sufficient to consider asset management as simply the maintenance of an asset [7], but rather as a holistic approach to the management of assets, incorporating elements such as strategy, risk measurement, safety, environment and human factors.

To aid in achieving optimum outcomes when managing physical assets, it is desirable to decompose asset management into a set of processes [8–16]. An asset management process is a set of linked activities and the sequence of these activities that are necessary for collectively realising asset management goals, normally within the context of an organisational structure and resource constraints [17]. Business process modelling is proposed as an approach to manage the complexity of asset management through the modelling of asset management. In simple terms, business process modelling is an approach for visually describing how businesses conduct their work [18], and is used for a variety of purposes in domains other than asset management to: increase awareness and knowledge of business processes; deconstruct organisational complexity; identify process weaknesses; adapt best business practices; design and communicate new business blueprints to relevant stakeholders; and design and configure software and workflow systems [19–21].

Curtis *et al.* [22] outlines that business process modelling typically includes graphical depictions of *at least* the activities (*i.e.* functions), events or states, and control flow logic, the combination of which constitutes the necessary elements of a process. A review of the literature reveals that asset management processes are currently implied, or at best, represented in part in a myriad of definitions, frameworks and textual contexts, stemming from both highly authoritative and lesser significant studies. Despite this, a sound foundation for research on the systematic application of business process modelling in asset management does not exist. Varying forms of business process modelling are used by organisations practicing asset management; initiatives such as this, however, are generally carried out in an ad-hoc manner or non-systematic manner.

This research addresses the current gap in knowledge by developing a fundamental method that outlines a.) the extraction of *core* asset management functions, and b.) the pooling of identified functions into appropriate levels of abstraction. Core functions are identified as those being common to industry types practicing asset management. This method outlines the use of a manual text mining and taxonomy approach, due to the varied nature of representation of asset management literature in both practitioner and academic arenas.

The remainder of this paper is structured as follows: the overall method is presented in Section 2; examples of applying the method are presented in Section 3; conclusions and directions for future research are presented in Section 4.

2 Method

The method to extract core functions is presented in the form of a flowchart, followed by accompanying details.

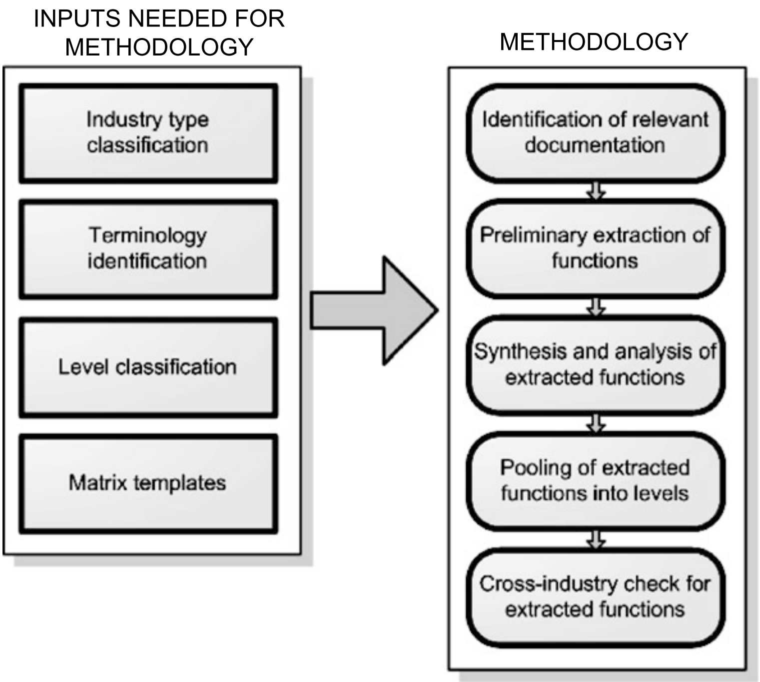

Figure 1 Overall Method

2.1 Industry Type Classification

The asset management literature is, more often than not, written in a particular industry context. As the aim of future research in this area is to identify common asset management processes (as well as the variation points within such processes in different industry types), it makes sense to first identify the industry *types*. Rather than developing a new classification of these different industry types, the classification developed by the Centre for Integrated Engineering Asset Management (CIEAM) is used [23]. This classification represents asset owners and management service providers of both infrastructure and industrial assets (*i.e.* physical assets) in the various public and private sectors. The main industry types practicing asset management, as classified by CIEAM are:

- State Treasuries and Agencies;
- Local Government Authorities;
- Transport Infrastructure including Main Roads;
- Water Facilities;
- Power Utilities;
- Manufacturing, Mining and Process Industries;

- Defence Organisations;
- Other Sectors: Education Facilities.

These industry types are utilised in the matrix templates, as per Section 2.4.

2.2 Identification of Terminology

Several terms, which have different meanings when used in different contexts, are used in this paper. To maintain consistency and set the context of the terms as used in *this* paper, a small glossary section is presented below. The terms that were selected for further clarification are: process, function(s), core function(s) and level(s).

Process:
In a generic sense, a process is an activity one performs, usually transforming an object from one state to another. For this paper, a comprehensive definition by Green and Rosemann [24] is used:

> *"A process is a self-contained, temporal and logical order (parallel or serial) of those activities that are executed for the transformation of a business object with the goal of accomplishing a given task."*

Thus, a process has a specific order of *activities* across time and place, with a beginning and an end and clearly identified inputs and outputs with a structure of action [25].

Function:
A function generally refers to what something does or is used for. In this paper, a function refers to the *activities* in the *above* definition of a process. That is, a function *is* an activity that uses inputs, and manipulates an object to produce an output.

Core Function:
A core function, as used in the context of this paper, is a function that is common to several industry types. A core function is also an essential *activity/function* within a core process, which if removed, would deem a process non-effective or unable to be continued. Core processes reflect the core competencies and value-adding activities of an organisation [26].

Level:
To successfully identify the core processes of an organisation, two methods can be used: top down and bottom up. Based on the corporate strategy of a business, the top-down method generates core processes from the strategic business fields [26]. These processes are then decomposed further in the course of modelling through

hierarchical refinement (*i.e.* using hierarchical levels in the process models). That is, models are shown in a high level of abstraction first, then decomposed into more detailed models as one moves down the levels.

2.3 Level Classification

Levels, as mentioned in the previous section, describe the level of abstraction of an overall process model or map. For example, a high-level manager is interested in the top-level processes, and thus, the top-level functions (*i.e.* coarse granularity). A lower-level manager is interested in more detailed processes/functions (*i.e.* fine granularity). Thus, when extracting the functions from literature, it is beneficial to follow the common practice of pooling functions into various levels. This is done by considering the relationship and significance of each function, in relation to other functions. In this method, functions are classified into generic layers. An example is shown in Figure 2.

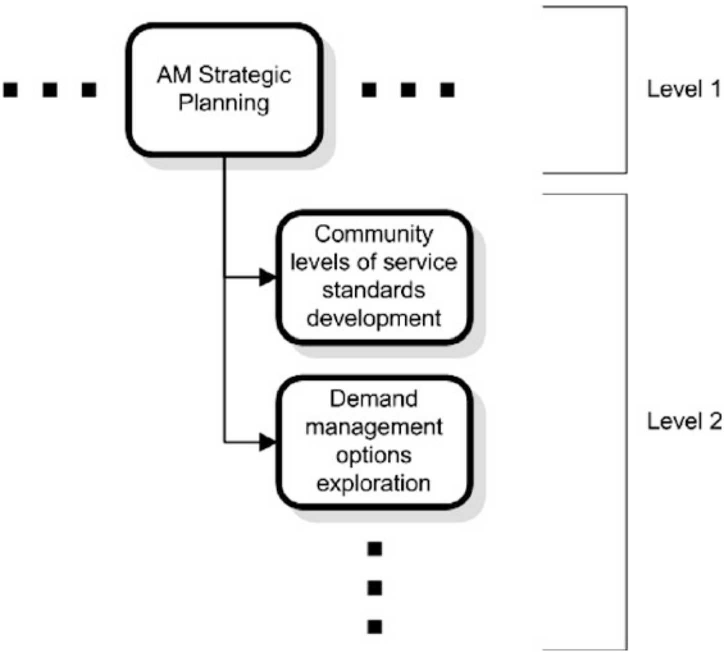

Figure 2 Example of Level Classification

2.4 Development of Matrix Templates

To summarise the information extracted from literature, two matrix templates are developed (shown in Tables 1 and 2). The first matrix template shows how relevant information from asset management can be extracted and represented in a common way. Relevant information from *individual* literature is mapped onto this matrix first. This matrix is used to capture:

- Document name;
- Industry type (context);
- Macro functions (*i.e.* high-level functions);
- Sub-functions (*i.e.* lower-level functions);
- Inputs and outputs of each sub-function (based on $IDEF_0$ notation).

The second matrix template is used to aid in summarising the extracted functions from the first matrix (Table 1) in order to demonstrate more meaningful information. The various industry types are shown in the top, horizontal row, whereas the extracted functions are shown as the left-most column. This matrix can assist to identify the common core functions across different industry types.

Table 1 Matrix Template for Individual Asset Management Documents

Reference	**Industry Type**	Main Functions **(Bold)** - Sub-Functions *(Italics)* - Inputs / Outputs		
[Name]	[Type]	**Function 1 - [title]** *First Sub Function* Inputs List of inputs Outputs List of outputs *Second Sub Function* Inputs List of inputs Outputs List of outputs *X Sub Function* Inputs List of inputs Outputs List of outputs	—	**Function X - [title]** *First Sub Function* Inputs List of inputs Outputs List of outputs *Second Sub Function* Inputs List of inputs Outputs List of outputs *X Sub Function* Inputs List of inputs Outputs List of outputs

Table 2 Matrix Template for Synthesised Core Functions

Core Functions	**INDUSTRY TYPE**		
	Industry Type 1	…	Industry Type X
Core Function 1	✓ | ✗	✓ | ✗	✓ | ✗
…	✓ | ✗	✓ | ✗	✓ | ✗
Core Function X	✓ | ✗	✓ | ✗	✓ | ✗

2.5 Preliminary Extraction of Functions

Text mining is the discovery, by computer, of new, previously unknown information, by automatically extracting information from different written resources [27]. In text mining, patterns are extracted from natural language text. A review of the asset management literature reveals a very diverse range of publications. Within these publications, an eclectic mix of text, diagrams and inconsistent formatting exists, which leads to the text mining procedure having to be conducted manually, rather than through the use of a computer. Conducting the process manually also allows for contextual information to be captured, which is generally not the case when done by automation. Manual text mining involves the scanning of text and identifying the three open word classes: nouns, verbs and adjectives. These three classes of words make up the majority of extracted text elements. Other word classes are used for contextual purposes and support the main word classes. Primary publications on asset management are used to extract *all* described functions within each publication (as per Table 1). These functions are then inputted into an *intermediate* second matrix, whereby *all* extracted functions are listed on the left hand side. This forms the necessary foundation for synthesis and analysis.

2.6 Synthesis and Analysis of Extracted Functions

Upon conducting an in-depth analysis of relevant literature, both inconsistency *and* similarity are encountered in the naming of functions, and the definitions and meanings of such functions. To manage this phenomenon, a taxonomy approach is utilised. A taxonomy of categories of terms and meanings is developed to capture all the possible combinations of naming and descriptions in the text of the publications. Functions are found to fit in one of the categories shown below.

a) **Same** function term or name | **same** function meaning;
b) **Same** function term or name | **different** function meaning;
c) **Different** function term or name | **same** function meaning;
d) **Different** function term or name | **different** function meaning.

When analysing the relevant literature, if a source is found to be describing a function using similar wording and implying a similar meaning, the described function is deemed to fit into category **a)**. This is the easiest combination to deal with. Category **b)** is arguably the most difficult to handle *i.e.* text found to be describing two similar meanings, yet using the same name. In these instances, the PAS 55 [2, 28] document is consulted to identify the most appropriate name for each meaning (PAS 55 being a quasi-standard in best practice asset management). Category **c)** is dealt with in a similar manner. When two pieces of text are found to be describing a similar activity, however, using different terminology, PAS 55 is used to identify the appropriate terminology for both function meanings. In category **d)** if the described functions are found to be not common in either name or meaning, then they are treated separately, as individual name-checked functions.

Following this, common functions are then pooled together based on the same taxonomy approach mentioned earlier, so as to eliminate similarly named functions, and produce only one account of that function (*i.e.* in Table 2). Whilst doing this, it is also cross-checked to see whether the different industry types currently acknowledge or practice the function, as extracted from available publications.

3 Examples

The first level of functions, extracted from relevant literature is shown in Table 3. These examples of method application were achieved by applying the steps in Section 2.

Preliminary findings show that high level functions are common to all industry types. That is, all industry types implement such functions in their asset management practice(s). However, at a lower level of abstraction, differences in functions begin to emerge (as per available literature). This is an important starting point in identifying the variation points in asset management functions and processes.

Table 3 Core Functions in Highest Level of Abstraction

Core Functions	INDUSTRY TYPE							
	State Treasuries and Agencies	Local Government Authorities	Transport Infrastructure inc. Main Roads	Water Facilities	Power Utilities	Manufacturing, Mining and Process Industries	Defence Organisations	Other Sectors: Educational Facilities
Existing Asset Knowledge Identification	✓	✓	✓	✓	✓	✓	✓	✓
AM Strategic Planning	✓	✓	✓	✓	✓	✓	✓	✓
AM Planning	✓	✓	✓	✓	✓	✓	✓	✓
Asset Performance Evaluation	✓	✓	✓	✓	✓	✓	✓	✓

Table 4 Examples of Core Functions in Second Highest Level of Abstraction for *AM Strategic Planning*

Core Functions	INDUSTRY TYPE							
	State Treasuries and Agencies	Local Government Authorities	Transport Infrastructure inc. Main Roads	Water Facilities	Power Utilities	Manufacturing, Mining and Process Industries	Defence Organisations	Other Sectors: Educational Facilities
…	…	…	…	…	…	…	…	…
Community Levels of Service Standards Development	✓	✓	✓	✓	✓	×	✓	✓
Demand Management Options Exploration	×	×	✓	✓	✓	✓	✓	×
…	…	…	…	…	…	…	…	…

4 Conclusions

This paper develops a method for the extraction of core asset management functions and the classification of such functions into appropriate levels. The method describes the use of a manual text mining approach. Examples show that functions at the highest level are common to all industry types considered. This research builds a sound foundation for further research in both asset management process modelling (AMPM), as well as the development of asset management process patterns through the identification of both common asset management processes and the variation points within such processes. Future work will see extensive effort in the development of asset management process patterns, based on the outcomes of an analysis on the comprehensive and complete matrix. The method described in this paper can be used for future work by both academics and practitioners. For a practitioner, the template can be used to map an organisation's asset management practice in a consistent manner, whilst identifying unknowns or 'gaps' in any identified function. A practitioner can also use the matrix as a benchmark tool to identify potential gaps in their overall asset management practice as compared to best practice asset management publications (such as PAS 55). This holds significance in building a foundation for the development of asset management process patterns, which encapsulate asset management processes common to several industry types. It lays the foundation for further research in the systematic, researched application of business process modelling in the asset management domain. Asset management is an immensely complex field; by decomposing this complexity, using an approach such as business process modelling allows organisations to optimise their asset management processes, in turn producing increased levels of efficiency in areas of their asset management.

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A Framework for Strategic Infrastructure Asset Management

Eric G. Too

Abstract Organisations owning and managing infrastructure assets are constantly striving to obtain the greatest life time value. This led to the development of the concept of asset management to provide a systematic approach to manage infrastructure assets. However, asset management as a discipline is still relatively new and as such lack well grounded theories. There is an urgent need to document the processes involved in the management of infrastructure assets. Through case studies, this paper aims to first, review the goals of infrastructure asset management and investigate the extent to which they reflect a business resource approach to infrastructure asset management. Second, the paper will identify the core processes of infrastructure asset management. These observed processes are then synthesised into a strategic infrastructure asset management framework to serve as a benchmark for practising manager looking to create value within their organisations.

Keywords Core processes, Infrastructure, Asset Management

1 Introduction

The concept of asset management is not a new but an evolving idea that has been attracting attention of many organisations operating and/or owning some kind of infrastructure assets. The term asset management has been used widely with fundamental differences in interpretation and usage. Regardless of the context of the usage of the term, asset management implies the process of optimising return by

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scrutinising performance and making key strategic decisions throughout all phases of an assets lifecycle (Sarfi and Tao, 2004). Hence, asset's management is a philosophy and discipline through which organisations are enabled to more effectively deploy their resources to provide higher levels of customer service and reliability while balancing financial objectives.

In Australia, asset management made its way into the public works in 1993 when the Australian Accounting Standard Board issued the Australian Accounting Standard 27 – AAS27. Standard AAS27 required government agencies to capitalise and depreciate assets rather than expense them against earnings. This development has indirectly forced organisations managing infrastructure assets to consider the useful life and cost effectiveness of asset investments. The Australian State Treasuries and the Australian National Audit Office was the first organisation to formalise the concepts and principles of asset management in Australia in which they defined asset management as "a systematic, structured process covering the whole life of an asset" (Australian National Audit Office, 1996). This initiative led other Government bodies and industry sectors to develop, refine and apply the concept of asset management in the management of their respective infrastructure assets. Hence, it can be argued that the concept of asset management has emerged as a separate and recognised field of management during the late 1990s.

In comparison to other disciplines such as construction, facilities, maintenance, project management, economics, finance, to name a few, asset management is a relatively new discipline and is clearly a contemporary topic. The primary contributors to the literature in asset management are largely government organisations and industry practitioners. These contributions take the form of guidelines and reports on the best practice of asset management. More recently, some of these best practices have been made to become a standard such as the PAS 55 (IAM, 2004, IAM, 2008b) in UK. As such, current literature in this field tends to lack well-grounded theories.

To-date, while receiving relatively more interest and attention from empirical researchers, the advancement of this field, particularly in terms of the volume of academic and theoretical development is at best moderate. A plausible reason for the lack of advancement is that many researchers and practitioners are still unaware of, or unimpressed by, the contribution that asset management can make to the performance of infrastructure asset. This paper seeks to explore the practices of organisations that manage infrastructure assets to develop a framework of strategic infrastructure asset management processes. It will begin by examining the development of asset management. This is followed by the discussion on the method to be adopted for this paper. Next, is the discussion of the result from case studies. It first describes the goals of infrastructure asset management and how they can support the broader business goals. Following this, a set of core processes that can support the achievement of business goals are provided. These core processes are synthesised based on the practices of asset managers in the case study organisations.

2 Development of Asset Management

The concept of asset management is not a new but an evolving idea that has been attracting attention of many organisations operating and/or owning some kind of infrastructure assets. The term asset management has been used widely with fundamental differences in interpretation and usage. Woodhouse (2006) suggested that there is at least 6 distinct current uses of the term as follows:

- The financial services sector has long used the phrase to describe the management of a stock or investment portfolio – trying to find the best mix of capital security/growth and interest rates/yield.
- Main board (usually financial) directors and some city analysts use the term in relation to mergers and acquisitions – buying and selling companies, re-organising them, divesting low value elements and trying to raise capital value and/or yields.
- Equipment maintainers have also adopted the name in an attempt to gain greater credibility and respect for their activities. As 'maintenance' has for so long been treated as a necessary evil and low on the budgeting priority list, perhaps calling it 'Asset Management' instead will raise awareness on the corporate agenda. 'Asset Management' becomes, therefore, a more sellable way of saying 'better and more business-focussed maintenance'.
- In line with the maintainers seeking greater corporate clout, the large number of software vendors selling 'computerised maintenance management systems' (*i.e.* asset registers, work management, history gathering, materials & cost databases) have relabelled their products as "Enterprise Asset Management Systems".
- In the information systems world, "Asset Management" is interpreted as just the bar-code labelling of computers and peripherals, and the tracking of their location/status.
- An increasing number of critical infrastructure or plant owners and operators have adopted 'Asset Management' to describe their core business – the combination of investing in, exploiting and caring for appropriate physical plant and infrastructure over its entire life.

In this paper, the last interpretation is adopted. This term of asset management has been adopted as the label for the integrated, whole life, risk based management of industrial infrastructure, as evolved principally in the North Sea oil and gas industry during the late 1980s and early 1990s (Woodhouse, 2003). Deregulation and privatisation of infrastructure such as utilities, transport and public services in the late 1980's and early 1990's have resulted in many organisations need to transform their infrastructure assets from cost centres charged with carrying out budget projects into profit centres charged with contributing to earnings growth. This has indirectly encouraged organisations to adopt this more holistic whole life approach to manage their infrastructure assets and hence the adoption of asset management.

However, two main barriers were observed that prevent the advancement and development of asset management in the context of infrastructure organisations. The first barrier to the adoption and advancement of asset management is found in the 'step child' status that is often bestowed upon asset management groups within organisations. Recognition and prestige are always accorded to finance and investment activities of new construction and development. On the other hand, asset management is frequently associated with only maintenance, asset inventory, and its related services and therefore considered to be of less strategic importance. For example, there are many asset management systems that have been used for years. These asset management systems focus on databases, asset inventories, technical models and other analytical tools. Most of these systems are used to monitor conditions and then plan and program their projects on a 'worst off' basis. As such, these systems typically function at the operations level and focus on one particular asset. This approach to asset management in general, and resource allocation and investment analysis in particular, is tactical rather than strategic. This view is supported by the findings and conclusions from the Australian National Audit Office Report No. 27 (Australian National Audit Office, 1995) in their audit of asset management practices common to 24 organisations. One of the main weaknesses identified related primarily to the lack of a strategic approach to asset management. Similarly, Woodhouse (2004) argued that emphasis has been disproportionately aimed at getting the jobs or functions done more efficiently resulting in "doing the wrong work 10% quicker and cheaper" and does not lead to a better total performance. Consequently, the concept of asset management as applied to infrastructure organisation is viewed in research more from an operational (engineering and maintenance) and asset management functional perspective rather than from the strategic and holistic management perspective. In view of the amount of emphasis in the analytical tools and technical models, there is a risk of leaping to the conclusion that the implementation of asset management should start through the development of more advanced technical modelling and other analytical tools that can talk to one another. The focus is more on individual assets rather than the long-term asset management needs of an organisation and is echoed by Stapelberg (2006) who noted that most asset management frameworks fail to have a system wide focus. Hence, a compelling argument against the progression of the concept of asset management is the general lack of interest from an organisation due to its operational perspective and therefore it is not able to contribute value to their stakeholders.

The second barrier is the contentious state of what constitutes asset management. Over the years many definitions of asset management have been provided. Some of these definitions are shown in Appendix 1. From the various definitions given, it can be noted that different perspectives have been taken by agencies and organisations to align their corporate objectives with their own asset management practices. These different frameworks were developed and used to suit each different organisation's business and corporate objectives and hence each has its own focus. Consequently, these diverse frameworks and guides, issued by different organisations being used in practice cover different aspects and principles of asset management in accordance with what asset management means to them. Stapelberg (2006) conducted a comprehensive review of various asset management models and frameworks of infrastructure and industrial assets owners both in the public and private sectors as well as those of asset management service providers. This review reveals that there are many asset management frameworks and models that have been developed in practice. These frameworks range in their level of complexity, design and specific details. Although many models and frameworks have been developed, they can be generally classified into 3 main categories.

1. The asset management framework adopted by industrial asset owners tends to be typical of the initial Enterprise Resource Planning (ERP) process frameworks that were developed in the 1990s (Stapelberg, 2006). They include industry strategies; enterprise management; supply chain management; and manufacturing and plant operations management.
2. The manufacturing sector is more inclined to adopt technology models that include components such as demand management, system engineering, configuration management, integrated (logistic) support and total quality management (Hardwick, 2008).
3. Thirdly, asset management frameworks adopted by infrastructure organisations such as utilities, transport and those of asset management service providers are more inclined towards a life cycle process approach. The processes range sequentially from asset planning, creation, operations, maintenance to performance measurement. These asset life cycle frameworks incorporate risk, quality and environmental management to form a total asset management framework.

The diverse and fragmented adoption of asset management by different organisations does not help in the development and advancement of asset management but rather, creates more confusion to practitioners. Consequently, organisations are struggling to come to terms with the constitution of asset management and how this can improve the performance of their infrastructure asset and this can have an enormous impact across the entire organisation.

The development of asset management discussed above suggests that infrastructure organisations need to pay attention to two key issues in order to improve their performance. Firstly, asset management needs to be viewed from a strategic approach in order to create value to the organisation. As owners, operators and maintainers of infrastructure assets, infrastructure organisations assume a significant responsibility in ensuring the successful performance of the assets to meet the service needs of their customers and expectation of stakeholders. Hence any infrastructure organisation should be striving to improve its operations, whether from the point of view of customer satisfaction, increased productivity, better asset quality, better environmental performance or any host of other performance indicators. For asset management to become a true value-adding pursuit within a corporate framework, it must be primarily concerned with filling a strategic role, *i.e.* an asset manager must be proactive not reactive in their approach. They must be able to forecast the needs of their organisations and make forward plans that will support the aims of the organisation in the future. This strategic view is important as it takes a long-term view of infrastructure performance and cost. A strategic approach can thus provide a better understanding of how to align the asset portfolio so that it best meets the service delivery needs of customers, both now and in the future (LGV, 2004). The need for a strategic and integrated approach has slowly gained attention. For example, Too *et al.* (2006) reviewed some of the current asset management practice by government agencies in Australia revealed that despite the different frameworks adopted in the practice, they are all advocating a strategic approach. Accordingly, it is pertinent to adopt a strategic approach to asset management that can support the broader and more strategic business goals.

Secondly, there is a need for a clear understanding of what asset management is. Asset management is more than a new management buzz word. There are still many questions about what asset management really means. Asset managers want and need a better understanding of its meaning, impact, and value to their organisations. The definitions given in Appendix 1 reveal that asset management is in some ways no different than what infrastructure organisations have always done. Decisions must be made about operating and maintaining infrastructure assets. New investments need to be planned. Resources need to be allocated, and budgets need to be specified. Knowledge about the condition of the equipment and structures has always been, and continues to be, valuable. A closer examination of the definitions reveals key unifying themes that form the heart of asset management and are described below:

1. Alignment of assets and operations with corporate objectives: The key goal of asset management is the creation of value to the organisation stakeholders from infrastructure asset (Jones, 2000; Humprey, 2003). It is about understanding and managing the trade-offs between financial performance, delivered operational and service performance and risk exposure (Jones, 2000). Hence, asset management provides a structure for driving and integrating customer expectations, legislative requirements, operating requirements, and financial objectives throughout an organization.
2. It links decision-making and action with information: Asset management is about obtaining the knowledge needed to optimise trade-offs among financial performance, operational performance and risk exposure (*e.g.* Jones, 2000; Sklar, 2004). It is about decision-making, rather than the blind pursuit of technical performance (Humprey, 2003). Decisions are driven by the actual condition and performance of assets individually and collectively as well as by the risks to corporate objectives from asset failure. Analytical methods and information integration are central.
3. Life-cycle costing is a key concept: Costs are minimized, starting with the initial investment, continuing through operation and maintenance, and ending with disposal (*e.g.* Austroads, 1997; Queensland Government, 1996; NSW Treasury, 2004; Brown, 2005). The connections between the choice of assets and the implications for the cost stream from maintaining those assets are critical.
4. It is a process: To understand asset management, we need to identify and define the activities involved. Asset management is about designing and implementing

a new business process that can deliver higher returns to corporate stakeholders (Kennedy, 2007). One of the precepts of the discipline is that all business units should make decisions based on the same criteria. A sound asset-management process ensures that business units do not sub optimize by emphasizing parochial criteria at the expense of overarching corporate objectives (Humprey, 2003).

Synthesising the above discussions and themes, strategic infrastructure asset management can be defined as follows:

Infrastructure Asset Management is a strategic and systematic process of optimising decision-making in resources allocation with the goal of achieving planned alignment of an infrastructure asset with corporate goals throughout its lifecycle.

This definition can provide guidance on the development of core infrastructure asset management processes. Craig & Parrish (2003), Brown (2004) and Sklar (2004) all support a holistic view of asset management as an integrated business process designed to optimise the use of a utility's assets while balancing the varying needs of key stakeholders. Similarly, Tao *et al.* (2000) proposed that from a business perspective, it requires an asset management framework that comprised of dynamic business processes to link all asset types together under a single business context. To enable an organisation to develop infrastructure, it needs a strategic framework to identify the specific infrastructure service needs, facilitate the selection and implementation of infrastructure projects, and to monitor the performance of infrastructure assets and services. Establishing a strategic infrastructure asset management process is therefore fundamental to improving efficiency and effectiveness of infrastructure delivery. To have structure and process in place, an organisation needs to identify and define the activities involved. Hence, there is a need to develop core asset management processes that can provide the bedrock for effective use of available asset management tools and systems (Clash and Delaney, 2000). This stronger focus on the integrated processes will then be able to deliver higher levels of customer service and reliability while balancing off the financial objectives for the business. For this reason, this paper aims to understand the core strategic processes involved in the management of infrastructure assets.

3 Method

This study used a multiple case design that allowed a replication logic, that is, a series of cases is treated as a series of experiments, each case serving to confirm or disconfirm the inferences drawn from the others (Yin, 2003). To build a better theory through multiple cases, the choice of cases must be based less on uniqueness of a given case, and more on the contribution to theory development within the set of cases (Eisenhardt, 2007). A particularly important theoretical sampling approach is based on a typology of cases. For organisations that manage infrastructure assets, the typology are (1) Infrastructure types (namely, water, airport, seaport, rail, road) (2) Level of privatisation (government owned corporation, government owned department, full privatisation) (3) Spread of infrastructure (co-located or spread over large geographical areas). Appendix 2 describes the three case organisations studied.

3.1 Data Sources

The data is obtained from discussions with senior managers responsible for the management of infrastructure assets and analysis of documents obtained from the organisations. The interviews are organised around two research questions: (1) What are the goals of infrastructure asset management? and (2) What are the core processes involved in achieving these goals?

Interviews: The purpose of the interviews was to understand the strategic core processes in delivering overall improvement to the management of infrastructure assets. Infrastructure asset management being a boundary-spanning function, three separate groups of interviewees were identified as representative of the infrastructure asset management function within each case. These three groups include executives from (1) senior management, (2) asset management and (3) asset operations. Interviews at each case organisation included at least one executive from each of the three groups to ensure adequate depiction of the infrastructure asset management function for each case.

Supporting Documents: In this research, interview transcripts were linked to other internal and external documents. For examples, while the interviews were taped, written notes were also made to record direct observations and other data. These notes include sketched diagrams used by interviewee to help explain their replies as well as their body language and the way they responded to certain questions. Direct observation when conducting the interviews can provide additional information about an organisation. The interview data was also supported, cross checked and compared with data from a broad range of sources. These documents include:

1. organisation policies and procedures such as departmental strategy, contractor selection procedures, corporate plans, annual reports, risk assessment guides, IT Strategic Plan *etc.*;
2. organisation charts;
3. Master Plans, Development Plans, Expansion Plan, Land Use Plan, *etc.*;
4. minutes of meetings, progress reports and memoranda, change management report, maintenance records, customer surveys *etc.*;

5. Consultant Reports such as economic reports, traffic reports, environmental reports, aviation reports, *etc.*;
6. Government reports such as Auditor General reports, Strategic Asset Management Plans, Rail Transport Infrastructure Plan, Infrastructure Plan and Program, *etc.*

Many of these documents are available in the case organisations' website. In addition, some of these organisations have provided access to their internal library that contained collections of many internal documents and reports. These documents offer more insights as they may not be directly observed during interviews. All these documents were reviewed to corroborate and augment the evidence gathered from interviews.

3.2 Data Analysis

A two-stage analysis suggested by Eisendhardt (2002) is adopted for this study; namely (1) Within-Case Analysis and (2) Cross-Case Analysis. Within-Case analysis is conducted initially by coding, that is, to 'chunk' the text into broad topic areas, as a first step to see what is there (Bazeley, 2007). This was done in the analysis of the first case to sort answers according to different components of asset life cycle such as asset planning, asset creation, asset maintenance, *etc.* This initial coding is useful to identify areas, which will need more data and identify text that is particularly relevant to the study. This process also helps to make the text manageable by selecting only the relevant text for further analysis (Auerbach and Silverstein, 2003).

Based on these broad-based nodes, further coding or 'coding on', a term coined by Richards (2005), from already coded text is performed. As 'coding on' continues, coded text can be analysed through categorization to reflect conceptual advance. From the broad-based nodes, further coding involved recording the repeating ideas by grouping together related passages. These repeating ideas were organised into some initial themes such as the asset management goals, significance of the strategic processes, the challenges faced, and approaches that can be adopted to support the business goals. Emerging themes such as significance of the strategic process in creating value to an organisation were further grouped into more abstract concepts consistent with the theoretical framework (Auerbach and Silverstein, 2003). This further coding gave rise to preliminary themes associated with the core strategic processes to support business goals of infrastructure organisations.

After the within case analysis for each case is done, the cross case analysis is next performed. The emerging ideas and concepts from each case were compared (Glaser and Strauss, 1967) to identify common themes and initial propositions. The purpose of this analysis is to test the overall validity of the proposed capability. This is to prevent the danger of reaching a premature and false conclusions as a result of information processing biases such as limited data (Kahneman and Tversky, 1973), overly influenced by the vividness (Nisbett and Ross, 1980) or by more elite respondents (Miles and Huberman, 1994), ignored basic statistical properties (Kahneman and Tversky, 1973), or sometimes inadvertently dropping disconfirming evidence (Nisbett and Ross, 1980).

The preliminary findings from the data analysis were compiled into a preliminary report to seek further validation. The report was sent to senior managers of case organisations for feedback and comments. Further meetings were arranged to discuss the findings face-to-face. These feedback were incorporated to refine the findings.

4 The Goals of Infrastructure Asset Management

From the strategic perspective, the principles of asset management must be soundly based on the alignment and fit of the organisation's resources, to best meet the needs of the customer within the environment in which it is required to compete in order to maximise returns to its stakeholders. The asset manager being the custodian of infrastructure organisation's main resource *i.e.* infrastructure assets, needs to align the goals of infrastructure asset management with those of the strategic business goals as defined by the asset owner so that it can achieve the long-term stakeholder value.

As in most organisations, the main reason for infrastructure organisation existence is to sustain the long-term shareholder value. Case data revealed that the most important context for managing infrastructure assets is to support the performance required by business operations. This is aptly shared by managers as follows:

> *"we are managing for the performance required by the business that uses the asset." (Port)*

> *"it all started with a business plan and underneath it you build an asset plan that support the business ... these asset plans contain both maintenance and an investment strategy." (Rail)*

As in most organisations, the main reason for an infrastructure organisation's existence is to sustain the long-term shareholder value. It is fair to say that the shareholder is constantly looking for financial return for their money invested in an organisation. Informants from all cases have viewed the financial returns from infrastructure assets as important in the management of infrastructure assets. Some of the managers commented:

> *"shareholders ... are looking for return on their investments ... and they want maximum return ... they will not want to invest million of dollars if there is no guarantee that it can generate a good steady income." (Port)*

"we make a full commercial return on our assets from the coal business." (Rail)

"the driver is that the asset must give us a return." (Airport)

However, Cokins (2004) cautioned against financial return being the only end goal and excessive focus on a financial goal is unbalanced because non financial goals can influence the eventual outcomes. The above suggests that in the formulation of goals of infrastructure asset management, it is important to look at stakeholders' values. Two obvious categories of stakeholders *i.e.* customers and owners/ investors' are central to organisations that manage infrastructure assets. Other stakeholders such as managers, employees, suppliers, community and general public may also need to be considered. There are many conflicts of goals between different stakeholders in the management of infrastructure assets. For example, to comply with the safety regulations, it is imperative to incur more cost and hence increase the cost structure. But this is in conflict with a shareholder view of maximising return. These differences must be recognised and addressed. To this end, goals and objectives should be a result of the interactions and consensus between various stakeholders. Hence, it is clear that the goals of asset management cannot include every concerns and wishes of all stakeholders. Woodhouse (Woodhouse, 2002) argued that the secret of success at the heart of asset management is "choosing the right direction despite the uncertainties and conflicting stakeholder expectations, and taking the whole organisation with you." Consequently, the infrastructure asset management goals need to address a few dimensions that reflect the interest of a wide range of stakeholders.

Organisations can achieve sustained shareholder value according to Kaplan & Norton (2004), by either a productivity strategy or a growth strategy. To achieve the growth strategy, business goals must aim at enhancing the opportunity to expand revenue and increase customer value. To achieve a productivity strategy, the business goals should be to improve the cost structure and increase asset utilisation. This relationship is shown in Figure 1.

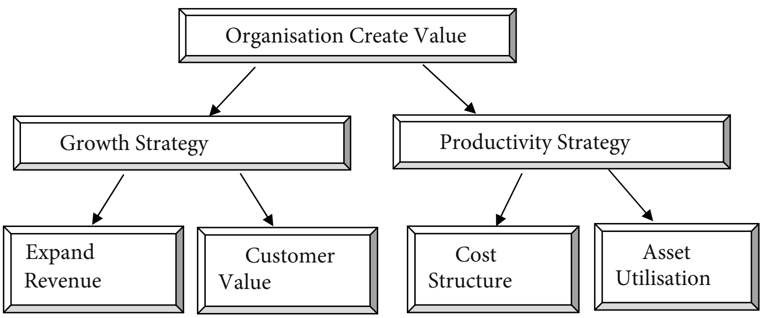

Figure 1 How organisation creates value (adapted from Kaplan and Norton, 2004)

Table 1 Goals of Infrastructure Asset Management

Goals	Port	Rail	Airport
Cost Efficiency	To achieve the design life of an asset at minimum maintenance cost	Some are very cost sensitive ... keeping cost down is a very important priority	Manage them efficiently, within the budget, to keep the asset in good conditions without spending too much money on it
Extend Service Life	To increase the service life of an asset with cost effective preventive maintenance	We will extend the life of the assets as long as the conditions allow us to do it	We can continuously maintain, upgrade, replace some of the components and extend the life
Capacity Matching	Once the occupancy rates reach more than 50 %, it signifies that it is time to expand the wharf facilities … Based on those forecasts, we conduct modelling to anticipate the infrastructure requirements	Depends on business context and customer demands, we will invest to provide those capacity Planning that analyse the demand and capacities and services needed and plan what kind of assets that we need to support those services	… ensure we are able to optimise existing capacity relative to demand
Quality & Durability	Aims to achieve excellence in engineering … No point giving them an asset that they are not satisfied with	Durability and robustness of our asset	We have to present our assets in a very good condition, in a very good way
Availability	Maximum availability of assets to support our business	It is really the business/customers demand aspects … both the reliability and availability	Make sure assets are available when our customers need them
Reliability	The reliability of that asset	Reliability can be paramount like the city network where we run the commuter service	Keep the assets operational and in good working order
Compliance	We have a big environment section that monitors all sorts of environment issues including noise, air, spillage, storm water *etc.*	We do the work under the regulation in a regulated monopoly scenario there is a prudency of scope and prudency of price test	Legislative requirement, because a lot of our assets and security revolving around the airport … maintain it to regulatory requirements
Market Leadership	We want to be the trend setter and we want to be the leader of the pack We look at trends that are emerging, we try to be well and truly ahead of the game We need to make sure we stay at the cutting edge of the port facility business	We need an innovative way of making things happen	If we do not enhance our infrastructure assets to serve newer aircrafts, airlines may not want to fly here … can affect our efficiency and our reputation as a premier airport

Figure 2 Symbiotic relationship between the Asset Management Goals and Business Goals

Regardless of the type of business, all organisations will have to consider these strategies in order to increase their performance. In the management of infrastructure assets, the asset manager should view the infrastructure assets under their care as an integrated business resource that needs to be managed as a total enterprise (Too and Tay, 2008). If infrastructure assets are a business resource, then the goals of infrastructure asset management must support the business goals *i.e.* infrastructure assets must generate revenue and meet the business needs without compromising the sustainability and competitiveness of the business in future. Hence, they need to develop the asset management goals that are aligned to these broad strategies in order to create value to the organisation.

These asset management goals must achieve one of those broad business goals in order to add value to organisations. Data from this research indicated that there are many goals being pursued in the management of infrastructure assets in order to support business operations. These goals are shown in Table 1.

Figure 2 illustrates the symbiotic relationship between business goals and asset management goals as observed from the case data.

4.1 Asset Management Goal 1 – Cost Efficiency

To achieve the broader business goals of improving cost structure, case evidence suggests that most asset managers interviewed are constantly looking at ways to improve their cost efficiency. In other words, the asset management goal is to manage and operate their infrastructure asset cost efficiently. For example, the following comments were noted:

"we aim to achieve the design life of an asset at minimum maintenance cost." (Port)

"we manage them (infrastructure assets) efficiently, within the budget, to keep assets in good condition without spending too much money." (Airport)

4.2 Asset Management Goal 2 – Capacity Matching

To achieve the business goals of asset utilisation, there is a need to match the capacity to the business needs to ensure that infrastructure assets are not over or under provided. Hence, another asset management goal is matching the capacity of infrastructure assets to support business needs. As one informant noted:

"certainly the capacity is fundamental but then the issue is of what services do you want to run to match that customer." (Rail)

"we are constantly looking at projected growth of the terminal and travelling public ... our operations department will feedback on capacity of current assets and the capacity going forward ... what we can do and what we can handle." (Airport)

4.3 Asset Management Goal 3 – Meeting Customer Needs/Requirements

To enhance customer value, it is necessary to provide an asset that users need and want. Customer value can be enhanced through providing "quality" assets which can be broken down into more detail such as reliability, dependability, compliance to safety and environmental regulation and timeliness. In addition, these infrastructure assets must not only be available but must also be in good, durable and reliable conditions that comply with regulatory requirements. The need to provide customer value is noted by some other informants as follows:

"we must ensure there is maximum availability of assets to support our business ... no point giving them an asset that they are not satisfied with ..." (Port)

"its maintaining reliability to meet customer standards and service ..." (Airport)

"there is also a compliance side of things where we have regulatory requirements to maintain and operate assets within certain guidelines." (Rail)

4.4 Asset Management Goal 4 – Market Leadership

To grow the revenue opportunity, it is interesting to note from the cases that one of the asset management goals included a need to be innovative and set standards in order to be a leader to remain competitive. In other words, asset management aims to be forward looking in order to sustain competitive advantage through market leadership, innovation and creativity. This sentiment is echoed by managers interviewed:

> *"we want to be the trend setter and we want to be the leader of the pack ... The other main goal is to adopt the best practice principles to make sure that we are adopting the best in everything we do." (Port)*

> *"The key driver is to maintain excellence in service delivery and standards ... if we do not enhance our infrastructure assets to serve newer aircrafts, airlines may not want to fly here ... it can affect our efficiency and our reputation as a premier airport." (Airport)*

> *"... this is like an innovative way of making things happen." (Rail)*

In short, the above goals will require asset managers to make decisions that will maximise their financial performance, achieving excellence in their service level and minimising their risk exposure. However, the difficulty is that these goals are not all independent but actually all outputs of the same infrastructure asset performance. The interdependency means it would be necessary to understand the interplay between these goals in order to effectively maximise overall infrastructure asset performance – or value (Jones, 2000). The asset manager has to make an informed and weighed decision to achieve a balance between these goals. Following this decision, strategies need to be developed to achieve the set goals. Core asset management processes underpin these strategies. The next section reports the findings from the interviews on the core asset management processes.

5 Emerging Framework: The Strategic Infrastructure Asset Management (SIAM) Processes

Having established the goals of infrastructure asset management, the strategies must be identified within the asset management function to describe how these goals can be accomplished. Brown (2005) suggested that these strategies within the context of asset management framework, are in fact processes in which an asset is effectively managed throughout its entire life cycle. The importance of asset management processes in any infrastructure organisation cannot be overstated, as it will ensure full accountability of the asset condition, use and performance (Brown, 2005). Specifically, the ability to improve business core processes involves the integration of business core operational processes and organisational strategic goals. This process effectively delivers the organisation's business objectives to match the corporate direction for the organisation within a pre-determined planning horizon (IMEA, 1994). These processes will require consideration from the start of the asset planning phase to allow investment decisions to be made on an asset's entire life cycle rather than the asset's initial purchase price (NPWC, 1996).

Stapelberg (2006), in reviewing the various asset management frameworks suggested that most infrastructure organisations are more inclined towards adopting an infrastructure asset life cycle process approach. Similarly, Hardwick (2008) suggested that all the frameworks developed in practice can be integrated into asset life cycle processes. Kennedy (2007) confirmed that the asset management process itself is a life cycle process and believed good asset management processes were essential. This thinking recognises asset management as an overarching business process that integrates into all aspects of the way the business functions to deliver its comprehensive corporate plans (NSW Treasury, 2004). This paper will thus identify the core processes around the infrastructure asset life cycle that are necessary for improving the performance of infrastructure asset. The infrastructure asset life cycle processes can generally be grouped into three clusters namely asset planning, asset creation and asset operation. Figure 3 illustrates how core asset management processes can support the asset management goals and the broader strategic business goals in order to create value to organisations.

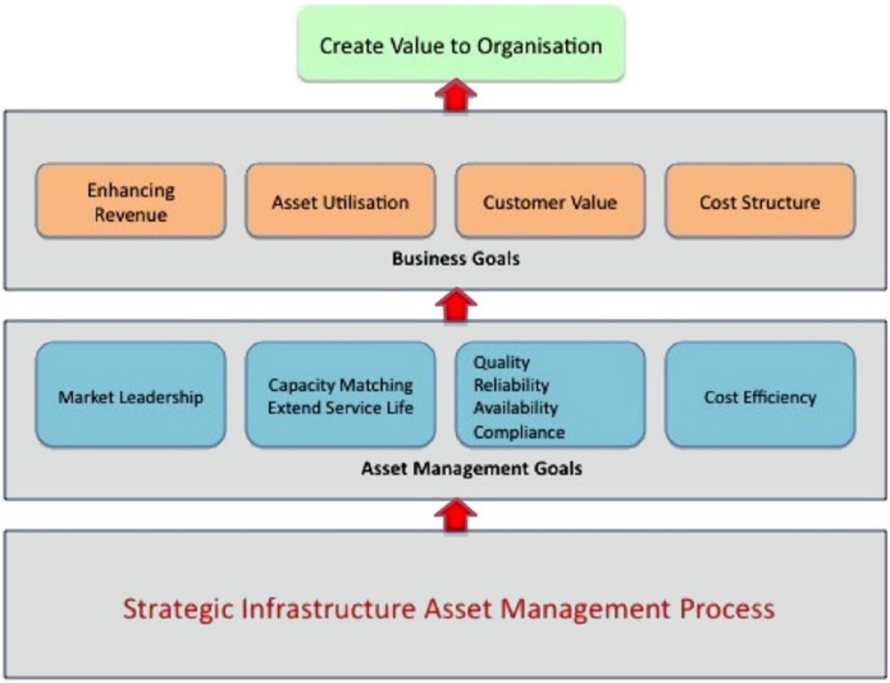

Figure 3 Core asset management processes must support asset management goals

Many organisations have found that good business processes – work that runs from end to end across an organisation – can lead to dramatic enhancements in performance, enabling organizations to deliver greater value to customers in ways that also generates higher profits for shareholders (Hung, 2001). In general, organisations will have many processes as are necessary to carry out the natural business activities defined by the life cycle of the infrastructure assets. However, many scholars also acknowledge that not all business processes can be a source of competitive advantage. For example, Kaplan & Norton (Kaplan and Norton, 2004) suggested that managers must identify and focus on the critical few internal processes that have the greatest impact on strategy and can create value to the organisations. When economic and technological complexity increases, such as is the case in infrastructure asset management, managers must devote more attention to definition and improvement of the few critical business processes that determine success and failure (Zehir *et al.*, 2006). In order to create value to the organisation, such business processes must support the business goals (*e.g.* Zehir *et al.*, 2006; Kaplan and Norton, 2004). Hence, the main concern of this paper is to understand what are the core asset management processes that can create value to infrastructure organisations.

The interviews with managers yielded information relating to the core processes of the participating organisations. The interviews revealed that many of these processes are fragmented and are developed based on senior management intuition. For example, all the organisations interviewed either did not have a framework guiding their infrastructure asset management practices or are still in the process of documenting their practices. As one manager noted:

> *"We are still documenting how we do things but we operate under the strategic asset management plan that sets out our overarching goals for asset management." (Rail)*

The focus on individual functional improvement does not always result in enhanced performance of infrastructure asset as a whole. Added to these difficulties is the complexity of infrastructure asset management processes as they usually involve many activities that are performed by different people over considerable time frames. The general feeling is that there is a lack of integration in such an approach. This sentiment is shared by a manager:

> *"structurally we are organised more around the major functional activities because of the demand of managing them and then we seek to integrate those back in to provide the service that the customers want ... so you need the integration." (Rail)*

Thus to resolve this complexity, there is a need to identify those processes that can significantly impact the performance of the infrastructure asset are being considered rather than trying to track each individual decision. To this end, the processes described here are the core processes, that is, the essential activities the infrastructure organisation must undertake to puts its idea for value creation into action on a sustained basis (Sanchez and Heene, 2004). From here, these core processes will be known as the Strategic Infrastructure Asset Management (SIAM) processes. Based on the informants' accounts of their current practices in infrastructure asset management, the findings are synyhesised to describe the framework of strategic infrastructure asset management processes as adopted in practice. This framework will be generic and can be applied to various types of infrastructure assets such as rail, airports, seaports, *etc.* because it focuses on the core processes of infrastructure asset management that applies across all infrastructure organisations. The following sections will provide case evidence to show common and recurring themes that emerged through the interviews leading to the identification of the core processes of infrastructure asset management.

The literature (*e.g.* Stapelberg, 2006) has suggested that asset management frameworks adopted by infrastructure owners such as transport and those of asset management service providers are more inclined towards a life cycle process approach. Since these forms of infrastructure are the scope of the current study, the processes illustrated here are based on the life cycle phases of infrastructure assets *i.e.*, asset planning, asset creation and asset operation. Each of the phases consists of a number of supporting core processes that will contribute towards achieving the asset management goals. These are: (1) capacity management (2) options evaluation (3) procurement & delivery (4) maintenance management (5) asset information management. Central to this framework is the asset information management process that store important information and knowledge.

These core processes are diagrammatically presented in Figure 4 and will be discussed in the following sections.

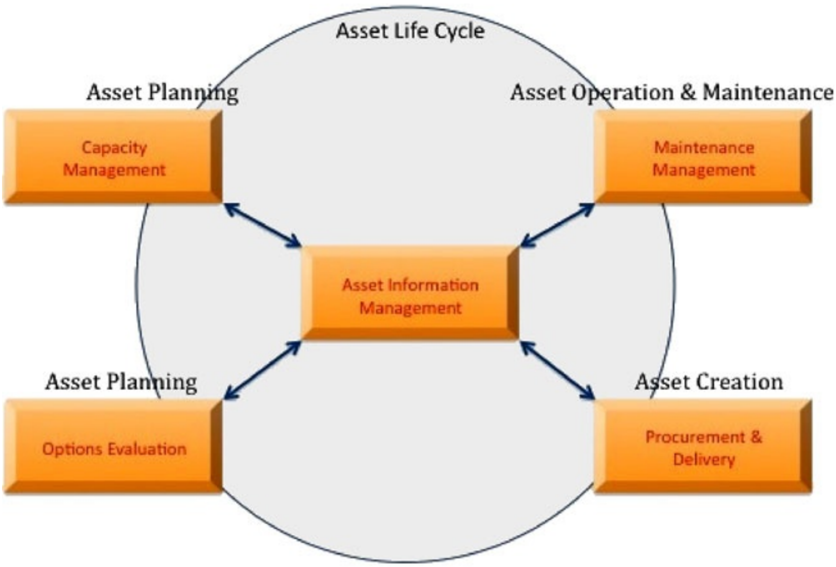

Figure 4 Strategic Infrastructure Asset Management Processes

5.1 Capacity Management Process

Capacity management is the process of ensuring optimal provision of infrastructure assets. Effectiveness in this process will enable the infrastructure asset owners and their stakeholders to receive full value on their investment. The Institute of Public Works Engineering of Australia (IPWEA, 2006) has suggested that in order to provide the maximum return, infrastructure assets must be utilised effectively and deliver the required level of service. This suggests that in infrastructure capacity management, organisations must ensure (1) the high utilisation of assets and (2) that the assets support their business operation.

To ensure high utilisation of infrastructure assets, infrastructure organisations need to examine their current infrastructure capacity and their productivity. This is important because capacity can be increased through various means such as operational efficiencies and/or improved maintenance efficiencies and not just through new capital investment. This is shared by comments from the managers interviewed:

> *"you can keep adding capital to a certain amount ... the other one is knowledge of the industry such that when you designing the port layout that is integrated with a proper and logical flow you can make the operation more efficient ... this can saves us from building more assets." (Port)*

> *"capacity increases can come from investment in physical assets such as additional trains, port expansions, stockpiling equipment, or from increased operational efficiencies by rail and port operators." (Rail)*

Hence, capacity can be increased through more efficient use of existing infrastructures via design, reconfiguration and integration of infrastructure assets. To have proper operational control to support business operations, capacity management process must be able to predict capacity under various circumstances and provide a clear picture of the risk of failure. Managers interviewed share this:

> *"we do capacity planning to get an idea of (what) the potential (for) failure of our infrastructure asset might be." (Airport)*

> *"we analyse the capacity and services needed and plan what kind of asset that we need to support those services." (Rail)*

Additionally, providing the right infrastructure is critical as it takes a long time to build and the asset is designed to last even longer. For example, in providing a wharf for the case of a seaport, which has a designed life of 50 years, they have to ensure that it is suitable for the ship and trades expected in that kind of lifetime. Similarly, getting the timing right is just as important as shown by the following comments from managers interviewed:

> *"the fundamental problem I see in the industry is to get the timing right ... especially when we deal with such large assets it is all about the timing ... building infrastructure*

too early and not getting the return needs to be balanced with building infrastructure too late and missing the opportunity." (Port)

"we only build if the demand is there but when the demand is there it is generally too late because we take 3 to 4 years to build." (Rail)

Capacity management is therefore essential to ensure that the goal of capacity matching is achieved and the right infrastructure can be planned and optimally provided to support business needs. All case participants echoed the importance of the capacity management process. This is summarised in Table 2 below.

Table 2 Importance of the Capacity Management Process

Case	Evidence showing the importance of Capacity Management
Rail	Certainly capacity is fundamental … we need to know what kind of assets that we need to support those services … a railway is a network asset … with any network, one of the key issues is capacity
Port	Managing the capacity and managing the growth are the key drivers here … it is the key to the future because we don't want surprises
Airport	Capacity planning is a significant focus and an important aspect that can affect our business operations … proactive capacity management can ensure that our operations are not affected … it can indirectly affect our efficiency and our reputation as a premier airport

5.2 Options Evaluation Process

From the many capacity-enhancing options identified, evaluations will have to be conducted to select the "best" and optimal solution that meets the business needs. This practice is shared by managers as follows:

"the business case will then compare a series of options." (Rail)

"any new infrastructure need to be evaluated ... we collect all the relevant information and build a business case" (Port)

Being commercially run organisations, financial return is the key hurdle to be clear before other evaluations are conducted. Table 3 illustrates this finding from the interviews.

When the financial viability of an option is established, a series of other evaluations are carried out before deriving at the final option. Such an approach allows organisations to focus on responsible use of resources such as investment, technology and technical development to ensure the activities pursued will benefit not only its bottom line but also the community, the environment and the economy. A balance and comprehensive evaluation of each factor can ensure the long-term

Table 3 Financial Consideration in Options Evaluation

Cases	Evidence
Rail	If somebody is there willing to pay and commit to a certain amount of tonnage then we can justify … we then work out which one is the best that can give us the best return … the team usually work together and consider the various options and various issues whether they are safety, environmental, operational, or technical
Port	Once it financially make sense with our current rate of return … it goes through quite a lot of evaluation … our evaluation is very much a balance … we have to do more evaluation to make sure it is timely and appropriate
Airport	Finance is key … the asset must give us a return … we then look at a host of other criteria … there is a huge process that goes through many evaluations by various departments and the public for comment

profitability of the business is maintained at a level of manageable risk. This translates into providing the right mix of infrastructure assets so as to provide the optimum value for stakeholders. The need to have a comprehensive and balanced evaluation, in addition to financial consideration, is evident in all cases from the following quotes from managers interviewed:

> *"in the past based on the government model we just built if it was required by the State ... now we adopt a more balanced evaluation to make sure it is timely and appropriate." (Rail)*

> *"... everything has an impact and that needs to be modelled and understood." (Port)*

> *"it will go through many evaluations ... there are obviously many evaluations to be considered ... you cannot take the economic issue only because the community may not agree." (Airport)*

The data also suggests that infrastructure organisations evaluate the infrastructure asset options based on a multi-criteria approach. The following criteria were observed from the case study: financial, technical, environmental, safety, and service quality. Table 4 summarises the criteria used in the evaluation of asset solutions.

In addition to the above findings, the importance of the options evaluation process is underscored by the need to minimise financial and legal risks as well as maintaining accountability to the stakeholders. The evidence gathered from the case interviews in this regard are presented below:

> *"on top of our evaluation, we also have some independent studies for legal reasons and risk, accountability and verification." (Airport)*

> *"everything has an impact and that needs to be modelled and understood ... this include risk assessment such as financial risk, forecasting risk such as how likely is the trade growth and those sort of issues." (Port)*

Table 4 Criteria for Infrastructure Asset Evaluation

Criteria	Rail	Port	Airport
Financial	We conduct a cost/benefit analysis and the prediction of end of service life Most of our investment decisions are analysed based on business cases using DCF analysis	We do financial analysis first, and if it financially makes sense with our current rates of return, the asset life and its life cycle cost *etc.*	We do a lot on whole life analysis and cost of all the assets to determine and make sure that these things will operate within the life they are designed for and it is economical to run until then
Technical	There is a series of fundamental engineering inputs Technical obsolescence with both signalling and communication is an issue to be considered … these assets become technically obsolete before they actually wear out	There is a technical evaluation such as engineering and ground condition We have to evaluate the technical aspect such as design and constructability, future maintainability	The technical aspect such as how we can plan the new investment with different stages to prevent disruption to operations
Environmental		There is evaluation that looks after the town planning and environment. For example, if we build a wharf on reclaimed land we will destroy many hectares of mangrove	We also need to consider the environmental issues as well Sustainability is an important issue … we have to consider the community issues and social cost
Safety	You need to have a maximum speed on different portions of the track for safety reasons and we need to ensure our signalling system won't let another train on the track until the first train is clear	Safety is very important for port operations, so we have to evaluate the safety aspect	We also look at users comfort and safety parameters and other compliance requirements
Service Quality	The service design can impact the network configuration and asset configuration and call up asset investment needs	We also have to assess from the operations perspective	You have to make assessment based on circulation space and see how long it takes for passenger movement and queuing assessment

5.3 Procurement & Delivery Process

Procurement has been defined as 'the action or process of acquiring or obtaining material, property or services at the operational level' (McGraw-Hill, 1984).

Construction procurement has been defined by the CIB W92 Working Commission on Procurement Systems as 'the framework within which construction is brought about, acquired or obtained' (Sharif and Morledge, 1994). The main goal of procurement and delivery of infrastructure assets includes maximising efficiency and effectiveness of organisational resources, meeting customer expectations, minimising adverse customer impacts and adhering to project scope, schedule and budget, and managing needed changes in projects and programmes (AASHTO, 2002).

Appropriate procurement strategies are needed to help achieve optimal solutions in terms of cost, time and quality (Kumaraswamy and Dissanayaka, 1998). Selecting the right service provider/supplier can help reduce time to completion and improve cost effectiveness by addressing project complexity, supplement staff skills with specialised expertise, and ensure more effective use of in-house resources more effectively. In the past, under a government owned model, most infrastructure assets were procured and delivered using only in-house resources and capabilities. For example, a manager from Rail case noted:

> *"we have certainly moved away from our traditional culture of doing it ourselves as we don't trust anybody to do it." (Rail)*

This position has changed in recent years. Infrastructure organisations tend to adopt a more formal method of evaluation. In deciding the most appropriate providers, most of the infrastructure organisations consider factors such as price together with a few other factors such as quality and delivery. Increasingly, infrastructure organisations that are considering outsourcing will rigorously evaluate their own capabilities, in terms of resources such as cost, equipment and expertise, against those of the external providers to determine an appropriate procurement strategy. Evidence from this research suggests that the procurement options used depend on project complexity (which includes risk, time, cost and quality) and the availability of in-house skills and expertise. For example, one informant indicated:

> *"the procurement method to use is driven by the complexity of the project ... we consider our interest, resource/skill capacity; consider the risk involved, consider time, cost and quality and size of the project." (Rail)*

Literature on strategy in selecting a supplier has noted that when uncertainty is low and a project is uncomplicated, the decision is made primarily on the basis of differences in technical capability (Hoetker, 2005). In other words, if an external provider is more competent to deliver the project this procurement method should be adopted. Conversely, if in-house resources are more competent, the project should be delivered using in-house resources. This is evident in the following quotes:

> *"we outsource most of our projects as this is not our core business." (Airport)*

"we have experience, expertise and skill because we have done a lot of it." (Rail)

"a wharf is a repetitive work where we have experience and in-house expertise ... so we usually do the design work in-house." (Port)

"all dredging is done in-house because we have all the expertise and specialised people to do the job ... and we have invested in all the costly dredging equipments ... so we can get better value if we do it ourselves." (Port)

For larger and more complex infrastructure projects, the tendency is to outsource to an external provider. The potential benefits of such an approach include lower costs, improved service, and opportunities to leverage the expertise of private companies, overcoming in-house staff constraints and risk-spreading.

"for bigger projects however, our in-house resources are struggling to cope ... we have to develop ways to partner with external organisations ... we are currently trying working out how to be slightly more innovative to deliver the tremendous increase in infrastructure project needed." (Rail)

Hence, the asset procurement and delivery process is considered an important process that can deliver value to an infrastructure organisation. The importance of process is echoed by all the case participants:

"we always try to generate value from our procurement ... such (an) arrangement allows us to have a better price and value from the service provider." (Rail)

"we try to achieve effective use of our external providers ... it is a cost and quality driven one." (Airport)

"we try to outsource what we can if it is efficient to do that and it is cost effective." (Port)

5.4 Maintenance Management Process

The maximum opportunity to reduce maintenance expenditure exists within the area of maintenance management of the overall operation and maintenance phase (NSW Treasury, 2004). The need to deliver maintenance is a fundamental requirement for any infrastructure organisation. The ability to deliver the required maintenance can have a significant impact on cost and operations. It is a business objective for any asset manager to focus on investing the minimum levels of maintenance dollars to deliver the services desired by the organisation, while meeting statutory obligations for the organisation's risk management and public liability as shared by one informant:

"to keep our asset in good condition without spending too much money on it." (Airport)

To achieve that, infrastructure organisations must continue to improve their maintenance management process. Maintenance planning is recognised at all levels of the industry and is becoming a key business driver because of the increasing demand pressure on infrastructure assets. The following views were shared by a manager interviewed:

> *"... improving our planning of maintenance is significant to create value to our customers." (Rail)*

> *"we have for some time now increasingly given attention to (maintenance) planning." (Rail)*

To ensure that maintenance planning can be carried out on a consistent and sustainable basis to achieve its objectives, all maintenance activities need to be captured via a common system (Killick and Thomas, 2008). Two main approaches to

Table 5 Maintenance Planning Methods

Cases	Rule based planning	Risk based planning
Rail	Some of the maintenance is cyclical and programmed which is more rule based and does not depend on finding defects such as rail grinding to be done after so many thousand tonnes over the track	We start with the plan to monitor the condition and as defects are found, we prioritise and plan to fix the defects within the time frame of priority … nearly all our maintenance depends on the result of condition monitoring and inspection We are doing probabilistic maintenance planning with our rail asset especially those that cannot afford to breakdown such as our signalling system
Port	We try to first meet all the standards and requirements … this is the cyclical maintenance that is rule based and standard and we know when they are exactly required	We need to include in our planned maintenance work based on the result of planned general inspection … from PGI we will know which type of maintenance work must be done by a certain time We do risk assessment based on past data to assess the likelihood of asset failure … and see how we can plan the maintenance to prevent the failure of such assets
Airport	We review the manufacturers' manual to find out what maintenance works are required under Australian Standards We have guideline and regulations that dictate the type of maintenance to be carried out	To ensure that we are able to plan well, there is a bit of data capture and analysis of those data … for example, on the runway we need to do friction testing because of the rubber build up We will do failure analysis to see whether the assets is going to fail We also do risk assessment to plan based on probabilistic

maintenance planning are evident from the cases. Firstly, maintenance activities are planned based on some rules and standards. This can be regulation mandate or manufacturers' recommendation. Secondly, maintenance activities are planned based on the assessed risk of asset failure based on conditions of the infrastructure assets. This includes predicting essential maintenance work that needs to be carried out to prevent failure of critical assets so as not to affect business operations. The two approaches are summarised in Table 5.

To facilitate effective maintenance planning, infrastructure organisations need to collect data on the conditions of their asset. A number of organisations are recognising the need to move away from the traditional time-based-maintenance approach to a more pro-active condition-based-maintenance philosophy. Jarrell & Brown (1999) support a condition based maintenance approach that provides benefits to the organisation in the areas of efficiency, reliability, and safety of the maintenance process. This will require constant monitoring of the conditions of the infrastructure assets and rigorous review and analysis of these data, to ensure the right mix of maintenance activities are delivering the improvements needed to provide sustained business success. This sentiment is shared by a manager:

> *"we need information on condition assessment and risk assessment ... to prioritise what we need to do first ... this will help us decide what our maintenance strategy is." (Rail)*

In short, the maintenance management process is essential to minimise the risk of asset failure that can have a devastating effect on business operations.

5.5 Asset Information Management Process

Infrastructure owners and operators are constantly struggling with the lack of knowledge about the condition of the assets they possess. This means that the scarce resources that are available for maintenance and repair are often used inefficiently and inappropriately (CERF, 1996). What is needed is a coherent picture of the current asset stock, its contribution to service delivery and the current costs of providing the assets (LGV, 2004). Information on current assets that are relevant include physical (*e.g.* location and condition); financial (*e.g.* service potential, risks and liabilities); and performance (both service performance and asset performance). All case participants echo the importance of asset information management as evident in the quote below:

> *"our key resource is information ... information is everything ... you live and die by information." (Rail)*

> *"one of our catchphrases is 'right job, right place and right time' so information is the oil for that machinery." (Rail)*

This can be achieved by having an IT system that acquires and stores the most updated and pertinent information on infrastructure assets known as the asset information management system. Some managers interviewed commented:

"IT database is the only way to be able to get an accurate reflective history of your assets." (Rail)

"we can actually pull out all information from the database and it can help us for better planning and control to promote improved asset performance." (Port)

"it got to be consistent and reliable ... if you work based on the wrong information, you work to a wrong priority and put resources in the wrong place." (Airport)

The importance of this process is evidenced from the cases where all organisations have adopted some form of computerised asset information management systems. This is summarised in Table 6.

Despite the availability of some computerised asset information management systems, case organisations are observed to be in the process of developing in-house asset information management systems to further improve the accuracy of their infrastructure asset information and to link them to infrastructure asset planning. For example, in Port case it has been said:

"we are currently developing software, specific for the port by our consultant called SAMMP, Strategic Asset Maintenance Management Plan. SAMMP is a planning tool." (Port)

In linking to infrastructure asset planning, it also suggests a recognition that the asset management system should extend beyond the asset portfolio by having a knowledge database of information that can be actively used to assess how a cur-

Table 6 Computerised Asset Information Management Systems

Case	Computerised Asset Information Management System	Information Captured in the System
Airport	We use a program called MAXIMO	All our assets data such as cost, location, scheduled periodic maintenance; record all the breakdown maintenance, *etc.* It also gives reports and things like that
Port	We have MP2 maintenance system	All the asset details including location, age, *etc.* all the maintenance recording, work scheduling details, cost of history and so on
Rail	Because of the diversity of assets … not one place that tends to be a portfolio of assets register with some metadata that links them up We are still working to make this happen with the help of a consultant	Overhead traction system is documented by people in electrical engineering, that configuration of data will sit at one place; in another place the people that manage the signal system have drawings and configuration data and so on

rent asset can be best utilised to achieve improvement in service to a customer. For example, one manager noted:

> *"we need information ... to help us decide that the capacity is not right and we need to do something else or we may just need to refurbish it." (Rail)*

Hence, asset information management is an important process for capturing all the necessary information to support decision-making of the other core processes.

6 Conclusions

The increasing use of infrastructure asset management has prompted the need to understand the processes involved. This paper has documented the core strategic processes adopted by case study organisations that manage infrastructure assets. The emerging framework is built based on the principle that these core processes can have direct consequence on assisting organisation to achieve the "best value" for its stakeholders. Synthesising these processes, a SIAM is proposed as a strategic, fully integrated approach directed to gaining greatest lifetime utilisation, effectiveness and value from infrastructure assets. At the heart of SIAM is a concept of continuous improvement to facilitate asset manager to identify, formulate and implement the most effective strategy and plans for improvement. It is based on a comprehensive strategy linking market conditions, business, and infrastructure assets. Given that there are many different approaches adopted in practice, care is taken to ensure that the proposed framework or processes are not over prescriptive but permit a certain degree of flexibility that ensures the characteristics and needs of individual organisations are taken into account. The framework, presented as a process model from a corporate level, is generic and can be applied to various types of infrastructure assets such as roads, rails, utilities, airports, seaports, *etc.*

Appendix 1: Definition of Asset Management

A methodology needed by those who are responsible for efficiently allocating generally insufficient funds amongst valid and competing needs (Danylo and Lemer, 1998)	The American Public Works Association Asset Management Task Force (US)
A systematic process of operating, maintaining and upgrading transportation assets cost effectively. It combines engineering and mathematical analyses with sound business practice and economic theory. The total asset management concept expands the scope of conventional infrastructure management systems by addressing the human element and other support assets as well as the physical plant (NYDOT, 1998)	New York State Department of Transportation (US)
The set of disciplines, methods, procedures and tools to optimise the whole life business impact of cost, performance and risk exposures (associated with the availability, efficiency, quality, longevity and regulatory/safety/environmental compliance) of the company's physical assets (IAM, 2008a)	Institute of Asset Management (UK)
The systematic and coordinated activities and procedures through which an organisation optimally manages its physical assets and their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organisational strategic plan (IAM, 2004)	British Standard, PAS 55 (UK)
The combination of management, financial, economic, engineering and other practices applied to physical assets with the objective of providing the required level of service in the most cost effective manner for present and future customers (IPWEA, 2006)	International Infrastructure Management Manual 2006 Edition (Australia, NZ and UK)
A comprehensive and structured approach to the long term management of assets as tools for the efficient and effective delivery of community benefits (Austroads, 1997)	AUSTROADS (Australia)
Provides a flexible service delivery approach, driven by present and future needs, and using both asset and non-asset solutions (NPWC, 1996)	The National Public Works Council (Australia)
Lifecycle management of physical assets to achieve the stated outputs of the enterprise (Kennedy, 2007)	Asset Management Council (Australia)
Provides a structured and systematic resource allocation approach to infrastructure and physical asset management so that resources are aligned with the service objectives of agencies (NSW Treasury, 2004)	NSW Total Asset Management (Australia)
The process of guiding the acquisition, use and disposal of assets to make the most of their service delivery potential ad manage the related risks and cost over their entire life (Victorian Government, 1995)	Victorian Government Asset Management Series (Australia)
Aims to provide an approach to the management of assets, encompassing the principles of integrated planning, asset planning, asset accountability, asset disposal and the internal control structure (Australian National Audit Office, 1995)	Australian National Audit Office, 1995 Auditor General's Report No. 27
The process of organising, planning and controlling, the acquisition, use, care, refurbishment, and/or disposal of an organisation's physical assets to optimise their service delivery potential and to minimise the related risks and costs over their entire life (CIEAM, 2008)	CRC for Integrated Engineering Asset Management (Australia)

Appendix 2: Case Profile

Type of Organisation	Informant	Key Infrastructure assets	Level of Participation
Rail	• General Manager • Executive Project Manager • Maintenance Manager	The track; structures such as culverts and bridges, bridges that support the railway and those that run overhead; right of way such as the access road & drainage; signalling systems that control of the safe working of trains; power supply and substations; overhead traction system.	Government-Owned Corporation
Airport	• General Manager • Terminal Asset Manager • Engineering Group Manager	The key assets are runways and all the assets on the terminal buildings such as baggage handling system, the check bag screening, aero-bridges, building fabrics, hydraulics, chillers, all the HVAC system, electrical system and communication system.	Full Privatisation
Sea Port	• Senior Manager • Infrastructure Planning Manager • Maintenance Manager	All port infrastructures that include channels and berths, wharfs and terminals, all services roads, water, power, telecommunications, sewer, storm waters. Properties include warehouses, buildings, and container handling equipment.	Government-Owned Corporation

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Part III
Scope (Investment and Cost Control)

Regulating Asset Management Through Serviceability and a Common Framework for Investment Planning

Derek Parsons

Abstract Regulation by output (albeit with an associated investment level assumption related to a price-cap) rather than input is one of the ways in which the Water Services Regulation Authority (Ofwat), the economic regulator of the water industry in England and Wales, incentivises companies to deliver effective asset management. The paper discusses how such arms-length regulation operates, and sets down output indicators for such a regime. The paper draws on experience of some fifteen years of operation and annual monitoring of trends in serviceability indicators, which are the foundation upon which the regulator judges the appropriate financing for capital maintenance at periodic reviews. It describes the UK water industry's risk based approach to the capital maintenance planning common framework (CMPCF) jointly developed by companies and regulators in 2002, and Ofwat's approach to its assessment of company business plans submitted for periodic reviews of prices in 2004 (PR04) and 2009 (PR09). The paper highlights issues arising from PR04, development of its asset management assessment (AMA), and setting formal numeric serviceability outputs at PR09. Together, the reviews in PR04 and PR09 allowed overall increases in capital maintenance expenditure of nearly 50 %. Ofwat recognises the need for such expenditure increases to maintain the flow of services to customers and to consolidate the benefits from previous improvement programmes. However, it is questionable whether we are now approaching a sustainable level of capital maintenance for the future.

Keywords Asset management assessment, Regulation, Water services infrastructure

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1 Introduction

The aim of this paper is to broaden understanding of Ofwat's approach to regulating capital maintenance through monitoring of serviceability outputs and its approach to capital maintenance assumptions used for price setting. Inevitably there are references to key documents that mark the step change in the planning of capital maintenance in the England and Wales water industry since the periodic review of prices in 1999 (PR99) which provide an essential platform for discussion.

Companies not only have to maintain a level of service to their customers and the environment, but demonstrate that service capability of the asset systems is not being compromised for the future. This could happen if performance of key asset groups were to deteriorate through lack of timely investment. Yet it is possible to be over cautious, or inefficiently apply capital maintenance which would elevate prices. So the drive is to demonstrate optimum interventions to maintain the flow of service to customers. The paper tracks recent developments in the regulation of capital maintenance of water companies in England and Wales, (Scotland and Northern Ireland have their own regulation authorities). First presented to the First World Congress of Engineering Asset Management in Australia in mid 2006 and updated in early 2010, this paper sets out Ofwat's approach to annual monitoring and its assessment of capital maintenance aspects of business plans at price reviews. Ofwat's assessment through the 2009 (PR09) price review has identified broad success against the implementation of its objectives set out in a letter to Managing Directors of water companies in April 2000, MD161 [1], following the 1999 (PR99) price review. Over the past two price reviews in 2004 and 2009, there have been overall increases in capital maintenance expenditure of nearly 50 % compared with the 2000-05 period. Ofwat recognises the need for such increases to maintain services to customers and to consolidate the benefits from previous improvement programmes. However, it is questionable whether we are now approaching a sustainable level of capital maintenance for the future. It is important that the companies improve their understanding of the benefits derived from investments already delivered to inform future decision processes.

2 Regulation of the Water Industry in England and Wales

Privatisation of water authorities in England and Wales occurred in November 1989, and in setting initial price limits for customers, the UK Government made some broad assumptions about the level of expenditure needed to maintain, or improve and maintain the asset base. At the same time, an independent regulator (in legal terms the Director General of Water Services, but in practice supported by an 'Office of Water Services' or 'Ofwat') was created. Its role is to regulate the industry from an economic standpoint to ensure value for money and review and set new price limits at appropriate intervals. In the event, the first price review was in 1994 (PR94) and three subsequent reviews have occurred at five yearly intervals in 1999 (PR99), 2004 (PR04) and 2009 (PR09). Some mergers have occurred, and there are currently 21 companies (plus one with only about 2000 customers) whose prices are set by Ofwat.

Sister quality regulators, now the Environment Agency and the Drinking Water Inspectorate, were set up and tasked to set and ensure compliance with standards, and advise Ministers on investment requirements to meet new objectives, mostly emanating from EU directives on potable water and the aquatic environment.

Recent legislation created a corporate structure for water regulation to replace the Director General of Water Services with the Water Services Regulation Authority with effect from April 2006 along with a new duty to contribute to sustainable development. The 'Ofwat' name has been retained for the new organisation.

3 Regulation of Capital Maintenance

Ofwat has elected to set price caps for companies every 5 years. Companies are required to submit to Ofwat their business plans for scrutiny which, although focussing on the next five years have a planning horizon for of 15 years (more in some areas). So every five years there is an opportunity for companies to register a need for a change to the planned investment which is then reflected in a new price cap. The price cap is a package encompassing all categories of expenditure and obligations. (There are mechanisms for interim price adjustments, but it is not necessary to digress into this area.)

The main challenges are to:

- monitor and challenge the effectiveness of capital maintenance;
- determine whether there should be a change to past levels of capital maintenance, up or down and by how much; and
- challenge efficiency.

This paper focuses on engineering aspects of optimum capital maintenance assessment. The technical detail of how Ofwat makes the efficiency challenge is a large subject and is beyond the scope of this particular paper, save providing an outline.

3.1 Monitoring and Challenging Effectiveness of Capital Maintenance

For a water utility, the principal requirement for capital maintenance is that it is sufficient to maintain service to customers. Ofwat operates arms-length regulation. It does not seek to micro-manage companies because that is resource hungry and ought to be unnecessary in a very mature industry. The regulatory focus is on service to customers. Ofwat, acting on behalf of customers, needs to be assured that service level is stable, and is likely to remain so in the future.

Ofwat has developed a set of metrics to monitor company asset systems, and between price reviews it monitors their stability or otherwise through annual review of detailed data returns. These are known as serviceability assessments, which are made at sub-service level (above and below ground asset systems distinguish sub-services). Where a sub-service is assessed as less than stable the company is called to account and is required to set down its proposals to remedy the situation.

The key point here is that at periodic review, the company, in accepting the price cap, has also accepted the requirement to maintain (or achieve and maintain) stable serviceability. If the company does this through a set of investments that cost less than Ofwat has assumed, it can retain the financial savings as part of its efficiencies. On the other hand, Ofwat expects a company to invest to maintain stable serviceability, even if this may require more expenditure than assumed at price setting. Thus the specific price limit accepted by each company contains both a profit opportunity and downside risk.

The mechanisms to resolve issues are beyond the scope of this paper, suffice it to say that:

- price reviews provide for a timely 'course correction' in funding assumptions (including a negative financial adjustment – rather than a punitive fine – for failing to deliver, or 'shortfall' [9]);
- between price reviews the companies have a financial incentive to maintain stable serviceability efficiently; and
- a company's prestige can be threatened by failure, because Ofwat publishes its annual serviceability assessments.

3.2 Determination of Changes to Historic Levels of Capital Maintenance

At the 2004 periodic review Ofwat adopted a four stage approach to challenge each company's business plan:

Stage A: Adjustment needed to maintain stable serviceability from a historical perspective.
Stage B: Is the future different?
Stage C: Scope for efficiency
Stage D: Take account of overlaps between capital maintenance and enhancement programmes.

In 2004, the English and Welsh companies 'asked for' over £9.4 billion capital maintenance for the period 2005–2010. 2004 price limits include £8.4 billion. The figures in 2009 were £13.1 billion capital maintenance for the period 2010–2015.

2009 price limits include £12.6 billion. This paper focuses on Ofwat's challenges at Stages A and B. Stages C and D are subjects in their own right and their approach is outlined in Sections 3.3 and 3.4. The remainder of the paper explains and develops the ideas behind Ofwat's Stage A and B challenges and issues that were emerging by the 2009 periodic review, and, in the event how Ofwat addressed them.

Stage A At PR04 the starting point was conceptually a long term historic average cost, corrected for price base. Companies were allowed to make adjustments in their business plan submissions for whether or not this was typical and whether serviceability could be maintained (see Sections 7 and 8). Ofwat then made its own assessment, and where the company view was greater expenditure than Ofwat's view at Stage A, the difference received further scrutiny by being fed into Ofwat's Stage B analysis (see Sections 8 und 9). At PR09, the process was simplified by using only the 5 years expenditure to 2010 (including a company forecast for 2010), with no adjustments other than correcting for price base. Companies thus knew their starting point at the outset, but were initially blind to Ofwat's treatment of it.

Stage B is essentially Ofwat's way of considering the validity of a change from the past rate of expenditure into the next period(s). In most cases, companies tend to seek more going forward. But how robust is the engineering business case?

3.3 Stage C – Efficiency Challenge and Incentive Mechanism

Ofwat commissioned several studies and reviewed contemporary work of others to come to a view on the **scope for efficiency**. This is the amount of capital expenditure that the water industry in total can be expected to save through capital efficiencies of one sort or another in the period 2005–10. Ofwat uses a carrot and stick approach, whereby the scope for efficiency is divided into two parts. It removes one part on behalf of customers (stick), leaving the other part as an incentive for the company (carrot). The size of the carrot and stick for each company depends on how near it is to the efficiency frontier.

Relative capital expenditure efficiency: this is the (percentage) difference in efficiency that has been observed using historic (and forecast) data between the capital expenditures of all the companies. The company with the lowest measured capital costs (in a specified category or basket of indicators) becomes the 'benchmark' company. Ofwat has assessed relative capital expenditure efficiency in two ways:

- using econometric modelling of total capital maintenance expenditures (averaged over a number of years) and various explanatory variables – this is known as the Capital Maintenance Econometric Analysis; and
- measuring the differences in company's capital scheme unit costs (procurement costs) – this is known as the Capital Expenditure Cost Base Analysis.

The company is allowed to keep its out-performance for five years. The details of the PR04 econometric models and cost base unit costs are set down in the 2003–04 issue of Ofwat's Water and sewerage unit costs and relative efficiency report. It covers both capital and operating costs, which also use benchmark econometric modelling. The impact of PR04 was to shave a further £0.5 billion from capital maintenance assumptions made at Stages A and B across the English and Welsh companies.

For PR09 a cost base analysis was retained [15] but capital maintenance econometric modelling was discontinued. (A less formal parametric comparison of unit costs using asset inventory data and expenditure at asset group level was used to inform the assessment of capital maintenance aspects of business plans, to help context company expenditure relative to the industry median.) Ofwat took the view that a new mechanism called the Capital Incentive Scheme (CIS) [16], a water industry development of 'Menu Regulation', would address the issue better. Refer "Setting price limits for 2010–15: Framework and approach", Chapter 4 [10]. The CIS is similarly beyond the scope of this paper. Suffice it to say that companies are incentivised to put forward what each believes are its true costs rather than to simply bid as high as it thinks will be accepted by Ofwat. Outcomes are presented in the PR09 Final Determination document, in Chapter 4, Table 29 [17].

3.4 Stage D – Adjustments for Enhancement Expenditure – Benefit to Serviceability

Stage D is the final adjustment made to derive the required level of capital maintenance expenditure. The Stage D adjustment allows for the impact on future serviceability from planned expenditure on enhancement projects, whilst taking into account any change in proportional allocation of enhancement expenditure to capital maintenance. At PR09 this stage was removed, since at PR04 the adjustments made were negligible, and were generally considered by companies within Stage B.

4 Economic Constraints to Limit the Price Paid by Customers

Ofwat holds the view that prices, which support maintenance of the vast asset base, should be no higher than they need to be to limit the price paid by customers. In the 1999 Periodic Review of Prices (PR99) the Director General of Water Services judged that the water companies had not moved sufficiently in their business practices towards a more efficient approach to capital maintenance. After setting prices for the period 2000–2005 he wrote, in April 2000 an open letter to Managing Directors of the water companies of England and Wales, MD161 [1]. He recognised that companies had put much effort into improving systems of information for asset management, resulting in more effective direction of capital maintenance activity. But the key message was that the companies' economic analyses fell short of expectations. Thus he wrote:

'Each company needs to demonstrate how the flow of services to customers can be maintained at least cost in terms of both capital maintenance and operating expenditure recognising trade off between cost and risk, whilst ensuring compliance with statutory duties. Appraisal of capital maintenance, operating expenditure and risk can be compared using discounted cash flows. All such appraisals would need to be set in the context of the framework of maintaining serviceability to customers. Such an approach should have been used to justify the future levels of capital maintenance included in the business plans.

It would have been helpful to include commentary on the material elements of the economic appraisals undertaken such as the:

- cost of any potential loss of serviceability to customers, including consideration of risk scenarios and their probabilities as well as illustrations of how serviceability to customers would decline, if the activity was not undertaken;
- impact on operating costs of capital maintenance activity, before and after assets are renewed;
- circumstances surrounding the timing of asset replacement;
- impact of obsolescence and newer lower cost technology; and
- any terminal values and the discount rates assumed.

This list is not exhaustive. The economic appraisals would also need to be balanced and justified against a strategic top down approach used to assess, for example, the impact of alternative scenarios on company financing, including an analysis of past and prospective accounting charges. Setting out examples of economic analysis in this way would go a long way towards demonstrating why companies have taken the view that the levels of capital maintenance since, say 1980, have been sub-optimal. This approach could also indicate the extent to which levels of capital expenditure should change, up or down, for future capital maintenance to be economic.'

So Ofwat puts the *customer*, not the engineering, centre stage. Exponents of PAS 55, take note of these stakeholders!

5 Maintaining the Flow of Services to Customers: 'Serviceability'

Specifically, the term used by Ofwat is 'Serviceability to customers'. This is *not* the same as serviceability of the assets deployed to deliver service – but there are close relationships between what service the customer wants and the ability of the assets to deliver it. Maintainers of assets sometimes find it is easy to forget why the assets are there in the first place.

The term encapsulates the concept of the continuing capability of a company's asset systems (and the associated operational activity) to maintain the level of service experienced by its customers and, where relevant, the receiving environment. The regulatory focus is on delivery of customer needs (both now and in the future) and not on maintenance of the assets to a specified state for their own sake. The 'right state' should essentially be determined by economics, albeit the default position in the absence of robust economic argument for change should reference to a suitable historic level.

5.1 Assessing Serviceability: Anticipating Future Problems from an Historical Perspective

Regulatory serviceability indicators have come in for a good deal of adverse criticism in the UK, cited as being 'backward looking'. The author contends that just

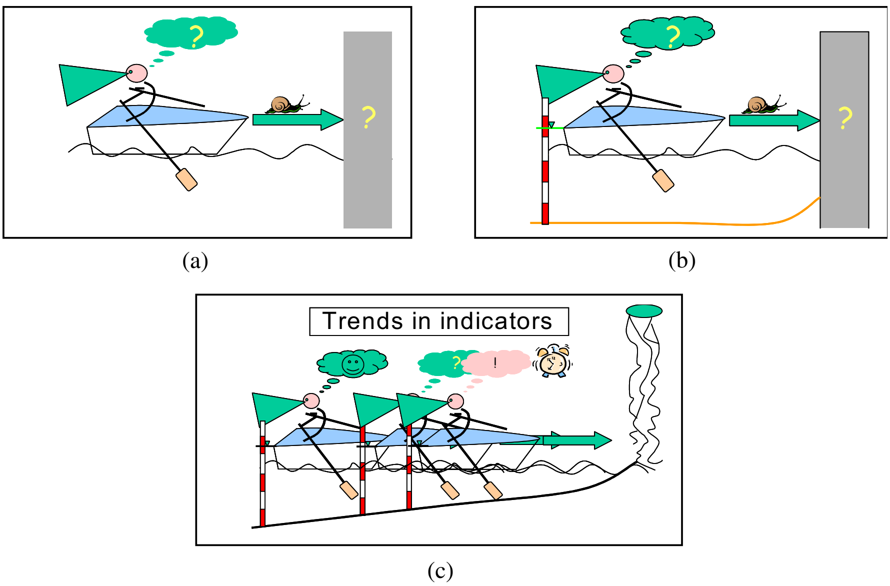

Figure 1 Backward looking indicators of future events

about everything that can be forecast about the future is based on past experience or past observation, and therefore invites the reader to re-consider whether they are, after all, useful by considering the following thought experiment. Suppose you are in a lake, rowing a boat, alone. You are facing backwards and have no view of the boat's forward, but slow progress. See Figures 1a and 1b.

How might you anticipate arriving at the shore? Perhaps measuring the depth might help?

At intervals you make a series of depth observations (Figure 1c). Perhaps monitoring the trend in the depth provides warning of your arrival at the shore? The conclusion is surely that rearward view of appropriate indicators, monitored at regular time intervals does indeed reveal useful information about change. (The analogy can, of course, be trivialised, because all you do is look over your shoulder. If only looking into the future was that simple!)

Put in its simplest form, such indicators provide the basis of assessing whether or not there has been change. And, stepping right away from the row-boat analogy into asset management, consider next what the inputs have been to maintain the status quo or cause change to our suite of indicators (a suite because more than one is required, as will be explained later).

Serviceability is considered at company level, by sub-service (that is, considering above and below ground asset groups separately, whilst recognising linkages). The aim is to ensure that the trend in serviceability remains at least stable, or if the start point is less than stable, then to achieve and then maintain stable serviceability.

Note the key word is **trend**. Absolute values of indicators are not important, although it is useful to compare and contrast each company's performance and to build a national picture. The assets being considered have relatively long service lives, and deterioration is relatively slow. Thus annual monitoring provides the opportunity to take timely corrective action.

6 Appropriate Serviceability Indicators

Figure 2 illustrates from where indicators of serviceability are drawn – courtesy of United Kingdom Water Industry Research (UKWIR) Report 02/RG/05/3 [2].

Clearly, a service indicator such as ease of telephone contact has little direct connection with capital maintenance needs. The basket of serviceability indicators comprises a selection of measures of service delivered and asset performance. A basket of measures is needed due to the complexity of asset systems and interdependencies. A combination of service and asset performance indicators is needed in order to capture current and likely future service capability. Each type as has certain characteristics and limitations.

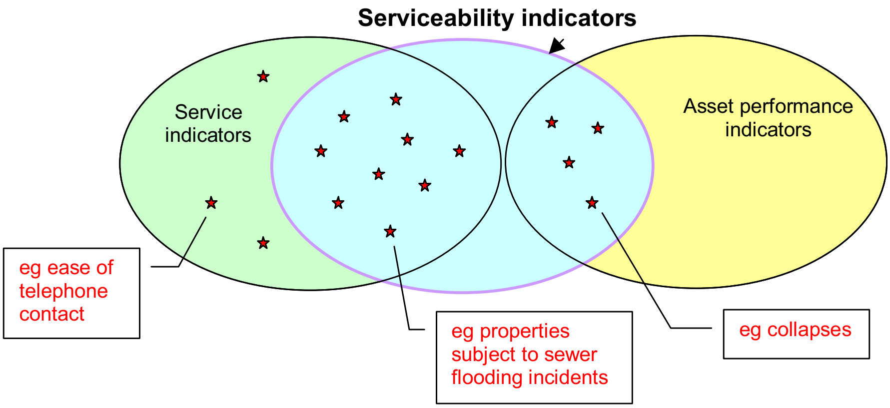

Figure 2 Selecting serviceability indicators (courtesy of United Kingdom Water Industry Research (UKWIR) Report 02/RG/05/3, [2])

6.1 Service Indicators

Service indicators are influenced by operational activity, and trends are to be assessed with caution. They inform on the capability of asset systems in the shorter term. The expectation is that trends are stable or improving.

6.2 Asset Performance Indicators

Asset performance indicators inform on capability over the longer term, that is whether the current service delivered is likely to be sustained. The expectation is that, whilst trends are stable or improving, they may deteriorate to a degree that does not compromise economic provision in the long term. In practice, the default trend for asset performance indicators is stable or improving. Asset performance indicators may have a direct or indirect impact on service delivered. They tend to be symptomatic of the state of the assets, but still can be influenced by policy on operational activity, for example increased leakage control activity in the case of water mains burst repairs.

6.3 Examples of Serviceability Indicators

Service indicators: properties with extended supply interruptions, properties receiving low pressure, properties flooding from sewers, pollution incidents. Compliance, such as the proportion of treatment works that are out of compliance.

Asset performance indicators: burst water mains, sewer collapses, mean time between failure. Sub-threshold indicators that indicate potential underlying problems but where the works have not failed. Examples are events where a threshold value, say half the permissible value, has been crossed.

6.4 Issues Around Serviceability Indicators

A very important point is that the same data must be collected, to the same definition, over the period of time which is assessed. This must be monitored closely, because both the levels of service and financial data which are essential for the historical perspective analysis are collected for other uses, and there is often a desire to 'improve' them for those uses. But a change in definition invalidates a time trend, and reliable and defensible time trends are the essence of the historical perspective analysis. Unfortunately, circumstances do arise where recording procedures change (or are found to have changed) and need to be reconciled. Remedies include dual reporting on past and new methods for a suitable period.

Although there will always be interplay between capital and operational maintenance it is assumed that the deferment of capital maintenance by increased operational maintenance will not be effective over many years. Nevertheless, for surface assets it is wise to look at the pattern of operational maintenance alongside the graph of capital maintenance. It is also important to check companies' explanation of recorded treatment failures. These are generally few in number and experience in the 1999 price review was that companies explained many of them as due to short-term events which had been quickly remedied. In fact they argued that capital maintenance had been adequate even though the serviceability analysis may have indicated otherwise, a conclusion Ofwat was pleased to accept.

From 2003 Ofwat added a limited number of additional indicators that aimed to inform future performance and to widen coverage of asset types [3]. It planned a further review after PR04. The review has now been carried out by UKWIR (2005-06), with Ofwat represented on the steering group.

6.5 Update on Serviceability Indicators

Ofwat responded to UKWIR's review in RD15/06 [7], generally endorsing the work and formally adopting definitions of stable serviceability, set out in Section 7.2. Work has continued on indicator development, and the current basket is set out in PR09/38, appendix 2 [14].

7 Assessment of Serviceability

Ofwat's initial assessments have been published annually in August or September in its 'Financial performance and expenditure of the water companies of England and Wales' (FPE) report, to 2007, and from 2008 appear in its 'Service and Delivery Report'. Below, in Figures 3 and 4 are examples of Serviceability Graphs at Industry Level for England and Wales, for water infrastructure and sewerage non-infrastructure sub-services respectively, which show indicator values normalised to their historic averages for trend comparison. In the respective 2004 and 2009

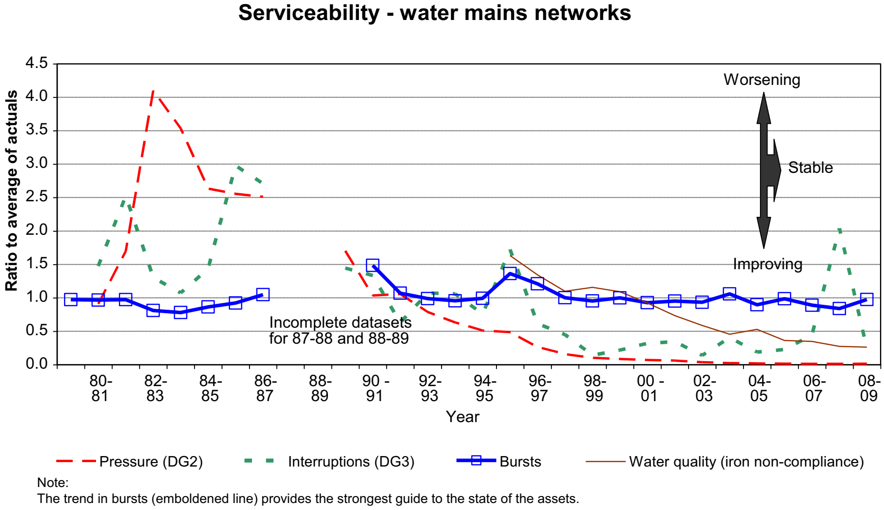

Figure 3 Serviceability Graphs at Industry Level for England and Wales

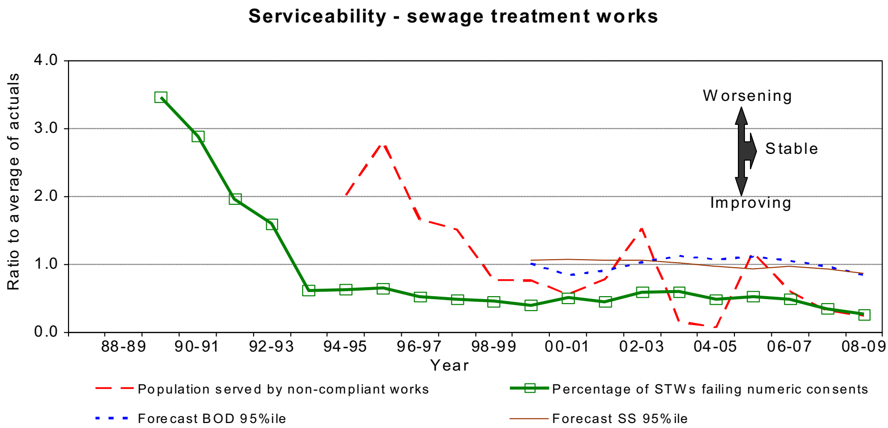

Figure 4 Serviceability Graphs at Industry Level for England and Wales

reports there is some general information (in appendices) about the size of the English and Welsh water companies' asset base, its replacement value and condition and performance.

7.1 Assessment Marks

The current marking scheme for serviceability trends is, best to worst: Improving, Stable, Marginal, and Deteriorating.

Data is inherently variable, often due to weather effects and care needs to be taken when considering what a normal range of operation is. Because underground assets in particular deteriorate slowly it is not easy to pick out underlying trends. Ofwat uses a suite of statistical tools to help inform its judgement. The statistics toolkit is not a substitute for judgement, simply an aid. It also provides a platform for discussion with companies on their view of the optimal levels for a particular indicator. Figure 5 illustrates a graph produced by the toolkit for one of the indicators.

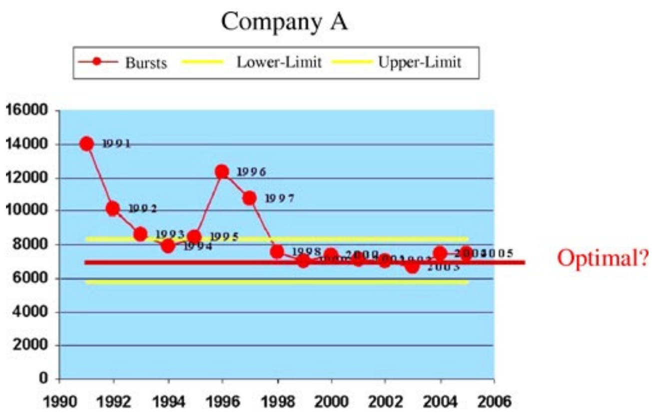

Figure 5 Plot of serviceability indicator with reference level and control limits

7.2 What Is Meant by 'Stable' Serviceability?

Serviceability is deemed to be stable when the assessment of trends in a defined set of service and asset performance indicators demonstrates that service is in line with the reference level of service and, by inference, is likely to remain so into the future. Note that there is no implication that the standard of service to customers or asset performance is satisfactory. These are separate issues, which should be addressed through a change in expenditure for improvement or economic argument.

The reference level of service is determined from a specific sub-set of public health, environmental and customer service indicators. Service indicators reflect the degree of compliance with statutory regulations, regulatory and company standards and customer preferences.

Asset performance indicators, measured at system level, are drawn from a specific sub-set of measures that inform current and future levels of service. Stable serviceability normally requires that asset performance is in line with the reference level of asset performance (Figure 5). Unless demonstrably sub-optimal or atypical, the reference levels of service and asset performance are taken as the best historic levels achieved by the company.

7.3 Issues Around Achieving and Maintaining Stable Serviceability

As the reader may imagine, things begin to get interesting for regulator and regulated when a company begins to fail to deliver stable serviceability. The serviceability assessments enable Ofwat to provide feed back to companies on how it thinks they are doing. Annual monitoring is normally sufficient for Ofwat's purposes, and, despite the indicators being high level, the process has, on occasion uncovered underlying shortfalls in asset management practice. It has thus become a powerful tool.

The assessments enable a regulatory response where companies are beginning to fail, and can provide evidential support for financial penalty or other legal sanction in the most serious of cases of shortfall. This provides motivation for companies to intervene with more effective monitoring and intervention (capital or operational expenditure), and yet still allows the company to decide what to do.

In Section 3 it was explained that the periodic review of prices provides scope for a 'course correction' if it is deemed that funding from customers should be changed to facilitate an economic level of capital maintenance. And once prices have been determined, and the company accepts (if not it can appeal to the Competition Commission for a new determination) it is up to the company to deliver stable serviceability. This is irrespective of cost to the company (subject to a high ceiling) since the company accepts this as a risk. But note that the 'course correction' at periodic review does not necessarily cover the cost of recovery to stable serviceability where there has been a shortfall in previous periods. The change is primarily to reflect what funding is needed by an efficient company to maintain stable serviceability.

The risk to serviceability accepted by the company at price review is to some extent a shared one. This is because there is incomplete knowledge, for example in the behaviour of assets and in the economic level of capital maintenance, and serviceability might in any case be changed by events that might render a rapid return to previous service levels impracticable.

In the past, companies have not been overtly penalised, for example where they have spent above final determination assumptions and still failed to maintain stable serviceability. Companies are expected to improve their knowledge of their asset base, for example through an improved application of risk based principles espouseed in MD161 in the period to 2010. This should lead to better assessments of need by the companies; and Ofwat has become less tolerant of serviceability shortfall.

Where a company is beginning to fail to deliver on serviceability, Ofwat deploys a staged approach to effect corrective action by the company, including in appropriate cases a requirement for setting down action plans with milestone dates for activities aimed at achieving and maintaining stable serviceability. Both the historic level and new information may inform the degree of recovery of serviceability that is required following a period of deterioration. And in the absence of robust justification to the contrary, the historic levels provide the reference level for serviceability.

This low level but firm regulatory action is aimed at bringing defaulting companies to heel and to prevent a situation developing that could cause a general or catastrophic failure of service. The requirement was strengthened in 2006, when, in MD212 Ofwat made it clear that companies that did not deliver stable serviceability would be found to be in shortfall of delivery of required outputs and could suffer a reduction in its regulatory capital value of up to 50 % of capital maintenance expenditure assumed in 2004 price limits. This materially reduces the amount a water company can earn as a return on capital, and had a galvanising effect. The detail on shortfalling is set out in PR09/06 [9].

During the period 2005–2009 seven companies were required to produce and execute action plans to restore stable serviceability. All but one achieved this goal. At the periodic review in 2009 two companies were found in shortfall on serviceability and (subject to referral to Competition Commission on 2009 price limits) will suffer a reduction in regulatory capital value. The detail on serviceability outcomes and treatment by Ofwat is set out in PR09/38 [14].

7.4 Monitoring Serviceability from 2010

By the 2009 Periodic Review, Ofwat had acquired considerable experience in monitoring and controlling serviceability and felt confident it could set formal numeric serviceability outputs in the form of formal reference levels and control limits for each serviceability indicator. The benefit to transparency, which enables each company to fully own the outputs, outweighs the reduction in discretion from a more judgemental approach taken by the regulator. The aim is that less intervention by the regulator will be necessary on serviceability. Ofwat thus expects companies to monitor each indicator and to manage and maintain assets such that all indicator values remain well within the control limits and exhibit a stable (as a minimum) or improving trend year on year and to demonstrate this in their June returns. It will recognise a stable trend as one where such variance that does occur must be either side of the reference level (save where the reference level is zero), and does not drift towards the upper or lower limit. Values persistently below the lower limit indicate an improving trend. Values persistently close to or persistently

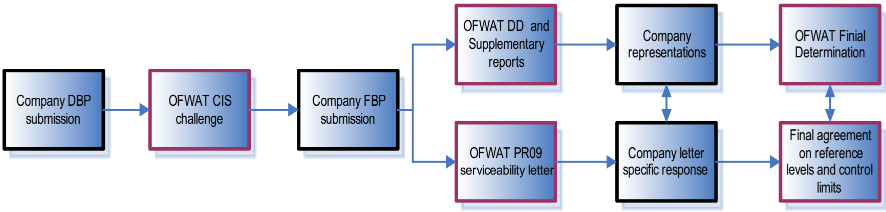

Figure 6 Development of serviceability outputs at PR09

Table 1 Template for water infrastructure serviceability outputs at PR09

	Serviceability indicator	Reference levels and control limits			Expected performance by 2014-15	Reasons for challenge
			Company FBP outputs	Regulatory output (during 2010-15)		
Water infra	Total bursts (nr)	Ref				
		High				
		Low				
	Interruptions >12h (nr)	Ref				
		High				
		Low				
	Iron non-compliance (as 100-mean zonal compliance) (%)	Ref				
		High				
		Low				
	DG2 Pressure (nr)	Ref				
		High				
		Low				
	Customer contacts – discolouration (nr / 1,000 population)	Ref				
		High				
		Low				
	Distribution index TIM (as 100 mean zonal compliance) (%)	Ref				
		High				
		Low				

above the upper limit indicate a less than stable trend and serviceability for the sub-service will be classified as marginal or deteriorating. The outputs were arrived at iteratively from draft business plan (DBP) and final business plan (FBP) submissions and respective challenges made by Ofwat when setting draft baseline (CIS), draft determination (DD) and final determinations (FD), thus (Figure 6).

The CIS challenge included explanations to the serviceability outputs challenge, whereas the DD and FBP serviceability outputs challenges were explained in separate communications.

PR09/38, which immediately followed the FD, explains the approach and consequences of failure and its appendix 2 gives definitions for each indicator. The template for water infrastructure outputs from PR09/38 appendix 1 (which also explains the analytical approach) is repeated in Table 1 for easy perusal.

8 Capital Maintenance Planning – A Common Framework (CMPCF)

In 2002 the UK water industry, through UKWIR, responded to MD161 with the development of the capital maintenance planning common framework (CMPCF) [2]. Ofwat regarded the CMPCF as a large step in the right direction, and redrafted its reporting requirements for PR04 business plan submissions to align with it.

The common framework is essentially a three-step process (similar but distinct from Ofwat's 4-Stage A, B, C, D business plan assessment used at PR04):

A Historical assessment, comprising an expenditure and service & asset performance review.
B Forward look, considering service risks and cost forecasting to develop optimal interventions.
C Comparison of the two approaches, drawing conclusions, look for further efficiencies and make the case for the required level of capital maintenance.

Application of the CMPCF includes two alternative planning objectives – a cost-effective approach or a cost-benefit approach. The cost-effective objective aims to provide steady or improving service to customers at minimum cost to the water company. The cost-benefit objective aims to provide the level of service to customers that represents an economic balance between the value to customers of the service provided (perhaps in terms of willingness to pay) and the associated costs to the water company (and thence its customers).

In fact there are over twenty steps at the detailed level, as Figure 7 shows. The main innovation is in the second step, 'B' that uses the analysis of risk (that is the probability and consequences of asset failure) to inform the economic analysis. Previous practice in UK water industry has been to attempt to convert condition and performance grades (captured with the asset inventory) into remaining asset lives and hence capital maintenance needs. The problem with that approach is that the grading tends to be overly subjective, generalised and asset centriced. Under the CMPCF companies must look to identify specific failure modes by asset type, and at an appropriate level of granularity, obtain the relevant asset observations, including historic failures, consequences and costs, then develop robust estimation methods for probability of failure and consequences for customers. These, together with service valuation studies for the cost-benefit approach, are developed into service and cost scenarios to inform the optimisation of interventions. By evaluating in this manner, expressed in economic-risk measures, the analysis is better focussed. The best exponents can locate where investment will be most effective and may build the programme of works at the time of drawing up the business plan. Unfortunately, in the short term sufficient data is not always available and judgement is needed in place of a history of asset observations. The process gives a powerful framework for the company to identify what asset observations it needs to improve its forecasting to facilitate optimum interventions.

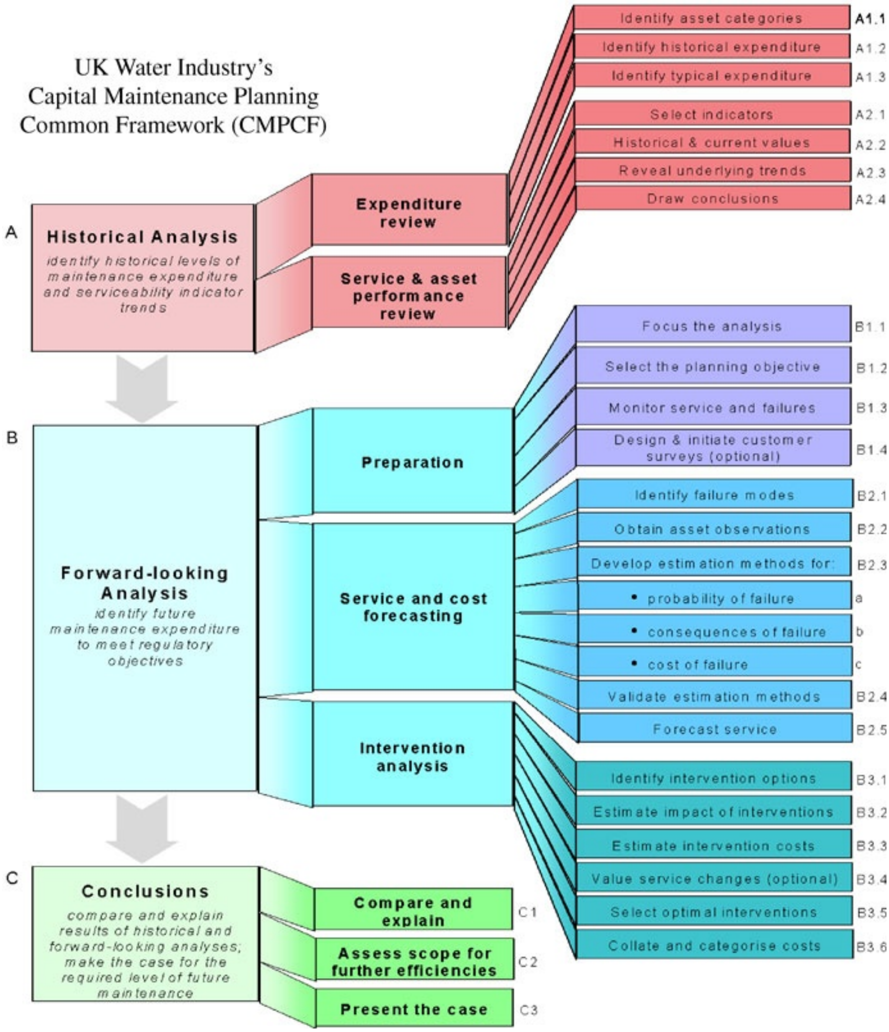

Figure 7 UK Water industry's "Common Framework" – courtesy of United Kingdom Water Industry Research (UKWIR) Report 02/RG/05/3 [2]

9 Assessment of the Application of CMPCF Principles

9.1 Assessment at PR04 (2004)

Ofwat's four stage approach provides a means of evaluating of a company's application of CMPCF principles. To challenge stage B uplift over past expenditure levels, Ofwat assessed each company's final business plan against 18 criteria (Figure 8). The criteria reflected the aspirations of MD161 and the agreed CMPCF. The criteria cover the three broad areas: data quality, forward-looking analysis process adopted and the approach to outputs. The criteria assessment became known as the 'Common Framework Assessment'. Ofwat communicated its assessments against each criterion to the companies in the form of radar plots, illustrated below. As with serviceability, this was done by sub-service. There were (in 2004) 64 sub-services in total among the companies – 10 water & sewerage co.'s x 4 (water/sewerage above & below ground) plus 12 water only co.'s x 2 (above & below ground). By 2009 a merger of two water only companies reduced this to 62.

An aggregated score (expressed as a percentage of the maximum) was derived for each sub-service. The criteria were weighted by pair-wise comparison of relative importance. Sensitivity analysis showed that total scores were not overly sensitive to the weights. For each sub-service, the 'score' was allocated into one of five ranking bands ('Leading' to 'Trailing'). The bands determined the factor

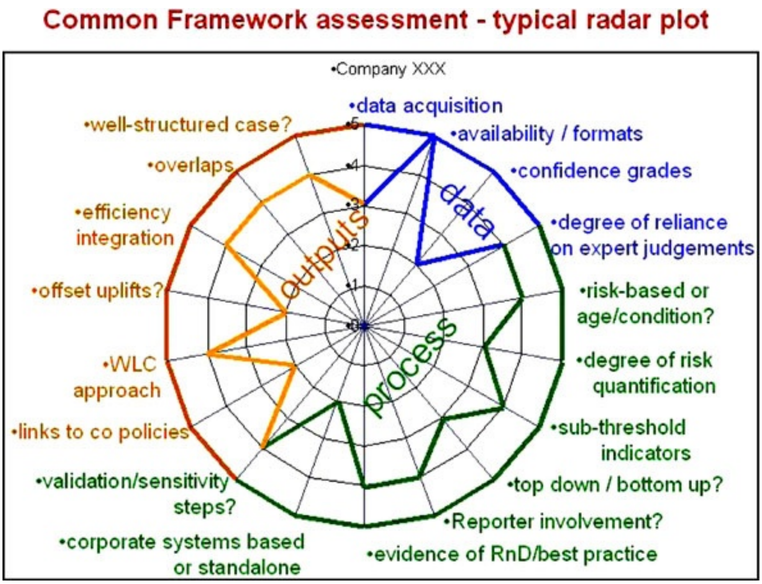

Figure 8 Assessment criteria for PR04 Common Framework Assessment

Table 2 PR04 Scoring scheme and challenge factors applied at Stage B

Band	Description	Score range	Factor	Number of sub-services
A	Leading	>= 70 %	100 %	5
B	Above intermediate	60–69 %	75 %	22
C	Intermediate	50–59 %	50 %	29
D	Below intermediate	40–49 %	25 %	7
E	Trailing	< 40 %	0 %	1

applied to the uplift in Stage B expenditure (post screening to exclude exceptional items assessed on their own merits). A 'leading' company will understand the risk profile of its assets and be able to assess the investment needed to manage this risk in the future. A company assessed as 'trailing' will have failed to demonstrate a robust risk-based approach for future investment in this sub-service. Companies with scores close to band limits were reviewed to confirm their position.

The scoring scheme and outcomes are summarised in the Table 2. The main problem for companies at PR04 was their inability to find suitable data, leading to more 'expert judgement' than desirable, and the inability to adequately identify operating costs at plant level to be able to get at whole life cost of ownership.

At the periodic review of 2004, this challenge on the quality of business plans was limited to the companies' forward look, that is (broadly) what companies wanted in addition to what they'd had in the past. And even then after exceptional items were excluded. So only around 20 % of company's capital maintenance expenditure was subject to the test.

9.2 Issues Around CMPCF Assessment at PR04

The impact of Ofwat's challenge at stages A and B amounted to some £0.5 billion, mostly at stage B. UKWIR has reviewed the CMPCF application [4] and outcomes post PR04, as has Ofwat. As always, Ofwat consults with the industry [5] and, at the time of first writing this paper in 2006 did so again [6]. The Ofwat view post PR04 was that there should be a stronger challenge to historic expenditure, to develop a fairer playing field. Options included simply improving understanding of reported historic expenditure, econometric benchmarking to cap Stage A, assessing part or all of historic expenditure in the Stage B challenge, analysing asset stocks and condition and age profiles. Econometric benchmarking has implications for the efficiency challenge and would need to be considered in conjunction with revisiting stages C and D.

The challenge for Ofwat is to encourage appropriate behaviours in business management; to challenge old habits and drive efficiency. The evolving approach gives companies strong incentives to use sound asset management processes.

Ofwat did this by strengthening incentives through its assessment processes. Ofwat also believes that the CMPCF approach, whilst it has been developed for capital maintenance, could potentially inform a more general application to all capital investment drivers. This is because of its focus on service to customers and risk in order to plan the scale and scope of investment.

9.3 Assessment at PR09 (2009)

In 2007 UKWIR, through Mott MacDonald developed a more detailed assessment process, Asset Management Planning Assessment Process (AMPAP) [8] for companies to use to self-assess their competence. (Their report includes a widely cast review of existing asset management frameworks.) The AMPAP process adopted nine high-level areas as critical for asset planning, each of which is divided into two or more key components (these AMPAP components number 33 in total), and further divided into criteria (some 119 criteria in total). Ofwat adapted the approach, using. eight of the nine AMPAP high-level areas in its Asset Management Assessment. This is set out in PR09/37: Capital maintenance and Asset Management Assessments (AMA) for final determinations – a technical note [13]. The ‘People’ high level area was excluded, but some aspects were included in ‘Management’ and Ofwat added a further one – ‘Balance’ – resulting in 31 components for its AMA (see below). To facilitate consistent assessment, Ofwat added aspirational statements for each high level area and adopted between one and eight assessment criteria for each AMA component.

Table 3 overleaf summarises the high-level areas, components and the number of criteria that Ofwat used in its assessment. The assessment results in a score (out of 5) for each component of each sub-service, using the criteria to inform the assessment and score. The same 31 components are scored for each of the four sub-services. For all but two of the high-level areas it is appropriate to apply the score at the sub-service component level; however for two high-level areas (‘Data’ and ‘Analysis’) it is appropriate to take more specific account of the differences between asset groups. (For example, within ‘water non-infrastructure’ there are different asset groups, such as water treatment, pumping stations and service reservoirs.) Approaches to data and analysis frequently differ for asset groups. So for these two high-level areas (13 components) Ofwat applied the AMA score at asset group level.

The radar plot, Figure 9 overleaf again illustrates how the scoring was communicated at industry level; companies received their own commercial in confidence scores alongside the industry position. Whilst the scoring system and its application in PR09 was very different to PR04, 20 sub-services scored over 70 % (when scored out of 5), which by terminology of PR04 (not used at PR09) could be said to be ‘Leading’ and the spread of scores is more closely grouped which indicates that all companies have got to grips with the CMPCF, resulting in a general improvement in the quality of business plans. At PR09 a score of 4 represents a fully justified plan. A sub-service score of more than 4 would receive a greater recognition of the programme in the baseline assessment (that is a score of 5 would receive recognition of 125 % of the proposed capital maintenance programme). A score of 2 or less indicates that a company's business plan submission demonstrates poor application of asset management practice, and we would question whether it is able to deliver effectively and focus even the current levels of expenditure.

Table 3 AMA Assessment at PR09

High-level area	Component		Number of criteria	Score weighting (%)
Stakeholder engagement	1.1	Engagement with customers and other stakeholders	2	11.20%
	1.2	Choice of planning objective	1	
	1.3	Valuation of service benefits	3	
Governance, policy and strategy	2.1	Governance	3	8.05%
	2.2	Policy	4	
	2.3	Strategy	3	
Management	3.1	People Management	2	7.82%
Processes	4.1	Integration into business processes	4	10.30%
	4.2	Planning processes	3	
	4.3	Information management processes	4	
	4.4	Quality safety and environmental management	1	
Systems	5.1	Systems for capturing and storing asset performance and condition data	6	8.95%
	5.2	Systems to support risk management processes and reporting	2	
Data	6.1	Asset observations	3	17.64%
	6.2	Serviceability data and associated costs	6	
	6.3	Interventions and impact data and associated costs	3	
Analysis	7.1	Historical analysis	7	16.18%
	7.2	Performance modelling	5	
	7.3	Service consequence modelling	4	
	7.4	Cost consequence modelling	4	
	7.5	Forecast service	2	
	7.6	System analysis	2	
	7.7	Intervention identification	5	
	7.8	Intervention impacts	3	
	7.9	Intervention costs	8	
	7.10	Intervention optimisation within asset group	4	
Reporting	8.1	External reporting	6	6.34%
Balance	9.1	Overall balance and phasing of business plan	5	13.52%
	9.2	Overall approach to risk	5	
	9.3	Overall quality of the business case	1	
	9.4	Programme optimisation	6	

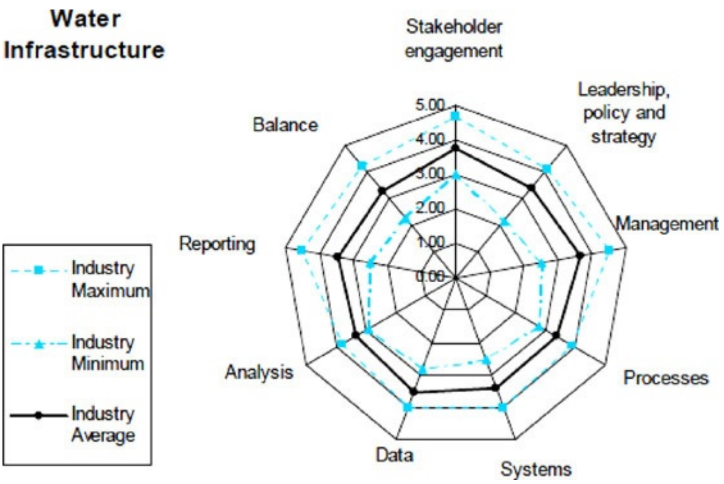

Figure 9 Example of industry level summary of PR09 AMA scoring for a sub-service (Company specific summaries were similarly presented in company confidential supplementary reports)

9.4 Behavioural Management Through Dissemination of PR09 Asset Management Assessments

Ofwat produced a number of technical notes on AMA during the periodic review. PR09/23 [11] gave a preliminary view of company draft business plans which revealed its analysis. In order to dissuade aspirational bidding, Ofwat had increased the exposure to the AMA challenge to twice the uplift over the Stage A expenditure, so the more increase over historic expenditure requested, the better the case needed to be. This tempered final business plans somewhat. At its draft determination, Ofwat included a further minimum challenge of 25 % of Stage A expenditure in line with views it had expressed but had not applied at the CIS baseline setting, but at the same time reduced the challenge by reducing the score needed to fully justify the plan from 5 to 4 (gross of efficiency assumptions), refer PR09/32 [12]. At the final determination Ofwat withdrew the 25 % minimum challenge following company representations, refer PR09/37 [13]. The appendices to PR09/37 explain key aspects of the AMA process for final determinations:

- Appendix A details the application of the AMA process.
- Appendix B reviews AMA outcomes for the final determination.
- Appendix C details the application of the AMA score to determine expenditure assumptions and explain its treatment of ‘exceptional items’.
- Appendix D provides the AMA scoring guidance applied.

9.5 Administrative Issues at PR09

The business plans are very substantial documents. The capital maintenance element of business plans from the 21 companies at PR09 grew from some 3,500 pages at draft to some 10,000 pages at final submission, and, due to interlinking with other issues, wider reading was also required. In addition, independent reports of similar size providing insight and verification are also essential reading. A query process essential to facilitate clarification inevitably slows the assessment. The quality of business cases within plans was variable. In one sub-service over 50 pages was devoted to some £300m, whilst elsewhere a mere 2½ pages 'justified' another £300m, which was about the same amount as the uplift over the Stage A historic spend for that sub-service. This extreme example highlights difficulties for the company business plan author in ensuring consistency and clarity of presentation and the challenge for the regulator's assessor to spot yawning gaps in justification amongst very strong and apparently thorough expositions when the reporter has not. All sides require a high degree of skill, and administration of the process needs very careful planning, coordination, resourcing and management.

10 CMPCF and PAS55

Both CMPCF and PAS55 are risk-based approaches to maintenance. In the view of the author the key difference between PAS55 and CMPCF is that PAS55 is asset centric, whereas CMPCF is overtly centred on service to customers. In the water industry this is particularly important, because there are so many facets to the service arising from the need to maintain product quality as well as continuity of service.

Ofwat uses its assessment of how well companies applied CMPCF principles its determination of price cap in respect of capital maintenance. Ofgem, the UK energy regulator, in contrast, has used PAS55 for re-assurance and not directly to influence its price review judgements. PAS55 is seen by Ofgem as good practice to aspire to. Interestingly, Ofwat's idea to use radar plots to compare current business practice was 'borrowed with pride' from Ofgem. Ofgem prefers to use other tools for price setting, due to a quite different regulatory environment. For example, competition exists on load (demand) in the electricity sector which strongly influences price. Therefore, for the moment at least, there seems not to be an incentive for Ofgem to further motivate electricity and gas companies to develop their application of the principles in PAS55. It will be interesting to monitor developments.

Several water companies have gained or are in the process of gaining PAS55 accreditation in the lead up to PR09. Whilst this is encouraging, PAS55 accreditation does not automatically lead to high scoring in Ofwat's AMA. Having good systems and processes in place is not enough – robust business cases still need to be made.

11 The Forward Look – Gaining Confidence in Deterioration Modelling

At PR04, Ofwat's four stage approach provided for both a historical review (Stage A) and a forward look (Stage B). The forward look embraced the CMPCF, and encouraged companies to demonstrate what is different from the past, going forward. Whatever approach is taken, some form of forecasting of asset behaviour is needed, in order to distinguish either a change in the rate of deterioration from no change, or a change in the volume of assets needing renewal. It is also essential to link asset behaviour (and failure modes) to service delivered. Some software tools were developed of varying complexity for company business plans at PR04. But all such tools are vulnerable to the axiom 'rubbish in equals rubbish out'. The drive now is not so much to develop new models, though the current initiatives through UKWIR are welcome, particularly on deterioration of sewers, but rather to gain confidence in deterioration modelling and application as a process. The need is to:

- expose assumptions in the models to rigorous scrutiny;
- broaden understanding of models and modelling techniques;
- peer review the models;
- define criteria for good data for the particular model;
- do a gap analysis and look for solutions to fill them;
- carry out sensitivity analyses on model outputs;
- validate the models by recognised techniques;
- demonstrate the application of the models; and
- link 'failure' to service failure and customer preference.

Whilst there is a degree of commercial interest that constrains this approach, the models earn their keep best when Ofwat has been convinced of their reliability, and, paradoxically their limitations. At the end of the day, judgements still have to be made, since, like the man in the rowing boat in the thought experiment he cannot see into the future. There is always an element of faith.

12 Discussion: Are the Outcomes of PR04 and PR09 Sustainable?

It is evident from successive periodic reviews of prices that, on the whole, companies have put forward in their business cases more expenditure than was, in the event, actually needed to maintain stable serviceability. But it does not take a genius to wonder, in the case of infrastructure whether the amount assumed is sustainable. The simple manipulation of figures – annual investment divided into the asset value gives an alarming view that the infrastructure assets will need to last for several hundred years. How is this right? Is it right?

The quick answer is, for the moment probably yes, based on the experience of today. 'It ain't so broke, so why fix it?' And, due to the well founded belief that infrastructure assets tend to deteriorate slowly, the capital maintenance assumptions can be ramped up over successive price reviews if deterioration in serviceability is detected. Also, some of these assets will outlive their usefulness due to redevelopment *etc.*, and therefore, there is no need to think that every pipe is going to need replacing.

The more measured answer is that the companies are managing the asset base quite well in an increasingly proactive way between price reviews. There are concerns, particularly for those companies with less than stable serviceability, which they were required to correct by 2010. These were monitored closely and all except one did. There remained a more general need for companies to get a better understanding of what increases in future expenditure might need to be, and whether or not the problem will remain manageable without earlier pre-emptive investment. It is this nagging uncertainty that drives the need to develop deterioration models for an aging (but generally adequate) underground infrastructure. And there remain similar uncertainties surrounding the renewal requirements from the new, above ground, non-infrastructure assets constructed since privatisation. These have very different characteristics from the earlier assets that they either replaced, or were built as new or advanced processes to meet higher standards. Thus for these assets, historic expenditure may not be the best guide going forward, a point well recognised by the introduction of the CMPCF. Companies need to continually develop their asset information and analytical tools to enable better forecasting of asset deterioration and the likely impact on service in both medium and long term, to develop a more robust, service driven, risk based approach that delivers economic capital maintenance plans.

All assets should be there for a purpose, and do not need to be maintained for their own sake. So whatever modelling of deterioration of assets is done, there has to be recognition that the risk to service from asset system failure is the prime concern. So the need for PR09 was to show how models for asset deterioration link to service consequences of failure and associated costs (remedies and impacts) in order to demonstrate that the company has identified robust optimal restorative interventions.

13 Most Recent Conclusions on PR09 – Taken from PR09/37

At PR09 Ofwat assessed some £13bn of proposed capital maintenance expenditure proposed for the period 2010 to 2015.

Table 4 shows that, compared with PR04, the gap between the expenditure the companies have proposed and our expenditure assumptions for the previous price setting has narrowed, as has the gap between the companies' proposed expenditure compared with the preceding AMP expenditure.

The increase in Ofwat's expenditure assumptions for price setting compared with its expenditure assumptions at the previous price setting is almost the same (22 % increase at PR04 and 21 % increase at PR09). But the total adjustments of company plans to reach expenditure assumptions fell from –11 % to –3.5 %, indicating an improvement in the quality of final business plans for capital maintenance.

Ofwat's assessment through the 2009 price review has identified broad success against the implementation objectives within MD161 and the common framework, although this is not universal across all the companies and sub-services. Continued development of these processes is essential in order to embed the common framework asset management planning principles into day-to-day application.

Over the past two price reviews, there have been overall increases in capital maintenance expenditure of nearly 50 %, compared with the 2000-05 level. Ofwat recognises the need for such increases to maintain services to customers and to consolidate the benefits from previous improvement programmes. However, it is questionable whether we are now approaching a sustainable level of capital maintenance for the future. Ofwat recognises that the industry has improved its understanding of asset behaviour and investment needs and that the common framework approach has served it well, contributing to a much-improved understanding of investment needs.

As Ofwat looks towards price setting in the future, there is a need to reappraise the common framework approach and develop potential improvements, particularly in the areas of risk management, programme optimisation and balancing service benefits. In particular, it is important that the companies improve their understanding of the benefits derived from investments already delivered to inform future decision processes. There is a considerable difference across the industry in the unit costs of delivery of each sub-service (particularly for water infrastructure and sewerage non-infrastructure). Ofwat wishes to further explore the extent to which these differences are driven by genuine asset needs or by efficiency and effectiveness.

Table 4 Comparisons of company proposals with Ofwat determinations at PR04 and PR09

Comparator	PR04	PR09
Companies' proposals compared with Ofwat assumptions for the previous price setting	+40 %	+25 %
Companies' proposals compared with preceding AMP expenditure	+25 %	+19 %
Ofwat assumptions compared with Ofwat assumptions for the previous price setting	+22 %	+21 %
Ofwat assumptions compared with companies' proposals	–11 %	–3.5 %

Ofwat will continue to work closely with the sector before the next price review framework is implemented, to develop both the common framework and the AMA approach in a timely, open and transparent way.

The Ofwat website: www.ofwat.gov.uk provides a wealth of information through its publications and public consultation processes, much of which is referenced in this paper. The full postal address is Water Services Regulation Authority, 7 Hill Street, Birmingham, UK B5 4UA.

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Optimizing Budget Allocations in Naval Configuration Management

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Abstract This paper describes a case study illustration of a technique that can be used to optimize capital expenditure budget decisions for engineering assets under multivariate objectives and uncertain costs. We define measures of capability increase relative to mission types and measures for risk, return and pseudo-correlation on potential maintenance upgrades, allowing portfolio optimization techniques from finance to be applied to asset management decisions. The results provide a risk-reward ratio for investment allocation decisions that is optimal. The work is aimed at capability management for naval platforms, but the technique has broader applicability in the field of asset management and multi-criteria decision making.

Keywords Optimization, Portfolio analysis, Engineering assets, Statistical Activity Cost Analysis

1 Configuration Management

The Australian Department of Defence defines configuration management as '… a discipline applying technical and administrative direction and surveillance to; first, identify and document the functional and physical characteristics of a configuration item; second, control changes to those characteristics; and third, record

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and report change processing and implementation status' (ADFP 101 Glossary, 1994). An important aspect of change control is the decision making process used to support configuration item change, replacement and upgrade decisions. Hence, the overall capability of a military asset (here, a naval platform) during its lifetime is largely determined through such decision making.

Configuration management is the controlling mechanism used to maintain, improve or prolong the capability of the platform to the greatest extent possible, while observing constraints on budget and available time, as well as safety, obsolescence and efficiency guidelines. The implementation of changes typically involves selecting a program of tasks from a wide range of possible options, taking into account budgetary and other constraints, to deliver the best outcomes. The types of tasks may vary from very minor work, requiring hours or less, to major refits requiring months or longer to complete.

One major difficulty in this area is defining what is actually meant by capability. For some assets, such as a bulk coal freighter, a straightforward capability measure involving tons per year delivered is probably adequate. For other assets with a single, well-defined mission, such as a commuter train, one might measure passenger miles traveled per year as the capability metric. However, this ignores other harder-to-measure objectives such as provision of regular and reliable services, comfortable carriages, and passenger safety.

In the case of an asset such as a naval platform, which can have multiple missions, the problem becomes more complex still. Moreover, in this context capability is not only defined in terms of a single platform, but also in terms of the capability of a fleet as a whole.

Currently, measures such as number of available days at sea are used for planning and benchmarking. However, these metrics do not take into account varying states of readiness or the capabilities of the platform in the context of broader mission objectives, and so must be used in conjunction with other qualitative considerations.

2 Existing Capability Management Approaches

The difficulty involved in trying to assign a precise meaning to capability suggests that a comparison-based approach may be easier to use when making capability decisions. One of the most widely used algorithms in this area is Saaty's (1990) Analytic Hierarchy Process (AHP) in which various outcomes are compared and ranked, producing a set of priorities that are implied by the given rankings. The technique is powerful in that it imposes a hierarchical decomposition on complex problems, thus allowing the decision process to be made in a holistic manner. However, the AHP also requires that the user gather large amounts of data from various parties to the decision-making process. This is usually time-consuming and expensive and acts as a significant barrier to widespread acceptance of the technique.

Other approaches to multi-criteria analysis (MCA) include the work of von Neumann and Morgenstern (1944), and Keeney and Raiffa (1976), which allows multi-criteria options to be evaluated in practice. Keeney and Raiffa require 'ways of estimating the parameters in a mathematical function which allows the estimation of a single number index, U, to express the decision maker's overall valuation of an option in terms of the value of its performance on each of the separate criteria' (Dodgson *et al.*, 2000). Although this tool has been applied to many real decisions in management and industry, it is also relatively complex and time-consuming to run. Dogson *et al.,* also overview linear additive models, outranking methods and fuzzy set-based approaches.

The theoretical basis for the statistical modeling of financial returns and risk using accounting data is provided in Willett (1991). It is founded on Statistical Activity Cost Analysis which models the uncertainties in cost and duration reflected in accounting systems. The approach supports both data-driven and expert system implementations.

The ideal capability management tool should possess the following features:

1. The tool should not require more information than can be supplied by a single individual in a couple of hours.
2. The tool must be usable by a single individual, allowing potentially unpalatable decisions to be explored without reference to outside parties.
3. Data entered by this individual should immediately lead to useful results.
4. Presentation is important. The tool must be easy to use, have an informative graphical interface, and provide useful reports, in order to assist acceptance from users.
5. The tool should be able to use uncertain data in the same analytical framework as firm, quantitative data.
6. Results should be auditable. The priorities and processes that led to the decision should be transparent and documented.

The approach described in this paper meets these objectives.

3 Defining Capability, Risk and Return

Capability improvement and maintenance are typically seen in terms of multiple simultaneous work packages whose benefits may be difficult to compare in numerical terms. For example, when a refit is planned it is usually only feasible to carry out a subset of tasks from a wide range of desirable enhancements, due to constraints in budget, time in dock, and availability of key staff and other resources. These tasks may vary from the addition of entirely new capabilities to refurbishment work that will prolong and amplify existing capabilities. Despite the existence of multiple priorities the project manager is required to select and rank the various tasks to be performed, to ensure that as much useful work as possible is carried out within budget.

In this section we provide three observations that allow us to apply standard mathematical optimization techniques to this complex decision problem.

Many of the difficulties that arise in capability measurement can be sidestepped by leaving the precise nature of capability *undefined*. Instead, we propose allowing the user to specify what capability means in any given context, not by assigning measures to current and future capability levels, but by assessing a subjective increase in platform capability for any given modification. This bypasses many of the problems that result from lower-level attempts to define capability in a qualitative sense, and allows the incremental costs of capability to be defined.

It is clear that there may be correlations between the capability measures of any two maintenance activities. If two proposed activities affect capability in the same way across a spectrum of mission types, we can say they are positively correlated. If they affect capability in opposite ways, then we can say they are negatively correlated. For instance, a submarine that is trailing a towed sonar array has its sonar capabilities increased, but its top speed decreased. The effect of this enhancement, when deployed, is to increase one capability (to detect targets) but to decrease another (to travel at high speed); so the two are negatively correlated. Since both capabilities are required at various times, the towed array is deployed at the discretion of the submarine's commander.

In this framework, we define the ideas of risk and return on configuration enhancements:

- **Return** is the expected net increase in capability per dollar spent for a given enhancement. Maintenance can be seen in the same terms, since if maintenance is not carried out the capability of the platform may decrease.
- **Risk** is defined as variability in return. If return is normally distributed, risk is measured by the standard deviation of return. If return follows some other distribution, a different measure of variability may be used.
- **Correlation** is the degree to which the returns from various activities move in tandem. A correlation of +1 between two activities indicates that they both add to, or subtract from, capability in parallel. A correlation of –1 indicates that if one activity adds to capability, the other always detracts from it (and vice versa). A correlation of 0 indicates no relationship between the contributions to capability of the two activities.

Given measures for risk, return and correlation between maintenance activities, we use the well-known framework of mean variance optimization (Markowitz, 1952; Elton and Gruber, 1995) to generate portfolios of activities that provide the greatest return (or increment in capability) at the lowest financial risk. In the language of portfolio theory, the universe of investible assets corresponds to potential maintenance activities to the given platform, where each activity has a particular expected return over time, and an associated risk. Mean Variance Optimization (MVO) has been applied in to other problems involving the allocation of non-financial resources, for instance in the oil and gas industry (*e.g.* Hightower and David, 1991) and in marketing strategy (*e.g.* Wind and Mahajan, 1981). However, we believe the current paper represents the first application of MVO to asset management operations.

With this data, we can construct an efficient frontier of suggested work packages (or portfolios) that dominate all others, in the sense that they provide the greatest possible increase in capability (or return) for given levels of financial uncertainty. Solutions that lie on this frontier therefore provide optimal usage of resources and capital.

These results can be generated using a limited amount of data. This is particularly important in light of the earlier comments on the effort required to make capability expenditure decisions.

The outcome is that, under a rigorous set of mathematical assumptions, it is possible to generate a family of solutions to the question ‘What improvements should we make to a given naval platform, to ensure that we are simultaneously making best use of capital and ensuring the lowest financial risk?’.

4 Discussion

One way to think of this proposed approach to capability management is that each potential maintenance activity delivers a certain level of capability improvement per dollar spent, at a given level of financial risk. However, when more than one maintenance activity is under consideration, it becomes necessary to examine the correlations between the various activities to see what effect they will have on the allocation of expenditure and risk. For instance, if two activities show strongly correlated increments to capability per dollar spent, then the financial risk of adopting both will be much higher than if they are negatively correlated, where risks have a higher probability of cancelling out.

The example at the end of this paper demonstrates precisely this behavior. By forming a portfolio of several activities with low ‘pseudo-correlation’, the net financial risk required to deliver a given level of capability improvement is less than for any single activity.

Corresponding behavior in a portfolio of financial assets is seen when we invest in a pair of stocks that are negatively correlated, so that although both may show positive expected returns over the long term, their prices will typically move in opposite directions over the short term. This leads to lower volatility in returns, since a loss by one stock is partly cancelled out by a rise in another. Conversely, if several securities are highly correlated, then they will move in tandem and if there is a market downturn they will all fall in value; so the financial risk will be much higher than for the uncorrelated portfolio. For this reason, prudent portfolio management often involves investment in various uncorrelated classes of assets.

The costs of proposed activities, and their variation over time, are often apparently uncorrelated since they are typically unrelated, so it makes little apparent sense to compare them in the same risk framework. However, by introducing the idea of the *amount of increased capability per dollar spent* for a given maintenance activity, we have a measure that has an expected value, an associated uncertainty, and that can have its 'correlation' measured with respect to other capability activity costs, which can then be compared to other activities. This allows us to use Markowitz (1952) mean-variance optimization to derive optimal combinations of expenditure on maintenance activities that give the maximum possible return on investment at the lowest risk.

5 Mean-Variance Optimization

Following Markowitz (1952), we describe the mean-variance model in the following form. Suppose that we have a portfolio of investible assets, such as stocks or bonds. The return of each asset is normally distributed, so that its uncertainty (or risk) is measured by the expected standard deviation of the observed return about the expected return. The returns are also correlated to various degrees. The returns, risks and correlations are assumed to be known in advance.

Given these quantities for the individual securities in the portfolio, the problem is then to minimize the overall portfolio risk for given levels of return. This is equivalent to solving the following set of equations:

$$\text{Minimise} \sum_{i=1}^{N} \sum_{j=1}^{N} x_i x_j \chi_{ij} \tag{1}$$

where,

$$\sum_{i=1}^{N} x_i r_i = R \tag{2}$$

$$\sum_{i=1}^{N} x_i = 1 \tag{3}$$

$$x_i \geq 0, i = 1, 2, \ldots, N \tag{4}$$

Here, x_i is the fraction of the portfolio held in asset i, r_i is the expected return for asset i, R is the return of the portfolio, χ_{ij} is the covariance between the returns generated by assets i and j, and N is the number of assets. The covariance matrix χ is related to the correlation matrix C by the expression $\chi = \sigma C \sigma$, where σ is an $N \times N$ matrix with standard deviations on the diagonal and zeros elsewhere. The solution to the system of equations (1)–(4) supplies the optimal combination of holdings that minimizes the portfolio's risk, given an expected return R.

Since R can take on a range of values, the solutions to (1)–(4) trace out a graph of risk against return, usually referred to as the *efficient frontier*. These solutions dominate all others, in the sense that they provide the least risk for a given level of return. For any solution that does not lie on the frontier, there is another that gives a better return for the same level of risk, or lower risk for the same level of return.

The assumption of normally distributed prices may well not be the case for maintenance activities under consideration in an engineering context, where a more realistic distribution could have a rigid lower bound, with higher values at lower probabilities (‘the cost will not be less than \$*x*, but it might well be more’). We consider this case in more detail below.

6 The Algorithm

Suppose that, for a given platform, we are considering a number of maintenance activities which can include enhancements and/or upgrades. The platform has a number of well-defined missions and tasks, some of which are purely military, while others involve a constabulatory or diplomatic component (see *Australian Maritime Doctrine*, 2000). One of the strengths of the proposed approach is that all types of missions can be handled in the same analytical framework. In the following we construct a “pseudo-correlation” measure for modeling purposes. In practice, this might be (and probably would usually be) replaced by direct estimates of standard correlation measures using sample data.

Step 1
To each mission type we assign a numerical rating p between 1 and 10, showing the importance of the mission, or the proportion of time to be spent undertaking that mission, for the current platform. For instance, a specialized vessel such as a minesweeper is unlikely to be called upon to perform escort duties, so the importance of an escort capability over this vessel’s lifetime is likely to be low, and p(escort) will be set to 1 or 2. Conversely, the importance of minesweeping will be very high, since this is the vessel’s *raison d’etre*; so p(minesweeping) will be set to 9 or 10. (The scale of 1 to 10 is purely arbitrary; any other scale that permits sufficient resolution between mission types will be just as valid).

Step 2
For each proposed maintenance or enhancement activity, define the effect that the activity will have on each mission type in terms of a simple scale. The lowest level of resolution might be (Low, Medium, High), but more levels can be used.

These capability increase estimates are then mapped to numerical values, with H as the highest and L as the lowest. For instance, (Low, Medium, High) might map to (–1, 0, 1). The numerical capability increase of activity i for mission type k is denoted by a_i^k .

For each pair (i, j) of proposed enhancements, we create measures estimating the degree to which they will work in tandem to change the capability of the vessel. First let the delta measure δ between the two enhancements be defined as:

$$\delta_{i,j} = \sum_k p^k \left| a_i^k - a_j^k \right| \tag{5}$$

Thus if the values of the a_i^k and a_j^k coefficients are the same, then the contribution to δ is zero. Conversely, if a_i^k has the lowest possible value and a_j^k the highest, then they lie at opposite ends of the scale and their contribution to δ is high. The differences between the contributions are further weighted by factor p to include the importance of each mission type.

Given this matrix $\delta_{i,j}$, we construct a matrix of pseudo-correlation measures using

$$\mathrm{corr}_{i,j} = 1 - \frac{2\delta_{i,j}}{\Delta} \tag{6}$$

where

$$\Delta = \sum_k p_k \left(U_k - L_k\right) \tag{7}$$

and U_k and L_k are the upper and lower ranges for values of the a_i^k. If a different expression were used for $\delta_{i,j}$ then the form of (7) would also change accordingly.

One way to interpret these pseudo-correlations is to regard them as the cosines of the angles between the various vectors of samples a_i^k. They therefore represent the degree to which one vector of capability increase is projected upon another. For instance, suppose that two potential activities i and j affect capability in completely different ways. The values of a_i^k and a_j^k will be completely dissimilar, so that when one is low, the other will be high, and vice versa. For instance, suppose that the effect of one possible activity is rated as (1, –1, –1) and the effect of another as (–1, 1, 1) where –1 and 1 are the lowest and highest possible rating values. Using the identity

$$\cos\theta = \frac{x \cdot y}{\|x\|\|y\|} \tag{8}$$

for the angle between two vectors x, y shows that the cosine of the angle between the two vectors is –1, implying a pseudo-correlation measure of –1.

Conversely, suppose that two activities have identical ratings of (1, –1, –1) and (1, –1, –1). In this case, the two potential activities i and j affect capability in exactly the same way, and the values of a_i^k and a_j^k will be identical for all k. The cosine of the angle between the rating vectors is zero, so from (6) the pseudo-correlation is +1.

As with a real correlation measure, a pseudo-correlation of zero does not generally imply independence. A zero pseudo-correlation can arise because of the interplay between the relative sizes of the various activity weightings and the mission importance weights p. Zero pseudo-correlation therefore indicates that there is a lesser degree of co-movement between one vector and another, compared to another pair of vectors with a higher absolute correlation.

Expression (5) is not the only one we could use to measure the degree of dissimilarity between two proposed maintenance activities. For instance, an expression of the form shown in (9), where α is real, would amplify the effect of differences between the a^k .

$$\delta_{i,j} = \sum_k p^k \left[\left(\frac{a_i^k}{a_j^k} \right)^{\alpha} - 1 \right] \tag{9}$$

In this case, Equations (6) and (7) would change accordingly so that a valid pseudo-correlation matrix, *i.e.* one with the same properties as a normal correlation matrix, was still produced.

Step 3

We now use the values of matrix a to calculate an estimated increase in overall capability for each upgrade i . This is given by a weighted sum of the estimated capability increments for each activity, using the mission importance weights p from Step 1:

$$\delta C_i = \sum_k p^k a_i^k \tag{10}$$

Step 4

For each proposed activity, enter upper and lower estimates for costs that cover ± 2 standard deviations, or 95 % of all cases in the form $[H_i, L_i]$. Since the distribution of these costs is assumed to be normal, each distribution can be described by the mean μ and variance σ^2 . Using this data, the mean can be calculated from

$$\mu_i = \frac{H_i + L_i}{2} \tag{11}$$

and the standard deviation from

$$\sigma_i^2 = \frac{H_i - L_i}{4} \tag{12}$$

The expected change in capability per dollar (the return, or capability cost) is then given by

$$\frac{\delta C_i}{\mu_i} = \frac{2\delta C_i}{H_i + L_i} \tag{13}$$

For instance, if a particular maintenance activity confers an increase in capability of 20 units at a cost distribution of ($\mu = \$10$, $\sigma^2 = \$2$) then each dollar spent on that activity increases capability by 2 units per dollar, respectively. Such a scheme allows the costs and risks of different maintenance activities to be compared directly. With the addition of pseudo-correlation measures from equation (6), we can also calculate optimal allocations for the various options on offer.

Step 5
With these estimates of capability return, financial risk and pseudo-correlation, we can now use standard mean-variance optimization routines, such as the *frontcon* package in MATLAB, to calculate the efficient frontier for this problem.

7 Numerical Issues

One difficulty that can be encountered in practice is that the pseudo-correlation matrix may not be positive semi-definite, which is a requirement of the Markowitz mean-variance optimization algorithm. A symmetric matrix is positive semi-definite if and only if its eigenvalues are all non-negative. This is a frequent problem in financial Value at Risk (VaR) simulations, where correlations may be estimated rather than derived directly from market data.

Following the approaches proposed by Rebonato and Jäckel (2000) and Dowd (2005), we note that any positive-definite matrix M can be written as

$$M = A^T \Gamma A \tag{14}$$

where A is a matrix of the eigenvectors of M, and Γ is a matrix with the eigenvalues of M on the diagonal and zeros elsewhere.

If the correlation or pseudo-correlation matrix is not positive-semi definite, the recommended procedure is therefore to calculate its eigenvectors and to set any negative eigenvalues to zero, and then to use (14) to construct a new matrix that does have the required properties. Rebonato and Jäckel (2000) give further justification for this approach.

Example 1
A fleet of frigates has a refit scheduled. In this example, for simplicity, we consider only maintenance activities which upgrade capability. The upgrades under consideration are:

- **A new radar**, at a cost of between $45,000 and $55,000 per ship. Radar will be in service for three years and provide better scouting abilities, after which a better model is expected to be available.
- **A gun refurbishment**, at a cost of between $30,000 and $40,000 per ship. Guns have an expected life-time of ten years and provide better offensive capability.
- **Improved crew quarters**, at a cost of between $20,000 and $30,000 per ship. The crew quarter upgrade will be in place until the end of the ship's planned lifetime, and will lead to better crew morale, resulting in longer effective periods at sea.

What is the best action, or combination of actions, that delivers maximum increase in capability for the fleet at a defined level of financial risk?

It is, of course, very difficult to compare the benefits of these various improvements to capability in any quantitative manner, since each modification improves the ship's capability in an entirely different way.

The first step is to set out a list of required platform capabilities and military missions. At this point, political and other non-military objectives may be introduced if these are seen as being significant. Hence, MVO can be undertaken in terms of prioritizing maintenance activities and upgrades against platform capabilities, military missions or other objectives, or a combination of these. In this example we consider "missions" to include aspects of all three elements described previously.

For a frigate these might include the following mission types:

- patrol;
- training;
- anti-submarine warfare (ASW);
- convoy escort;
- good-will visits;
- conforming with foreign treaties.

A good-will visit is not a military mission. However, the ability to deploy a warship can nevertheless be seen as a separate function of a frigate. For instance, the decision to withdraw HMS Endurance from the South Atlantic station at the end of the 1981–1982 season was widely seen as a triggering event for the subsequent Falklands conflict; see Hastings and Jenkins (1983).

Next, we define how each proposed configuration change adds to the ship's capability for each type of mission. For instance, better crew quarters will increase the length of time the ship can stay on patrol, although the direct effect on anti-submarine warfare capability is zero.

For illustrative purposes, it is worth considering one function in detail. Looking at 'Patrol', a radar upgrade will have a 'Medium' effect on patrolling capability. Better radar is always useful to have, but the existing set has usually been adequate. Besides, the set considered for upgrade will only be in place for three years until it is replaced with another set.

The effect of a gun refit on patrol capability is 'Low' since the guns are small caliber and seldom used on patrol missions.

An upgrade to the crew quarters will have a 'High' effect on patrol capability, as morale has been a problem in this type of vessel due to poor living spaces. A better environment will both allow longer time on patrol and (probably) decrease crew turnover.

The provision of these assessments requires a high level appreciation of the effect of the proposed changes, and is therefore best left to an individual or a small team with a broad view of the issues involved. For instance, a flag-rank officer may not be intimately familiar with the capabilities of competing radar sets, but he or she will undoubted have staff who can give an accurate assessment of their effects on overall capability.

Table 1 User-assessed effects of upgrades on capability

Mission type	Effect on mission capability			Importance of mission type (p)
	Radar upgrade	Gun refit	Crew quarters upgrade	
Patrol	Medium	Low	High	6
Training	Low	Medium	Low	3
ASW	High	Low	High	2
Convoy escort	Low	High	High	1
Good-will visits	Low	High	Low	1
Foreign treaties	Low	Low	Low	3

Here we have also assigned weights, or estimates of importance p, to the various mission types on a scale from 1 to 10. For instance, 'Patrol' has a weight of 6, indicating that the vessel is expected to spend much of its time in this role in the immediate future. On the other hand, the ship is unlikely to be used for 'Convoy escort' duties, and so this is assigned a low weight.

The next step is to find the cost spread for each proposed upgrade. From the data supplied, these are as follows:

Table 2 Cost distributions for upgrades

Cost measure	Cost of capability upgrade		
	Radar upgrade	Gun refit	Crew quarters upgrade
Upper cost limit	\$55	\$40	\$30
Lower cost limit	\$45	\$30	\$20
Mean cost	\$50	\$35	\$25
SD of cost	\$2.5	\$2.5	\$2.5

(Note: All figures are in multiples of \$1000)

Mapping the range (Low, Medium, High) in Table 1 to the numerical range (1, 2, 3) and using equations (5) to (7) gives the pseudo-correlation matrix

$$C = \begin{bmatrix} 1 & -0.0625 & 0.5 \\ -0.0625 & 1 & -0.3125 \\ 0.5 & -0.3125 & 1 \end{bmatrix} \tag{15}$$

The next step is to calculate the weighted sum of the various capabilities. Converting Table 1 into numerical form gives

Table 3 Overall capability increase for upgrades

Mission type	Importance of mission type (p)	Effect on mission capability		
		Radar upgrade	Gun refit	Crew quarters upgrade
Patrol	6	2	1	3
Training	3	1	2	1
ASW	2	3	1	3
Convoy escort	1	1	3	3
Good-will visits	1	1	3	1
Foreign treaties	3	1	1	1
Total		26	23	34

The numbers in the last row of Table 3 are the raw capability measures, calculated by multiplying each capability rating by its weight; thus the total capability measure for 'Radar' is $(2\times6)+(1\times3)+(3\times2)+(1\times1)+(1\times1)+(1\times3)=26$. We refer to these numbers as *capability units.*

The final step is to calculate the per dollar cost of the capability increase conferred by each potential maintenance activity or upgrade. This is simply calculated as the increase in capability, divided by the expected cost, as shown in Table 4.

We now have everything needed to run a mean-variance analysis on this problem. Specifically:

- The returns for each potential upgrade, in terms of capability units per dollar, are given by the last line in Table 4.
- The risks, or standard deviations of cost for each potential upgrade, are shown in the last line in Table 2.
- The pseudo-correlations between the returns for each capability upgrades are as shown in matrix (15).

Substituting these pseudo-correlations, returns and risks into standard portfolio optimization software (such as MATLAB's *frontcon* routine) produces the efficient frontier graph in Figure 1, showing how risk (financial uncertainty) varies against return (increase in capability) for this combination of inputs.

This figure also shows risk plotted against return for 1000 random portfolios, where every portfolio is subject to the conditions (2)–(4). Each point on the graph shows the financial risk and increase in capability for a random set of budget allo-

Table 4 Per dollar cost of capability increases

	Capability upgrades		
	Radar upgrade	Gun refit	Crew quarters upgrade
Assessed capability increase	26	23	34
Expected cost	\$50	\$35	\$25
Capability Increase per dollar	0.52	0.66	1.36

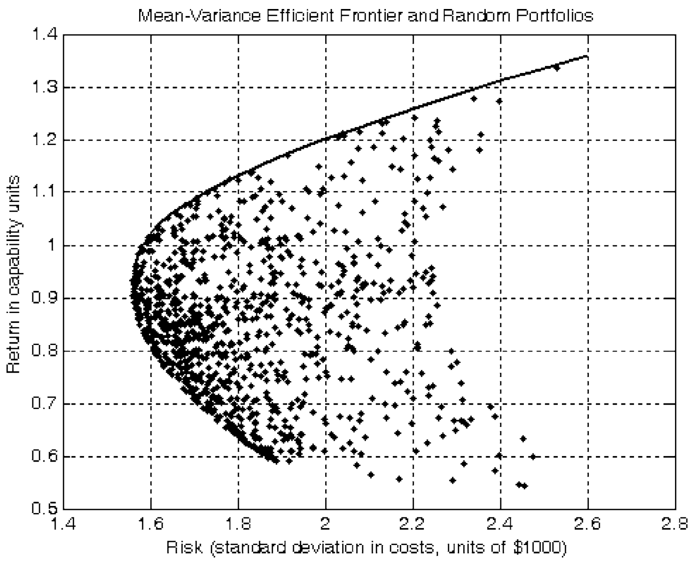

Figure 1 Random portfolios and the location of the efficient frontier

cations to the various enhancements under consideration, where the allocations are positive and sum to 100 % of the total budget.

Financial risk, shown on the bottom axis, shows the standard deviation of costs for a range of work packages in dollars, while increase in capability is shown on the vertical axis.

The thick line that rises monotonically from the left hand side of the scatter region to the upper right corner of the diagram is the efficient frontier. This shows how the increase in the vessel's capability rises as the financial risk, or uncertainty in expenditure, increases. Points on this line represent the best possible increase in capability, given an overall uncertainty level in costs. By convention, solutions that lie on the border of the feasible solution region but that represent the worst possible return for a given level of risk (in this case where return is less that 0.95) are not regarded as lying on the efficient frontier, since for every such solution there is another that delivers the best possible return.

This diagram also illustrates that most possible expenditure allocations are suboptimal, in that they do not generate as much increase in capability for a given level of risk as do the portfolios on the frontier. The range of possible solutions is bordered by the efficient frontier, whose equation may be determined analytically under the assumptions in Markowitz (1952).

For given levels of financial risk, the actual allocations to the various upgrades are as shown in Table 5. The optimal spending allocation varies as the desired level of financial risk (or, alternatively, the desired increase in capability) varies. For instance, at the half-way point, the standard deviation of costs is $1,790, the capability return is about 1.12 units per thousand dollars, and the portfolio corresponding to this return allocates about 33 % of budget to the guns and the remainder on upgrading the crew quarters.

Note that this table is entirely consistent with Figure 1. Inspecting Table 4 shows that the maximum capability increase possible is about 1.36 units; this is only possible by allocating all the budget to the guns. However, Table 5 shows that this option also carries the greatest financial risk, with a standard deviation in costs of around $2600.

The lowest-risk solution allocates approximately equal amounts to improving the crew quarters and to upgrading the guns, with only a very small amount to be spent the radar. This gives the lowest variability in expected costs, with a standard deviation in cost of $1560, but results in a lower overall increase in capability of approximately 0.92 capability units, compared to alternative configurations.

The most conservative solution, which has the lowest uncertainty in expenditure, is also the one that returns the least in terms of capability increase, while the most aggressive financial strategy returns the most capability increase.

No improvements to radar are suggested except for the very lowest levels of risk. This is consistent with the input data, since radar is the most expensive upgrade, and it has a low contribution to capability and to the platform's most critical missions.

Table 5 Financial risk, capability improvement, and budget allocation for work packages on the efficient frontier

Risk (uncertainty in expenditure per thousand dollars)	Return (capability increase per thousand dollars)	Budget allocated to radar	Budget allocated to guns	Budget allocated to crew quarters
1.56	0.92	8 %	53 %	39 %
1.56	0.94	5 %	53 %	42 %
1.57	0.97	3 %	53 %	44 %
1.58	0.99	0 %	53 %	47 %
1.59	1.02	0 %	50 %	50 %
1.61	1.04	0 %	46 %	54 %
1.65	1.06	0 %	43 %	57 %
1.69	1.08	0 %	40 %	60 %
1.74	1.10	0 %	36 %	64 %
1.79	1.13	0 %	33 %	67 %
1.85	1.15	0 %	30 %	70 %
1.92	1.17	0 %	26 %	74 %
1.99	1.20	0 %	23 %	77 %
2.07	1.22	0 %	20 %	80 %
2.15	1.24	0 %	17 %	83 %
2.23	1.27	0 %	13 %	87 %
2.32	1.29	0 %	10 %	90 %
2.42	1.31	0 %	7 %	93 %
2.51	1.34	0 %	3 %	97 %
2.60	1.36	0 %	0 %	100 %

As long as one of the solutions that lies on the surface defined by Table 5 is chosen, the user is making optimal use of capital. Conversely, a decision to spend 20 % on crew quarter upgrades and 80 % on the radar does not correspond to any of the solutions shown, so such an expenditure allocation would not give the best value for money. In fact, Figure 1 indicates the existence of other budget allocations that show either a higher increase in capability for the same budget uncertainty, or a lower uncertainty in budget for the same increase in capability. If the risk against return was calculated for this portfolio, it would fall into the area under the graph in Figure 1 instead of on the efficient frontier.

Example 2

Now suppose that the quoted cost of upgrading the crew quarters increases quite substantially, from the current range of [$20,000, $30,000] to [$50,000, $70,000]. While the pseudo-correlations remain the same, both the expected spend and the spread of costs will be higher, as shown in Tables 6 and 7.

Table 8 shows that the maximum amount to which capability per dollar can be increased is now about 0.66 capability units, compared to 1.35 capability units in the previous example. This is because the cost of one of the most attractive options has more than doubled, which completely changes the results of the analysis.

At the lowest levels of risk, 57 % of the budget has now been allocated to upgrading the guns, with most of the remainder on the ship's radar. Conversely, expenditure on the crew quarters has become a less attractive option, both because the capability increase per dollar spent has dropped, and because the uncertainty in the eventual cost has increased. In fact, the strategy that delivers the highest increase in capability per dollar is now to spend the entire available budget on improving the ship's gunnery capabilities.

Table 6 Cost distributions for upgrades (example 2)

Cost measure	Cost of capability upgrade		
	Radar upgrade	Gun Refit	Crew quarters upgrade
Upper cost limit	$55	$40	$50
Lower cost limit	$45	$30	$70
Mean cost	$50	$35	$60
SD of cost	$2.5	$2.5	$5.0

(Note: All figures are in multiples of $1000)

Table 7 Per dollar cost of capability increases (example 2)

	Capability upgrades		
	Radar upgrade	Gun refit	Radar upgrade
Assessed capability increase	26	23	34
Expected cost	$50	$35	$60
Capability Increase per dollar	0.52	0.66	0.57

Table 8 Financial risk, capability improvement, and budget allocation for work packages on the efficient frontier (example 2)

Risk (uncertainty in expenditure per thousand dollars)	Return (capability increase per thousand dollars)	Budget allocated to radar	Budget allocated to guns	Budget allocated to crew quarters
1.88	0.60	42 %	57 %	1 %
1.88	0.60	40 %	59 %	2 %
1.89	0.60	37 %	61 %	2 %
1.89	0.61	34 %	63 %	3 %
1.90	0.61	32 %	65 %	3 %
1.91	0.61	29 %	67 %	4 %
1.93	0.62	27 %	69 %	4 %
1.94	0.62	24 %	71 %	5 %
1.96	0.62	21 %	73 %	5 %
1.98	0.63	19 %	75 %	6 %
2.01	0.63	16 %	77 %	6 %
2.03	0.63	14 %	80 %	7 %
2.06	0.64	11 %	82 %	7 %
2.09	0.64	8 %	84 %	8 %
2.12	0.64	6 %	86 %	8 %
2.16	0.64	3 %	88 %	9 %
2.19	0.65	1 %	90 %	10 %
2.23	0.65	0 %	93 %	7 %
2.28	0.65	0 %	97 %	3 %
2.35	0.66	0 %	100 %	0 %

8 Future Work

This work is part of an ongoing project to implement Statistical Activity Cost Analysis concepts in the management of engineering assets (Colin *et al.*, 2010). Several ways exist to extend this work.

First, the simulations reported here assume that cost is continuous, and does not take account of the fact that some expenditure may only be made in discrete portions. For instance, one cannot buy half a helicopter. The algorithm described in the paper can be readily extended to accommodate this situation.

Second, it would be of particular interest to extend this analysis to multi-level capability expenditure decisions, starting (for instance) at the fleet level and working down to the level of individual ships.

Third, we are currently investigating the effect of non-normal cost distributions. This requires the use of extensive Monte Carlo simulation to determine the efficient frontier for expenditure decisions. Little work has been done in this area to date due to the analytical intractability of the problem, but there are some indications (*e.g.* Markowitz & Todd, 1987, p 67) that some degree of non-normality will not affect the results substantially. This remains to be confirmed in practice, however.

Fourth, further work is required on the development of the ideas contained in the calculation of the pseudo-correlation matrix. On-going implementations will clarify the validity and usefulness of the construct relative to the use of empirically estimated statistical correlations.

Fifth, the multi-dimensional nature of the capability and financial return and risk matrix and the relative reliabilities of ratio measures (as used in this paper) and absolute measures of capability and cost need to be assessed.

Finally, the capability and cost measures need to be grounded in a rigorous measurement-theoretic treatment to justify their use in the mean-variance analysis.

9 Conclusions

We have demonstrated an innovative approach to the assessment of capability in a financial context, using ideas from the theory of finance. Benefits of this approach include the ability for rational decisions to be supported by a relatively small amount of information. Quantitative and qualitative judgements can be combined in the same framework and provide auditable decisions based on objective evidence. The outputs of the model are readily interpretable by the lay user but are nevertheless based on firm and rigorous mathematical foundations. While such a decision-support system cannot and should not replace the carefully considered assessment of the individual expert, its more refined development should provide a useful addition to the armoury of the engineering asset manager operating in a complex environment.

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Modelling Total Cost of Ownership of Rail Infrastructure for Outsourcing Maintenance Services

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Abstract In the recent years, outsourcing maintenance services has become a part of strategies for cost and risk management. Outsourcing reduces upfront investments in infrastructure, expertise and specialised maintenance facilities. However, decisions on this need to take into account the total cost of ownership rather than the usual practice of procurement cost. The primary objective of this paper is to develop models for prediction of total cost of ownership and estimation of contract price for outsourcing maintenance services of rail infrastructure. A total cost of ownership model is developed considering procurement, maintenance, inspection and risks associated with the operation of a rail network.

Keywords Total cost of ownership, Outsourcing services, Rail infrastructure

1 Introduction

Rail networks play an important role for transportation of material over wide geographically distant areas. It is expensive and complex for industries to install and mange complex and capital intensive assets (Murthy and Ashgarizadeh, 1995). Outsourcing reduces upfront investments in infrastructure, expertise and special-

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ised maintenance facilities. There is a trend from an asset infrastructure focussed approach in decision making to a service focussed approach. In determining the worth of outsourcing services, one needs to analyse each case based on costs and benefits. Total cost of ownership (TCO) includes the cost of acquisition, operation, and maintenance. Estimation of this cost is complex. There is a need to develop mathematical models for understanding future costs to build it into the contract price. Failure to do so may result in loss to the service provider or the user because of uncertainties associated with reliability, availability, maintainability, safety and security (RAMSS) and their implication for business. Heavy haul rail operation usage can be modelled as a function of tonnage accumulation in million gross tones (MGT) for design, operating and maintenance conditions.

This paper develops a total cost of ownership model and contract price for outsourcing services out of rail infrastructure. The outline of the paper is as follows: in Section 2, total cost of ownership is discussed. Section 3 deals with the development of mathematical models for total cost of ownership and contract price for outsourcing services of rail infrastructures. In the final section, the scope for future work is discussed.

2 Total Cost of Ownership

From its origins in defence equipment procurement in the US in the early 1960s, the use of the total cost of ownership concept has extended to other areas of the public and private sectors (Kumar *et al.*, 2006). It can be used to assist in budgeting, cost control, and a range of other activities including maintenance, leasing and replacement decisions of complex assets. It covers acquisition (purchase or lease), operation, and maintenance and support costs, Kumar *et al.* (2004). The following elements are a major component of this model:

- *capital costs*;
- *the discount rate*;
- *operating and maintenance costs*;
- *disposal cost*;
- *life of the asset*.

  The useful lifetime of an asset can be defined as the lifetime of the asset and assumed to be terminated in some finite, random time horizon. Termination can also result from technological obsolescence, ownership change, and technical or commercial reasons. The estimated life (Chattopadhyay and Rahman, 2008) of an asset can be as follows:

  – Physical life – the period over which the asset might be expected to last physically (up to the period when replacement or major rehabilitation is physically required).

- Technological life – the period until technological obsolescence due to the development of technologically superior alternatives.
- Economic life – the period, over which the need for the asset exists.
- Ownership life – the period until a change of ownership occurs.

3 Total Cost of Ownership for Rail

Cost of acquisition, maintenance services, inspection to detect the potential rail breaks, risks associated with derailment, and cost of disposal at the end of the lifecycle of rail considered in this model are given by C_{TW}:

$$\mathrm{C}_{TW} = C_A + C_S + C_I + C_R + D$$

where the variables are defined as follows,

C_{TW}: Total cost of ownership.
C_A: Cost of procurement or acquisition.
C_S: Cost of maintenance over the lifecycle.
C_I: Inspection cost.
C_R: Cost of risk associated with accident due to derailment.
D: Costs and revenues from disposal of the discarded rail.

3.1 Modelling Costs of Maintenance Over the Lifecycle

Rail infrastructure maintainers use both corrective maintenance (CM) by cutting damaged or broken rails and welding and preventive maintenance (PM) by lubrication and rail grinding. These strategies are classified as per degree of restorability of the rail as shown in Figure 1.

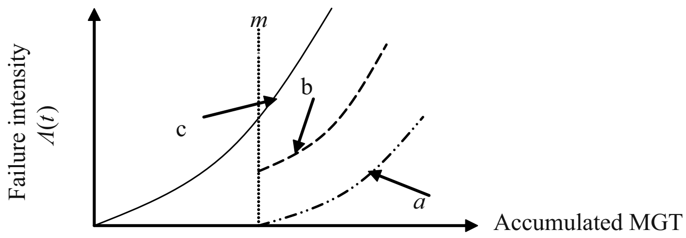

Figure 1 Failure rate with effect of various maintenance actions (Rahman and Chattopadhyay, 2004)

Rail servicing strategies assumed are:

1. *Replacement*: Replacing a rail segment turns the failure rate of the segment to zero (see curve '*a*' in Figure 1).
2. *Imperfect repair:* Rail grinding and lubrication are the examples of this type of servicing strategy. It is normally used in cases of planned preventive maintenance. It can restore a substantial portion of a segment and the hazard/failure rate after this action falls in between "as good as new" and "as bad as old" (see curve 'b' in Figure 1).
3. *A minimal repair:* a replacement or repair of the damaged or broken portion of the rail is an example of minimal repair. The condition of the rail segment after maintenance is "as bad as old" (see curve 'c' in Figure 1).

Modelling rail failure:

Rail failure is modelled as a point process with an intensity function $\Lambda(m)$ where m represents millions of gross tonnes (MGT) and $\Lambda(m)$ is an increasing function of m indicating that the number of failures increases with MGT (Rahman and Chattopadhyay, 2010). Older rails with higher cumulative MGT passed through the section are expected to have more probability of initiating defects. If undetected further passing of traffic can lead to failures. As a result, the number of incidents becomes a function of usage MGT, m, and is a random variable. This can be modelled using an intensity function $\Lambda(m)$ (Chattopadhyay *et al.*, 2005). Let cumulative MGT of rail, m, be known and $F(m)$ and $f(m)$ denote the cumulative rail failure distribution and density function respectively,

These can be modelled as:

$$F(m) = 1 - \exp(-(\lambda m)^{\beta}) \tag{1}$$

and

$$f(m) = \lambda\beta(\lambda m)^{\beta-1}\exp(-(\lambda m)^{\beta}) \tag{2}$$

with the parameters $\beta > 0$ (known as the shape parameter of the distribution) and $\lambda > 0$ (known as the inverse of the characteristic function of the distribution).

A value of β greater than 1 indicates an increasing failure rate of the item and that ageing is a predominant factor in the failure mechanism.

Then the failure intensity function $\Lambda(m)$ derived from 1 and 2 is given by

$$\Lambda(t) = \frac{f(m)}{1-F(m)} = \frac{\lambda\beta(\lambda m)^{\beta-1}\exp(-(\lambda m)^{\beta})}{1-(1-\exp(-(\lambda m)^{\beta})} = \lambda\beta(\lambda m)^{\beta-1} \tag{3}$$

Rail maintenance services:

Figure 2 is the graphical representation of rail maintenance strategy over the lifecycle of a rail segment with a constant interval preventive maintenance plan. Each

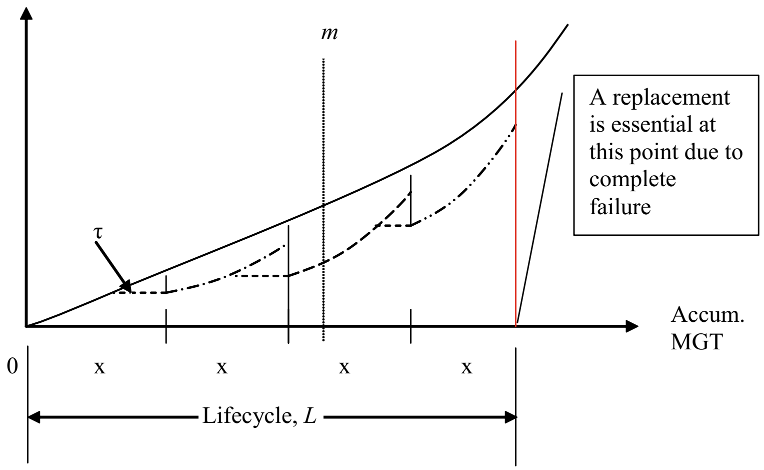

Figure 2 Graphical representation of maintenance service for rail

PM improves the reliability of the rail. Between successive PMs, there may be a number of corrective maintenance actions.

We define the expected total cost of maintenance service as:
= (Expected total cost of minimal repairs over the lifecycle
+ Expected cost of preventive maintenances over the designed lifecycle $L)/(1+r)^n$

where, r is the discount rate over the period n and n = 1, 2, 3, …

The expected total cost of all minimal repairs over the contract period is given by

$$C_{mr}\sum_{k=0}^{N_i}\int_{kx}^{(k+1)x}\Lambda(m-k\tau)dm \tag{4}$$

When failures are modelled as per NHPP then, the failure intensity is, from Equation 3,

$$\Lambda(m)=\lambda^{\beta}\beta m^{\beta-1}$$

Therefore, Equation 4 can be expressed as Equation 5 below by substituting the value of $\Lambda(m)$ and integrating.

The expected cost of minimal repair is then

$$=C_{mr}\left\{\sum_{k=0}^{N_i}\lambda^{\beta}x^{\beta}\left[\left(k-k\alpha+1\right)^{\beta}-\left(k-k\alpha\right)^{\beta}\right]\right\} \tag{5}$$

where, $\tau=\alpha x$, where, α is the quality of PM.

The expected cost of preventive maintenance during the contract is

$$= C_{pm} N_i \tag{6}$$

Therefore, the total expected maintenance cost (C_S) over the designed lifecycle can be expressed by adding Equations (5) & (6) as Equation (7),

$$C_S = \left[C_{mr} \left\{ \sum_{k=0}^{N_i} \lambda^{\beta} x^{\beta} \left[(k - k\alpha + 1)^{\beta} - (k - k\alpha)^{\beta} \right] \right\} + C_{pm} N_i \right] \Big/ (1+r)^n \tag{7}$$

The minimal total expected cost per unit time is obtained by differentiating equation 7 with respect to x and equating to zero.

3.2 Modelling Inspection Cost

Discounted inspection cost over the asset lifecycle can be developed in line with Reddy *et al.* (2007). Let I_f be the inspection interval in MGT and c_I be the mean cost of each inspection. Then the total inspection cost (C_I) over the rail life can be given by:

$$C_I = \left\{ \sum_{n=1}^{N} c_I / (1+r)^n \right\} \tag{8}$$

where

$$N = \text{Integer} \left[\frac{M_N}{I_f} \right] \tag{9}$$

M_N is the total accumulated MGT for the rail lifecycle up to the end of period N and r is the discounting rate associated with the interval of non destructive testing (NDT).

3.3 Modelling Risk Costs

Let b be the expected cost of repairing potential rail breaks and a be the expected cost per derailment. Then b and a could be modelled in a similar manner to the above. The risk cost associated with rail breaks and derailments is based on the probability of detecting potential rail breaks, rail breaks not being detected, derailments and associated costs.

Let $P_n(B)$ be the probability of detecting potential rail breaks and $P_n(A)$ be the probability of undetected potential rail breaks leading to derailments during the interval between the nth and $(n+1)$th periods. Then the risk cost is given by:

$$C_R = \frac{\sum_{n=0}^{N} E[N(M_{n+1}, M_n)] \times [P_n(B) \times b + (1 - P_n(B)) \times (P_n(A) \times a]}{(1+r)^n} \tag{10}$$

where, $E[N(M_{n+1}, M_n)]$ is the expected number of rail breaks on an emergency basis over the interval of MGTs M_n and M_{n+1}.

3.4 Total Cost of Ownership

The total cost of ownership is obtained by adding the components given by equations (7), (8) and (10) over the designed life of the asset. This can be expressed as

$$\mathrm{C}_{TW} = C_A + C_S + C_I + C_R + D$$

or

$$\begin{aligned} \mathrm{C}_{TW} = C_A &+ \\ &\left[C_{mr} \left\{ \sum_{k=0}^{N_i} \lambda^\beta x^\beta \left[(k - k\alpha + 1)^\beta - (k - k\alpha)^\beta \right] \right\} + C_{pm} N_i \right] \Big/ (1+r)^n{}_S \\ &+ \sum_{n=1}^{N} c_I / (1+r)^n \\ &+ \frac{\sum_{n=0}^{N} E[N(M_{n+1}, M_n)] \times [P_n(B) \times b + (1 - P_n(B)) \times (P_n(A) \times a]}{(1+r)^n} + D \end{aligned} \tag{11}$$

where C_A is the procurement price of rail and D is the one-time revenue earned by selling the discarded rail at the time of disposal.

The contract price for outsourcing rail maintenance service can be modelled by

$$P_c = \frac{C_{TW}}{L}$$

where, L is the designed lifecycle of the rail in MGT of traffic for a particular axle load.

4 Contribution and Future Scope

This paper proposes a service based model for the prediction of the total cost of ownership for rail infrastructure and a contract price for outsourcing services by freight line users. This model could be further extended by including provisions for penalty rates, for not complying with maintenance standards or reducing availability, keeping provision for used items in rectifications, leasing and risk preferences of freight line users.

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A Statistical Activity Cost Analysis of Engineering Assets[1]

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Abstract In this paper, Statistical Activity Cost Analysis (SACA) is used to identify the interaction of mutually dependent physical and financial aspects of a fixed asset-like system configuration. The novelty of the approach is, having established a rational description of the uncertainty inherent in both domains, the analysis of their interaction. Little research to date has investigated the duality of engineering and accounting aspects, in a statistical setting. Our approach is conceptual rather than empirical. We use an illustrative 4-component model, a) to explain the concept of SACA by means of a software demonstration tool, b) to relate financial issues of cost to engineering asset capacity to perform specified tasks, and c) to demonstrate how to produce quantified measures of return and

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risk, both of which are relevant in areas of life-cycle analysis, budgeting and planning decision-making.

Keywords Statistical Activity Cost Analysis, Dualism Reliability-Cost, Uncertainty, Risk an Return, Financial and Physical Relationships

1 Introduction

The motivation for the research upon which this paper is based is to scientifically model the linkages between economic and physical processes. This is necessary to enable us to relate engineering decisions regarding the management of physical assets to financial consequences in terms of return and risk. It is also necessary to understand how financial decisions effect physical asset capacity to perform specific tasks.

Little research to date has investigated the effects of cost uncertainty and its variation in conjunction with the physical operation of fixed assets. The ability to identify sources of uncertainty, which require more attention than others and the quantification of the risk in areas of planning, budgeting or life-cycle analyses, facilitate better decision-making. In this paper we advocate that the cost variable in engineering models needs to be a random variable to achieve this goal. Observed costs in invoices or transaction's data give us realisations of this random variable.

In accounting, a rational framework which provides such an interpretation of costs is Statistical Activity Cost Analysis (SACA) due to Willett (1987, 1988, 1991) and extended by Gibbins & Willett (1997) and Falta & Wolff (2004). To date, applications of this framework to aspects of reliability theory, maintenance or life-cycle analysis have been limited (Falta, 2005).

From the perspective of engineering, physical aspects of assets described by concepts of reliability and maintenance are well-understood (*e.g.*, Kumar, Crocker, Knezevic & El-Haram, 2000). However, the literature that considers the uncertainty of cost and physical asset properties *jointly* is more sparse. Most literature in engineering and operations research assumes costs are a directly observable, and in this sense, deterministic attributes of maintenance, production or usage processes. Compare, for example, an optimisation procedure for costs and safety considerations on component systems (Vaurio, 1995), statistical life-cycle cost analyses (*e.g.*, Jiang, Zhang & Ji, 2003; Monga & Zuo, 2001), literature that targets specific assets such as water mains (*e.g.* Engelhardt, Skipworth, Savic, Saul & Walters, 2000), costs, efficiency and environmental implications of gas pipelines (*e.g.*, Bergerson & Lave, 2005) or railway maintenance (*e.g.*, Lamson, Hastings & Willis, 1983). In the operations research literature, costs of physical aspects of assets have been investigated, for example, in relation to software reliability (Pham, 2003), machine replacement decisions (*e.g.*, Dogramaci & Fraiman, 2004), policy-making for replacement or standby decisions (*e.g.*, Hsieh, 2005).

Common to the above literature is the lack of a simple generic model that relates physical characteristics to the uncertainty and variation of corresponding costs that result from dependencies in the physical and financial dimensions of process. Using the principal *representation theorem* of SACA, which explicitly superimposes the financial structure of business processes on the input-output relationships of activities in the physical structure, costs can be modelled as *random sums of random variables*. This lays the basis for a comprehensive analysis of the financial risk involved in engineering processes.

In Section 2 of this paper we employ some fundamental concepts of the SACA framework, based on ideas given in Vaurio (1995), in a system of four components that are in a series constellation. Our focus in this section lies with the demonstration of these theoretical concepts by means of the *SACA Concept Demonstrator*. We conclude in Section 3 with some brief final remarks.

2 The SACA Concept Demonstrator

We have developed an illustrative software tool called the SACA Concept Demonstrator in order to better visualise the capabilities of the SACA approach to relate costs to engineering asset capability[4]. Let, for example, an asset have four components functioning in series with their failure characteristics described by exponential time-to-failure distributions with parameters λ_i, $i = 1,\ldots,4$, for each component i. After each maintenance operation on a component with expected cost C_i let the system be as-good-as-new and the MTTF (Mean Time To Failure) be $1/\lambda_i$.

For this simple hierarchical system, the SACA Concept Demonstrator is applied to two scenarios in the first of which we minimise the maintenance costs given an *a priori* minimum reliability level. In the second scenario we maximise the reliability of the system, given a budget.

2.1 Scenario 1: Cost Minimisation with Set System Reliability R_{min}

Assume that maintenance operations on a component i may be carried out at any time within the time interval s, that is with no restriction on availabilities of personal or dockings, and at any frequency f_i. The f_i's are the number of maintenance

[4] Asset capability is a somewhat general expression and refers to an asset's ability to perform certain tasks. We use the reliability function to describe engineering asset capability, the physical condition of an asset.

windows to be equidistantly scheduled during a time period or year. Then the total cost of maintaining the system over a single interval s is

$$C_s = \sum_i \frac{C_i}{f_i} \tag{1}$$

We achieve minimum costs C_s, considering for the system reliability $R_s \geq R_{\min}$, by optimising f_i in Expression (1). Using the method of Lagrange multipliers and after some calculus (cf. Appendix A) yields an explicit expression for f_i in terms of λ_i, C_i and $R_{\min}$,

$$f_i = -\left(\frac{C_i}{\lambda_i}\right)^{1/2} \cdot \frac{\ln\{R_{\min}\}}{\sum_i (\lambda_i C_i)^{1/2}} \tag{2}$$

In Table 1, we have displayed the results from a simulation study with $R_{\min} = 0.97$. The overall minimum cost is $C_s = \$2187.28$ (sum of Column (6)). Using Microsoft Excel's Solver function for the same optimisation problem yields for $C_s = \$\,3606$, 39 % higher than the cost calculated by the present method.

In the SACA Concept Demonstrator, the expected maintenance cost and its variance, assuming the Normal as the underlying distribution, for each component can be altered and so can the MTTF parameters, assuming exponential reliability functions. In practical applications, both cost parameters can be either estimated from observed data in form of invoices or transaction statements or fitted by theoretical distribution functions. A starting value for the MTTF parameters is usually provided by the manufacturer which, if feasible, can be later adjusted by the operator.

For each setting of expected maintenance costs and MTTFs of the system, the SACA Concept Demonstrator calculates the optimal number of maintenance operations per interval (rounded-up numbers) at minimum costs with a reliability threshold of 0.95. The calculations are performed according to Expression (2) and the results in the SACA Concept Demonstrator are displayed according to single

Table 1 Simulation Outputs. Results from simulation for a four component system in series for given maintenance costs C_i, parameters λ_i and minimum system reliability $R_{\min} = 0.95$. Results from using Expression (2) yield maintenance frequencies f_i, the number of maintenance operations per interval and respective total maintenance costs per component, and the (minimum) component reliabilities.

(1) Component	(2) C_i	(3) λ_i	(4) f_i	(5) # Maintenance Operations	(6) Total Costs	(7) Reliability
1	\$10	0.1	0.03732	26.7974	\$267.97	0.9963
2	\$20	0.2	0.03732	26.7974	\$535.95	0.9926
3	\$10	0.4	0.01876	53.5948	\$535.95	0.9926
4	\$20	0.5	0.02360	42.3704	847.41	0.9883

Table 2 SACA Concept Demonstrator Output. Results from variations of parameter settings of expected maintenance costs and MTTFs of single components. The results are displayed in the following form: component 1/component 2/component 3/component 4.

Expected Maintenance Costs [$]	MTTFs [month]	Optimal Maintenance Frequency f_i at $R_{\min} = 0.95$
20/20/20/20	8/13/6/8	10/8/11/10
20/20/20/20	8/14/6/8	10/7/11/10
20/20/20/20	8/15/6/8	9/7/11/9
26/18/37/20	8/9/6/8	10/11/10/11
26/18/41/20	8/9/6/8	10/11/9/11
26/18/45/20	8/9/6/8	10/12/9/12

lines in Table 2. Note that due to the character of Expression (2), the MTTF of one component is reciprocally correlated with the f_is of every other component but positively with its own f_i. Thus, increasing, for example, λ_2 and maintaining constant expected costs for all components might change f_1, the number of maintenance operations for component 1. Compare Table 2, Rows 2 to 4 for this example. Similarly, because the expected maintenance cost C_i of one component is negatively correlated with the expected costs of all other components for constant MTTFs, increasing C_3, for example, may increase f_i, $i = 1,2,4$, with respect to the other components while decreasing f_3, the number of maintenance operations performed on the component itself. Compare Table 2, Rows 5 to 7 for this example.

2.2 *Scenario 2: Reliability Maximisation with a Set Budget*

In the second scenario, we use the same four component system as above, however, with a given fixed budget B. It is now of interest as to how one should allocate the maintenance frequencies in order to derive the highest possible reliability.

Expression (1) becomes

$$C_s = \sum_i \frac{C_i}{f_i} - B, \tag{3}$$

and we derive the optimal maintenance frequencies according to

$$f_i = -\left(\frac{C_i}{\lambda_i}\right)^{1/2} \cdot \frac{\sum_i (\lambda_i C_i)^{1/2}}{B}. \tag{4}$$

Details of the derivation of Expression (4) are given in Appendix B.

In Table 3, some results from simulation are displayed for a budget of $ 1500. The maintenance frequencies that give the budget at maximum reliability are derived in the first column of the table. Note that the product of all component reliabilities has decreased to 0.9565.

Table 3 Simulation Outputs. Maintenance frequencies that yield maximum system reliability, given a fixed budget on maintenance.

(1) Optimal Maintenance Frequency f_i	(2) # Maintenance Operations per Interval	(3) Costs	(4) Reliability
0.054415	18.38	$183.77	0.994573
0.054415	18.38	$367.54	0.989176
0.027208	36.75	$367.54	0.989176
0.034415	29.06	$581.14	0.98294

2.3 *The SACA Concept Demonstrator Displays*

2.3.1 Reliability vs. Cost

From the above calculations, it is straightforward to plot a curve for the total cost C_s at any level of reliability. This curve is the dark, continuous line displayed in Figure 1. The impact of an increase in expected maintenance costs for single components increases with increased reliability, as would be expected (cf. left and right panel in Figure 1). In the left panel, the expected maintenance cost for components 1 to 4 are $15, $20, $12 and $39, and in the right panel, $26, $20, $19 and $39, respectively.

The scatter around the reliability versus cost curve derives from the variation in maintenance costs, a parameter that can be varied. In Figure 1, the cost over and underruns are displayed by single dots at each reliability level for a given set of

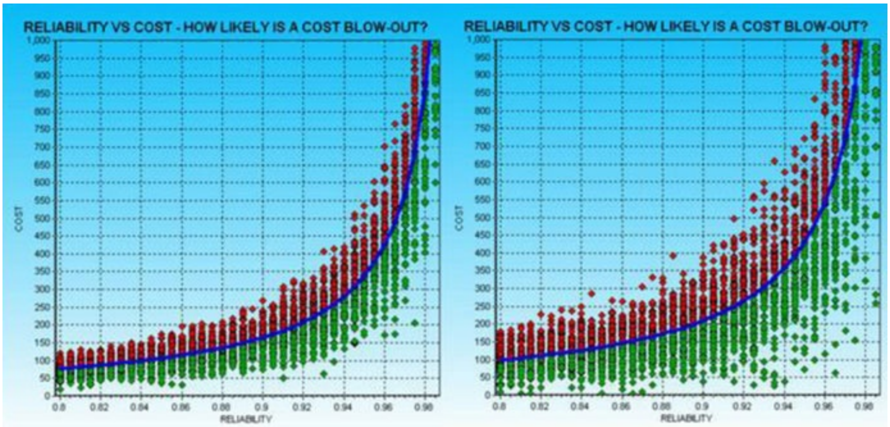

Figure 1 Printed screens from the SACA Concept Demonstrator. Curves for reliability level versus total maintenance costs (dark, continuous line). The scatter around the curve results from the variance of maintenance costs and can be used as an indicator of the risk for cost overruns (above the line) or cost savings (below the line)

variances of maintenance costs. Notice that the increase in spread in the right plot of the figure, which is due to an increase from \$6 to \$12 of the variance of maintenance costs of component 1, is rather sensitive. All other parameters remained constant.

In practice, it is usual that the quality of estimates for maintenance and repair costs varies, for some are robust and others more vague. Therefore, visualisation and quantification of the likely cost overruns will be of utmost importance for the decision-maker.

2.3.2 Risk Attribution

The functionality for risk attribution is displayed on the top panel of Figure 2. The pie charts display the percentage contribution of single components to achieve the stated budget at a confidence level of 95 % and given reliability.

Thus, the decision-maker is able to assess the source of risk and quantify it. The parameter settings for the left pie chart are, for components 1 to 4, expected maintenance costs of \$15, \$20, \$12 and \$30; variances of \$6, \$15, \$8, and \$10; MTTF parameters of 8, 21, 12, and 44 months; and calculated numbers of maintenance operations of 7, 4, 7 and 2, respectively. The difference in the pie charts results from an increase (\$6 to \$12) of the variance of maintenance costs of component 1. The increase in variability of this component has not changed the optimal number of maintenance operations. However, the impact on numbers in the pie chart is significant: to guarantee, at a 95 % level of confidence, that reliability remains above 0.95, a budget of \$365.07 has to be invested as opposed to \$323.88, as displayed in the left top panel. For this 12.72 % increase in the budget necessary to maintain the reliability of the system, all the additional resources are consumed by component 1 (\$290.09 instead of \$200.83) and is accompanied by an increase in uncertainty from 28.61 % to 36.67 %. The costs of components other than component 1 remain constant with their percentage uncertainty decreasing.

2.3.3 Quarterly Budgets

In the bottom panel of Figure 2, the quarterly upper 95 % confidence limits are displayed (dark bars on the right of the light bars) for identical parameter settings as shown in the pie charts. The four graphs on the left bottom panels correspond to the pie chart in the top left panel. The same pattern applies to the right side of the figure. Note the different scaling of the abscissae. The varying numbers for the quarterly risk thresholds result from assigning the given numbers of optimal maintenance operations N_i, $i = 1,\ldots,4$, as follows: the numbers N_i are distributed across the interval (year) at equidistant durations.

This display holds two different pieces of information for the decision-maker. Firstly, for every single period the risk of cost overruns is displayed. In organisations where budget allocations across divisions or projects are a matter of reality, the funds receiving party is able to demonstrate, on a rational basis, the adequateness of any amount allocated. Secondly, the series of amounts at the confidence limit sheds light into the time series of maintenance costs. Actual maintenance costs correct the estimates for passed time intervals and update the estimates for future time intervals. The latter point, including to account for other time intervals than quarterly periods, leads to the world of time series and financial option analysis, which we leave for future research.

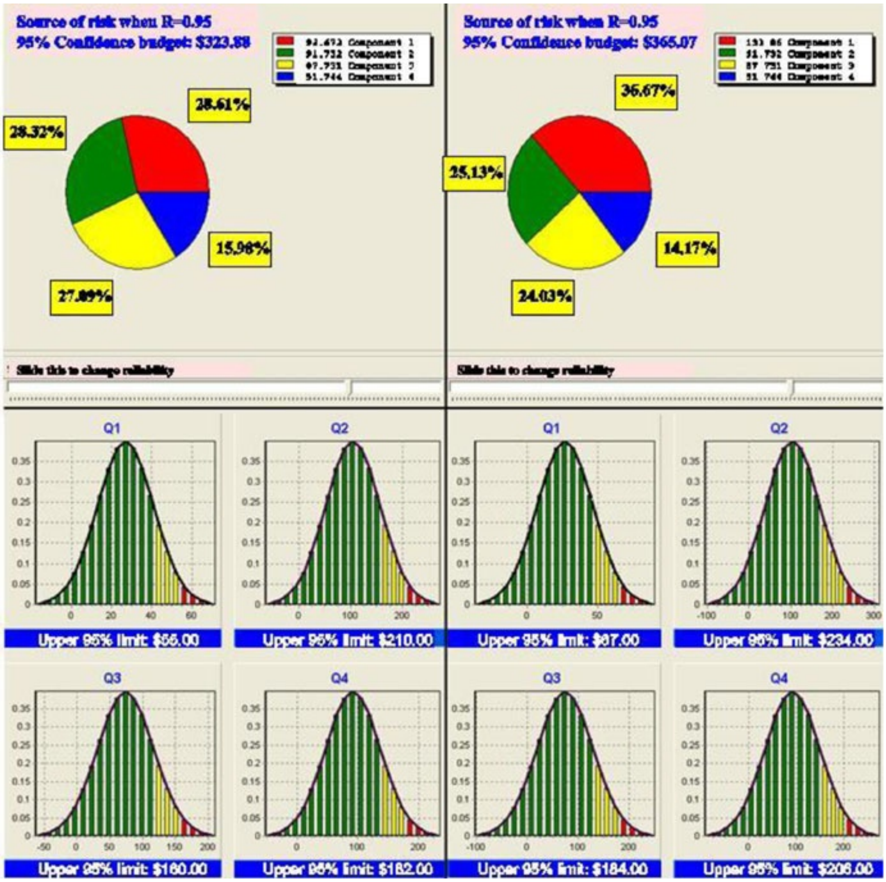

Figure 2 Printed screens from the SACA Concept Demonstrator. *Top panel*: the calculated budget is based on the optimal number of maintenance operations for a given set of simulation parameters. The pie charts display the source of cost uncertainty from each component in order to achieve that budget at a 95 % confidence level for a given level of reliability. An increase in the cost variability of component 1 from $6 to $12 increases the necessary budget to guarantee the given reliability at the 0.95 level. *Bottom panel*: quarterly upper 95 % limits corresponding to the pie charts in the same column above. Numbers that add up to the total number of optimal maintenance operations for each component have been assigned to each quarter according to the simple rule described in the text.

2.4 Comments on the SACA Concept Demonstrator

We have demonstrated how the SACA framework can be applied to the financial assessment of a physical system and, in particular, how the cost variations can be expressed by statistical distributions. We have furthermore demonstrated how the results can be used by the decision-maker for maintenance scheduling and budget planning.

The underlying model can be extended in various directions. Below we have listed and elaborated on some of these.

1. The assumption that maintenance may be carried out at any time of the year and at any frequency is a limitation when considering practical applications. Usually there are scheduled maintenance windows or maintenance opportunities at discrete time intervals of set durations. It is a matter of choice whether these constraints should drive the simulation, or whether the results of such simulations should be used to modify the time and frequency of operations.
2. To improve realism, should this tool be further developed in order to be useful for practice decision-making, various further concepts may be considered. This would include, considering financial aspects, opportunity and unavailability costs, or costs for environmental and safety aspects. The SACA modelling approach can easily accommodate these. Physical aspects are discussed below so are the reasonable constraints that may be imposed on boundary values (maximum or minimum) for the variables considered.
3. Greater detail in the analysis of the cost-reliability relationship can be achieved by allowing for the general *k*-out-of-*n* parallel and series systems. Our choice to consider exponential time-to-failure distributions is based on the following. The illustrative 4-component model can be viewed as a reduced representation of a more complex reliability block diagram.
4. It is usually the case that the larger the number of components and actors in an entity the larger the number of failure modes, and as a consequence the more random and unpredictable the times of failure. The exponential time-to-failure distribution models this type of situation because it implies a Poisson distribution for the number of failures during equal time intervals. For empirical evidence we refer to, for example, Davis (1952) who concluded that "the exponential theory of failure appears to describe most of the systems examined [in the article]". Any other time-to-failure distribution such as the Weibull distribution, a popular choice among engineering practitioners, may be chosen if it is appropriate to do so. A further remark on this topic is given in Point 5.
5. The lower bound used on reliability levels in the model assumes that all components are functioning at their lowest reliability, even if a maintenance operation has just been performed. A time-dependent reliability function can describe a more refined physical description of the system.
6. The resulting cost *vs.* reliability curve displayed in Figure 1 is continuous and represents the expected costs. This curve can be seen as the effective frontier,

a concept used in portfolio analyses, as arbitrarily higher amounts of dollar may be spent on the maintenance of a component without improving the total system reliability, at any level.

7. For other distributions that describe the component reliability, particularly those with more complex forms such as those with a bath-tub shape, numerical simulations might be the first choice for parameter estimates.

3 Final Remarks

We have used a simple four component system in order to demonstrate new concepts in the field of accountancy. Invoices of maintenance operations are modelled using statistical distributions, which describe the uncertainty of varying costs incurred by businesses. For some of the components expected costs can be determined quite accurately from prior experience, others have to be estimated from observed data. The variation resulting from the former suppositions and latter estimates contributes to the overall risk of budget overruns. With the SACA Concept Demonstrator, a simple module with a graphical user interface, implements the methods described in the paper. In doing this and in further developments, we intend to bridge the fields of accountancy (finance), reliability theory (physical) and maintenance (policy) to improve fixed asset management.

Of the limitations in the model, of most immediate concern to us are the need to extend the physical model to *k*-out-of-*n* parallel redundant systems and to use observed data, which necessitates the use of reliability distributions that describe actual component behaviour.

This paper illustrates the applicability of the SACA framework to an assessment of the return and risk linkages between decisions regarding physical asset properties and financial outcomes, *and* between financial decisions and physical outcomes. The framework can be applied to any asset and typically requires information to be extracted from both accounting and physical asset management systems. At the present time this approach to modelling is being applied to assets of the Royal Australian Navy as part of the Logistics Cost of Ownership initiative of the Australian DMO (Defence Materiel Organisation). It has also applied in the Australian food processing and utilities industry.

Appendix A

For a series system, consider constraint

$$R_{\min} \leq R_s = \prod_i R_i = \prod_i \exp\left(-\lambda_i T_i\right) \tag{A1}$$

Since $T_i \geq 1/f_i$ a lower bound on each component's reliability is given by $R_i \geq \exp(-\lambda_i f_i)$ and Expression (A1) is violated if

$$R_{\min} > \prod_i \exp(-\lambda_i f_i) \tag{A2}$$

implying that

$$\ln\{R_{\min}\} > -\sum_i (\lambda_i f_i). \tag{A3}$$

Note that Expression (A3) is unnecessarily strong since it assumes that the lowest component reliabilities will always hold.

Expressions (1) and (A3) together form a constrained optimisation system which we solve using Lagrangian multipliers. Thus, combining constraint and target expressions respectively as

$$f_c(f_i) = \sum_i \lambda_i f_i + \ln\{R_{\min}\} = 0 \tag{A4}$$

$$f_t(f_i) = \sum_i \frac{C_i}{f_i}, \tag{A5}$$

so that

$$\frac{\partial f_c}{\partial f_i} = \lambda_i \quad \text{and} \quad \frac{\partial f_t}{\partial f_i} = -\frac{C_i}{f_i^2}. \tag{A6}$$

The solution to

$$\frac{\partial f_t}{\partial f_i} + \hat{L}\frac{\partial f_c}{\partial f_i} = 0 \tag{A7}$$

is an extremum of the function f_t subject to the constraint $f_c = 0$, where $\hat{L}$ is a Lagrange multiplier. We can therefore reformulate this problem by writing

$$\frac{C_i}{f_i^2} = \hat{L}\lambda_i. \tag{A8}$$

The system of equations in $n+1$ unknowns represented by Expressions (A4) and (A8) is solved by substituting the implied Expression for f_i in (A8) back into (A4) yielding

$$\sum_i f_i \left(\frac{\lambda_i C_i}{\hat{L}}\right)^{1/2} + \ln\{R_{\min}\} = 0 \tag{A9}$$

which gives

$$\hat{L} = \left(\frac{\sum_i \lambda_i C_i}{-\ln\{R_{\min}\}}\right)^2. \tag{A10}$$

Substituting the last expression into (A8) yields Expression (2) of Section 2.1.

Appendix B

Similar to Expressions (A4) and (A5) we have functional forms for constraint and target, respectively,

$$f_c(f_i) = \sum_i \frac{C_i}{f_i} - B = 0 \quad \text{and} \quad f_t(f_i) = \sum_i \lambda_i C_i . \tag{B1}$$

Thus,

$$\frac{\partial f_t}{\partial f_i} = \lambda_i \quad \text{and} \quad \frac{\partial f_c}{\partial f_i} = -\frac{C_i}{f_i^2} \tag{B2}$$

and we solve the expression

$$\lambda_i = \hat{L} \frac{C_i}{f_i^2} \tag{B3}$$

which, substituting for f_i back into the first equation of Expression (B1) yields

$$B = \sum_i \left(\frac{\lambda_i C_i}{\hat{L}} \right)^{1/2} . \tag{B4}$$

Substituting the resulting value of $\hat{L}$ into Expression (B3) yields Expression (4) of Section 2.2.

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Capacity Investment Planning Based on Real Options

Tony J. Rosqvist

Abstract Capacity management of a plant in capital-intensive industries is a challenging task: volatile markets, aging and deteriorating equipment and a competitive environment raise challenges for capacity management. Essentially, capacity management is decision-making under uncertainty at the plant-level. Risk-informed, dynamic, capacity management is a prerequisite for achieving optimal capacity in a production plant. One way to deal with uncertainty is the active management of real options. Investment portfolios consisting of real options provide opportunistic value in capacity investment decision-making. A framework for the specification, evaluation and exercising of real options is presented for capacity managers. The analysis is based on a decision cycle which is temporally divided into two market outlook periods. The first market outlook period represents the current, emerging market situation for which real options, planned in the previous decision cycle, may be exercised, thus optimising production capacity according to current demand. The second period represents an uncertain production environment for which real options can be planned, based on demand & supply forecasts. The decision cycles repeat, each entailing planning, evaluation and exercising of real options included in the investment portfolio. The framework supports the computation of the probability distribution of profits coupled with alternative investment portfolios. The paper introduces a straightforward way of adopting options theory in the context of real options in capacity management.

Keywords Capacity analysis, Capacity management, Capacity investment, Flexible manufacturing, Real options

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1 Introduction

Asset management of a production plant includes outsourcing, investments and capacity management as described in Komonen *et al.* (2006). *Real options* represent one means among others for achieving optimal production performance. In particular, real options represent an asset management tool exploiting the value of any flexibility inherent in the technological and operational traits of the plant. Ramezani (2003) demonstrates how managerial flexibility and the underlying uncertainty in investment decision-making increases the value of real options. He also categorizes companies in terms of the value of real options for managing (physical) assets and conjectures that companies relying on prospective research make the most of utilising real options. Consequently, any company engaged in a dynamic, uncertain, business, could gain from real option thinking.

The use of real options in capacity management has to be tied to investment portfolio management. Basically, real options are distinct investment projects that can be aborted, deferred or continued, depending on the changing business environment, or strategic choices in general.

Nowadays, more than 100 documented portfolio selection methods can be found. Investment portfolio management process models have usually four distinct stages: 1) strategic considerations, 2) individual project evaluation, 3) portfolio selection, and 4) stage/gate evaluation. An investment portfolio management process comprising all these stages is shown in Figure 1, and is based on Martikainen (2002) and Archer and Ghasemzadeh (1999).

The investment management process model is general in the sense that all types of investments are subjected to similar analytic phases. An interesting point worth noting is the Gate stage that implies a decision option whether to stop or continue with the investment plan. This feature is further explored in the paper by taking into account the basic set of real options discussed in Trigeorgis (1996) and Yeo & Qiu (2003): Option to defer, Staging option, Option to alter operating scale, Option to switch (input/output), Growth option (product, process, knowledge extension) and a Sourcing option (change of business model). These provide a more nuanced and structured approach to investment decision-making. A good review of real options in the context of manufacturing flexibility is found in Bengtsson

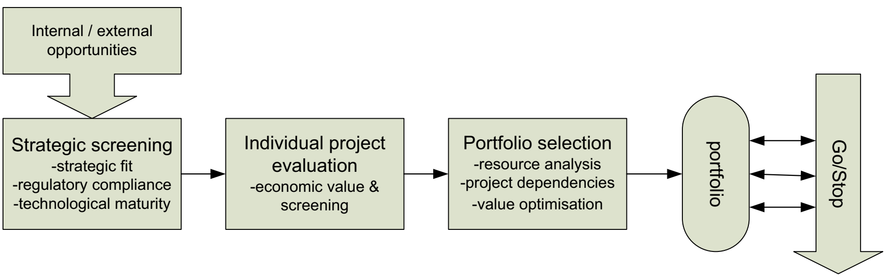


Figure 1 Phases of the investment management

(2001), which adopts the flexibility types defined by Sethi and Sethi (1990) as the starting point for the classification of real options. For the purpose of the paper, however, it suffices to follow the definitions of Trigeorgis (1996).

The *valuing* of investment portfolios, based on real options, is not as straightforward a task as traditional Life Cycle Cost assessment (Fabrycky and Blanchard, 1991). Traditional Net Present Value (NPV) – methods give a bottom line which has to be adjusted upwards according to the effect of exercised real options that have been planned beforehand as i) safeguards against unfavourable events in the market, or ii) a means to seize emerging opportunities in the market. Figure 2 shows the effect of active management of an investment portfolio including real options compared to the NPV of a passively managed portfolio as assumed in traditional LCC assessments. Due to uncertainties in prediction, the NPV has to be given in the form of a probability distribution P_{NPV}.

An extensive study on the added value of flexible investment decisions is Keswani and Shackleton (2006) in the case of a two-staged decision cycle. A generalization to multi-stage investments is presented in Fontes (2008), where the decision and state space is modelled as a binomial lattice and dynamic programming is used for calculating the portfolio value. A dynamic programming approach is also described by Kulatilaka (1988) where investment decision rules are valued in order to find out optimal switching rules (optimal use of process and product flexibilities) under stochastic price dynamics. A comprehensive review of methods for real option analysis is found in Miller and Park (2002), where the need for developing analytic methods and tools for production managers is advocated.

A typical factor leading to complex real option analysis is the modelling of linked decisions in multiple stages under stochastic exogeneous demand and price processes. The decision model becomes hard to specify for practical purposes due to the large number of parameter to be estimated. Also the typical way of modelling uncertainty by diffusion models can be criticized: the most severe uncertainties of a production plant relate to strategic risks which are usually surprises (technological, market, *etc.*) and are beyond the realm of probabilistic modelling.

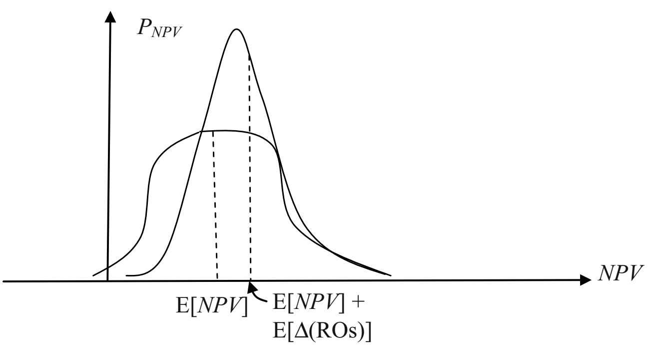


Figure 2 The added value Δ (ROs) and its expected value E[Δ (ROs)] related to the active management of real options (ROs) in the investment portfolio, in comparison with the expected Net Present Value (NPV) of a portfolio where projects are assumed to be fixed

Thus, the first assumptions for rendering a real option analysis for *capacity management* is reducing the number of decision stages to two, reflecting short- and long-term.

Thus, there is a need for a more simple way of applying real option theory, if the theory is to find its way to real investment problems related to manufacturing systems. We will focus on capacity management problems in the following.

This paper presents an *application method* for analyzing real options in which the decision cycle is two-staged, representing the current and the following capacity planning period, and where the demand is modelled using a simple demand model for order rate and order size for a one- or multi-product production system. Monte Carlo simulation is used for computing the added value of real options that are included in investment portfolios.

The paper is organised as follows: In Section 2, definitions of capacity and real options are provided and a two-period decision cycle for the planning and evaluation of real options is described. Section 3 presents the approach in detail; the required initial information and the quantitative parameters, the computational method for evaluation, and the output formats of the evaluation results. Section 4 presents a worked example that is based on a real capacity management problem of a plywood mill in Finland. Section 5 concludes the paper with a summary.

2 Capacity Investment Based on Real Options

2.1 Definitions of Capacity

The production capacity of a production system (*e.g.* machine, factory) is its ability to produce goods according to demand. In production and operations management, three types of capacity are often referred to:

Potential Capacity: The flexibility of the production system in terms of inherent technology and operations allows capacity management to mobilise additional capacity with minor modifications and changes in operations. Mobilisation of potential capacity is seen in the increase of either immediate capacity or effective capacity, or both.

Immediate Capacity: The amount of production capacity that can be made available in the short-term (‘everything is running’). This is the maximum productive capacity achievable by current operational procedures, *i.e.* the capacity that can be made available with 100 % Overall Equipment Effectiveness (OEE). By operational and reliability control this goal can be pursued, but, in practice, will never be achieved for long periods.

Effective Capacity: Not all immediate capacity is actually used or usable due to OEE losses (see http://www.oee.com/oee_six_big_losses.html) and planned outages. It is important for production management to identify means to increase the effective capacity (at least within the bounds of immediate capacity).

In general, capacity, being the *ability to produce work in a given time*, is measured in the unit of work. For example, consider a plant that has a capacity of 1,000 'machine hours' every week. Suppose the weekly operative hours are 40 mh. The actual volume of product or specific product mix that the factory can produce will depend on:

- the amount of work involved in production (*e.g.* product A requires 5 mh and product B 10 mh);
- any additional time required in production (*e.g.* machine set-up, maintenance) *i.e.* productivity or effectiveness of the plant.

As an example, assume that customer X wants products A and B in numbers of (10, 50) and customer Y in numbers of (20, 20), ordered at the same time with a delivery time of one week. Is the plant able to deliver these orders assuming that immediate capacity is as given in the above? A simple calculation shows that $(10+20)\times 5+(50+20)\times 10=850$ 'standard hours of work', and the answer is thus 'yes' under the assumption that we can run one week with immediate capacity. If not, further analysis is required with respect to OEE for that week.

In production management there are usually two potential constraints at the operational level – *time and capacity*. Time may be a constraint as a customer may have a required delivery date for the amount of goods. In this situation, the production managers often "plan backwards". They allocate production tasks backwards from the date of delivery to the latest start point. This production planning process reveals whether there is a) sufficient time to meet the production demands given the current effective capacity, and, if not, b) the amount of extra capacity needed in the short term.

2.2 Definitions of Real Options

The typology of real options may be summarized into seven main types (Yeo and Qiu, 2003; Trigeorgis, 1996) that are relevant for expanding the bandwidth of opportunity in business management. The role and examples of these options are listed in Table 1, with minor rewordings compared to the above references, together with an indication of relevance for the capacity manager (CM).

When a company is able to systematically consider and assess real options' individual and combined effects on production performance, it will be able to expand the bandwidth of opportunity without excessively increasing risks. Especially, real options embedded in structural investments (physical assets) are valuable, because they allow management to take rational, value-adding actions in

Table 1 Real option types and suitability for capacity management (CM)

Real option	Description	CM
Option to defer	An investment or project that can be postponed allows learning about technology and market developments. Also the stochastic nature of prices and demand make deferment options desirable before making a commitment. (This option is included in the staging option.)	(+)
Staging option	A series of outlays with check points in between allows for abandoning a project in midstream if new information turns out unfavourable for the project	+
Option to alter operating scale (scaling option)	If market outlook is more favourable than expected, the plant can expand the scale of production. Conversely, the scale of production can be reduced, or even halted	+
Option to switch input/output (switch option)	If prices or demand change, the output mix of the plant can be changed (production flexibility). Also, the same product mix may be produced using other inputs (process flexibility)	+
Growth option (product, process, knowledge extension)	An investment in R&D for (1) multiple product generations, (2) new generation products or processes, (3) acquisitions to enter new markets, (4) strategic core capabilities	–
Sourcing option (change of business model)	Utilisation of supply networks: *e.g.* outsourcing and subcontracting can transfer risk of in-house failure or avoid committing internal resources	–
Option to abandon	If market outlook is declining severely, management can abandon current operations and realise the salvage value of the production assets	–

terms of timing, scale, and scope, optimising the characteristics of the production system and capacity in accordance with observed changes in the business environment. It is, however, important to note, that for *options to have value, they must be carefully planned and collectively fit to foreseeable changes in the production environment*. As planning related to modification and improvement of the plant consumes man-hours, it is obvious that *every real option comes with a premium which should be factorized into the cost of the investment portfolio*.

2.3 Two-Period Investment Model: Planning and Decision-Making

The larger the uncertainties in the market and production environments, the greater is the value of planned real options in the investment portfolio. The planning of real options is divided into *two market outlook periods* (MOPs), where we consider the *current* market outlook period to be almost certainly known with capacity management ready to execute real options that can be exercised in the short-term. To be able to make more substantial changes in the capacity, planning of real options needs to be carried out during the current MOP for exercising in the *subsequent* period, according to an unfolding market outlook.

The division of the planning horizon into two periods reflects the strategic planning cycle in production plants: the current production period accompanied by the forward looking strategic planning for the next production period. What comes after the 'next period' is usually not considered relevant by the plant managers. One comment received by the author was: 'Thinking too far in the future may be just counterproductive – there will always be surprises that can change business more radically than ever imagined'. In the words of Sethi & Sethi (1990), forecast horizons, *i.e.*, the time period beyond which forecast of future data may not have significant impact on current decisions due to uncertainties, need to be specified. Thus, adopting a two-staged decision cycle, the exact time point between the 'current' and the 'subsequent' MOP is, in practice, arrived at when the planning of the real options associated with the long-term planning are ready to be exercised and decision-making related to 'Go/Kill/Defer' becomes relevant.

During the current MOP we will exercise those real options in the investment portfolio that best meet the current need of production, and concurrently start the planning of real options for the next MOP, based on demand and supply forecasts. The basic planning process, including the specification and evaluation of real options for inclusion in an investment portfolio, is always followed by decision-making in terms of exercising real options in the investment portfolio. This is shown in Figure 3a, b.

To be able to identify feasible real options to be included in the investment portfolio, results from market and capacity analysis should be available. Market analysis entails analyses of possible changes in customer habits, competition, *etc.*, as well as expert forecasts on the demand of the produced products for the next decision cycle. Market analysis gives the capacity manager information about possible capacity needs for a product or product mix. Based on the market analysis, a predictive model for product demand is specified (see next section).

Capacity analysis is a technical analysis of the potential capacity of the plant as well as the change of capacity as a function of operating time under the current maintenance program. Generally, OEE will decrease as a function of operating time if maintenance planning does not take into account the increasing need for preventive maintenance of aging equipment.

It is important to keep in mind that active management of real options in an investment portfolio is a continuous management task, where one decision cycle follows the previous one. In the following section we will focus on the specific analytic tasks related to the planning and decision-making phases of a decision cycle.

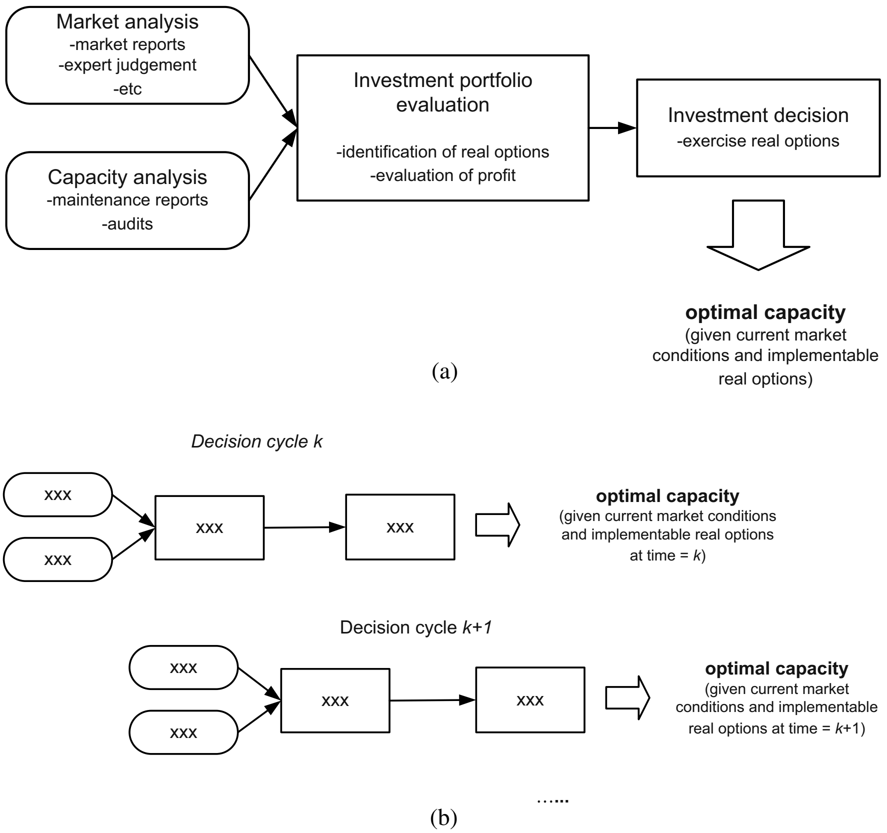


Figure 3 (a) The required analyses for defining real option in an investment portfolio: Market analysis provides information on future demand, whereas capacity analysis reveals the effective and potential capacities. Together this information gives ideas on what real options are justifiably prepared and included in the investment portfolio. (b) The framework adopts a two-period decision cycle, with the decision phases of exercising real options and planning of new ones appear with one period overlapping for the sequential decision cycles

3 Investment Portfolio Assessment

3.1 Specification of Feasible Real Option

The challenge for capacity managers is to balance the demands of product mix volumes and the production capacity of the plant; promising to deliver what cannot be delivered, with the risk of loosing customers, can be as devastating for business as retaining an excessive capacity capable of satisfying sudden peeks of demand, but with the penalty of high unit cost. Both scenarios may severely decrease profitability.

Flexible capacity control requires the managers from the sales, production and maintenance to set capacity requirements, identify real options and build project implementation preparedness continuously to be able to adjust to changes in demand and supply. We use the term *investment portfolio* to highlight the fact that the inclusion of real options in the portfolio permits different project implementation paths to be followed, according to the unfolding market situation, on one hand, and the system dependability (due to aging equipment), on the other.

Based on the market and the capacity analyses, feasible real options are identified and assessed in terms of cost and capacity performance (see Figure 3a). Factors that influence the latter quantities are organisational, as well as technical implications of adopting one or more real options. Such factors are work shifts, know-how of operators and maintenance personnel, the inherent flexibility of the production technology, technical fit of newly introduced technology, *etc.* Cost and performance estimates are subsequently needed in the valuation of the investment portfolio.

3.2 Evaluation of the Investment Portfolio

The evaluation is comparative in the sense that we will always have an investment portfolio consisting of the dummy real option RO0; ‘real option zero’ denoting that we have no real options in the investment portfolio. It is important to note that selecting “No extra investment” does not mean that the asset value and productivity will remain at the current level, due to the fact that equipment deteriorates by time, resulting in decreasing OEE, as demonstrated by the bathtub curve of aging equipment.

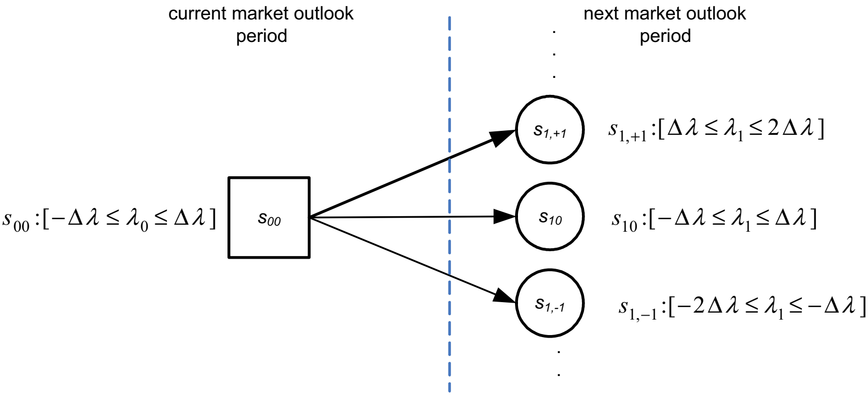
3.2.1 Predictive Model of Product Demand

The predictive model of the demand of a product is based on two variables: the overall rate of orders and the fractions of ‘volume’ & ‘delivery time’ (VxD)-order events on a predefined grid, specified for the two market outlook periods ‘current’ and ‘next’. The extension to product mixes is straightforward as each product will have its own VxD-grid. A relevant reference on the relationship between product mix and capacity is Hallgren and Olhager (2009). For simplicity, we will only discuss the single-product case.

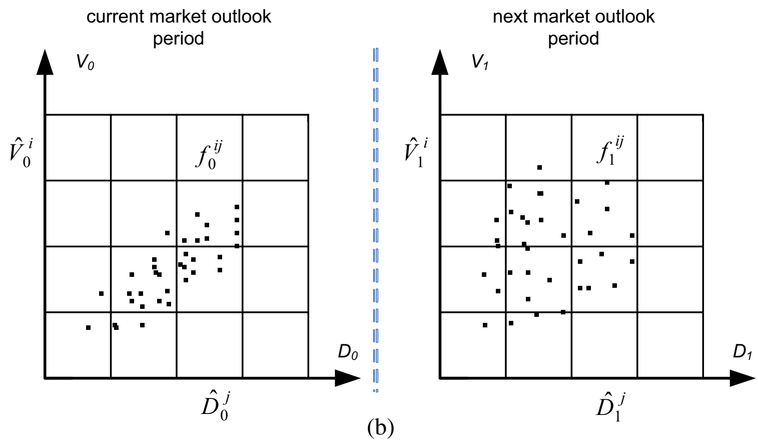
The uncertainty will be modelled in the following way: for the current MOP we know the rate of order to be within some range, whereas for the following MOP the range of the rate of order is uncertain. This is shown in Figure 4a.

Furthermore, there is uncertainty related to the order event in terms of volume and delivery time; and how these characteristics are distributed over a grid representing size groups and delivery time intervals. Uncertainty is depicted by the extent of spread of this distribution, as shown in Figure 4b, where uncertainty of the type of order is greater during current MOP compared to next MOP.

To define the uncertainty related to the rate of orders, states of rate of orders are specified, and their probabilities estimated (see Figure 4a). This entails the specification of a deviation parameter $\Delta\lambda$ of fixed length, and the states as adjacent value ranges of length $2\Delta\lambda$. The number of intervals should be such that all conceivable,



(a)



(b)

Figure 4 (a) Predictive model of demand: the rate of order of the current market outlook period is known within given bounds, whereas there is uncertainty at which level (state) it will settle during the next period. (b) Predictive model of demand: the distribution of orders in terms of volume and delivery time may be more uncertain for the next production or market outlook period in comparison with the current period. This uncertainty is shown by the greater spread in the distribution of orders over the 'volume and delivery time' (V x D-grid) but realistic, future rate of orders are covered. The specifications are based on expert judgement, in practice.

Similarly, expert judgement is required to assess the fractions of VxD events over the 'volume' and 'delivery time' grid (see Figure 4b). Uncertainty is illustrated by the distribution of outcomes over the grid: the relative number of outcomes, f^{ij}, is an estimate of the fraction of orders belonging to the order type represented by the grid element *ij*.

The frequency of orders for the current market outlook period (λ_0) can be assumed to be practically known, whereas for the subsequent period (λ_1) it is dependent on the current value.

3.2.2 The Quantitative Specification of Real Options

The quantitative information required for specifying a real option is shown by the influence diagram in Figure 5. The cost effect of a real option is both positive and negative. As discussed earlier, the positive effect is the better fit of capacity with respect to the emerging market situation, with increased productivity and profitability. The negative side is the sum of costs incurred by the planning of real options and the costs related to active projects (exercised real options) at different levels of completion.

It should be noted that possible abandoned projects are considered as sunk investments and thus not taken into account in the cost assessment. The cost variables in the investment portfolio are associated with the actively running projects and the planning effort of real options (= possible future projects).

The quantitative estimates in Figure 5 are obtained by a joint effort involving experts from sales, production, maintenance and management. The ability to give quantitative judgements is based on the knowledge on the flexibility of the production system *i.e.* the potential capacity.

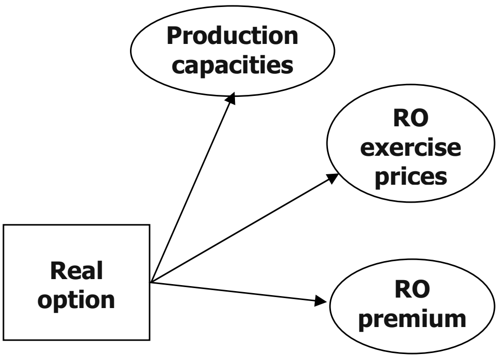


Figure 5 Influence diagram of cost and capacity variables related to a real options included in an investment portfolio

3.2.3 Evaluation of the Investment Portfolio

The evaluation of an investment portfolio is based on Monte Carlo (MC) simulation. MC simulation allows evaluation of individual real options as well as their combinations. The capacity investment assessment entails the following steps:

1. define market outlook scenarios qualitatively;
2. specify the predictive model of demand for each scenario;
3. specify real options to meet the capacity management challenges depicted by the scenarios;
4. simulate a time series of orders and sample their type based on the fractional distribution over the VxD-grid for a given scenario;
5. check the approvability of the orders against the backlog that is governed by the current production capacity: accept an order if there is free production capacity to meet the order, otherwise reject;
6. simulate to a time point when the current market outlook period ends (this is determined by the relevance and applicability of the real options in the investment portfolio);
7. for each investment portfolio, exercise real options singularly or in combination (based on pre-defined decision rules) – record the costs representing both the option premium (project planning costs) and the exercise price (project implementation costs);
8. check the approvability of the orders against the backlog now governed by the new production capacity: accept an order if there is free capacity to meet the order, otherwise reject – record the corresponding revenue;
9. simulate to a time point representing the end of the two-period decision cycle;
10. return to point iv) and select the next scenario;
11. after all the scenarios have been assessed compare the conditional distributions of the profits as computed for the investment portfolios.

The profit distributions are conditional on the market outlook scenario. If the scenarios are given occurrence probabilities, then we can compute the expected profit of each investment portfolio using the Law of Total Probability.

The above steps and the required input data for the MC-simulation are illustrated by the worked example in the section “Investment portfolio assessment”. The algorithm was implemented in Excel 5.0 with the AtRisk5.0 tool.

3.2.4 Limitations of the Evaluation Method

If real options are temporally dependent on each other (compound options), *i.e.* one real option is irrelevant if another real option has not been exercised before, then the described two-period assessment method has to be expanded to three-periods or more. The evaluation technique becomes much more technical and requires a suitable simulation tool. Such a tool should be embedded in a Decision Support System that would consist of market information, equipment reliability data, expert judgements and real option analysis techniques, as described in Kumar (1999).

4 Worked Example

The worked example is a modification of the example in Rosqvist *et al.* (2007). It is based on informal discussions with a plywood mill production development manager. The numbers presented are, however, fictitious.

A plywood mill produces several types of plywood products. The market for product Q is uncertain as one competitor is assumed to stop producing a similar product thus increasing the demand for Q (scenario A 'good'), but there are also rumours that a new product by another competitor will soon enter the market, changing the competitive position of the plywood mill (scenario C 'bad'). No new market entries and no withdrawals are also possible (scenario B). The probabilities for the scenarios A, B and C are judged to be 0.6, 0.3 and 0.1, respectively. Confronted with the above scenarios management is assumed to have one year to make plans regarding the possible changes in capacity demand.

Table 2 shows the current product and production characteristics needed in the evaluation of the investment portfolio. In the current market situation practically all that can be produced (according to effective capacity) will be sold.

Table 3 shows the specified feasible real options including the reference situation 'no options' that is used as a reference in the valuation of the real options. We note that the variables in Figure 5 have been addressed for each real option considered, *i.e.* a switch option and a scaling option.

Table 4 shows the real option content of two alternative investment portfolios that are evaluated. The investment portfolios have been for demonstrative purposes only. In practice, we would define one or two investment portfolios based on qualitative reasoning – screening out real options and their combinations that are not deemed feasible in the view of the defined market outlook scenarios.

Table 2 Product and production characteristics of product Q in the example

Characteristic	value	unit
Unit price	1	[k€]
Production time of Q	20	[machine hour]
Capacity of production line Q	50	[machine hours per week]

Table 3 Feasible real options in the example

Real option (RO)	Opportunity/hedge related to scenario	Capacity level/change to status quo	Option Premium (planning cost)	Exercise price (project cost)
RO 0: ‘status quo’ *i.e.* no additional investments	–	50 work hours	0 k€	0 k€
RO I: switch of capacity to other product with similar production characteristics, but unit price is 50 % lower	C	100 % switched to other product	10 k€	20 k€
RO II: scaling up of production capacity	A B maybe	+ 80 %	20 k€	40 k€

Table 4 Investment portfolios defined in the example

Real option	Investment portfolio (IP)		
	IP 0	IP 1	IP 2
RO 0	yes	yes	yes
RO I	no	yes	no
RO II	no	no	yes

Let us assume the following parameter values for the demand model (see Section 3.2):

$$\lambda_0 = 1$$

$$\Delta\lambda = 0.5\lambda_0$$

$$f_0^{11} = 0.4,\ f_0^{12} = 0.1,\ f_0^{21} = 0.3,\ f_0^{22} = 0.2$$
$$f_1^{11} = 0.4,\ f_1^{12} = 0.1,\ f_1^{21} = 0.3,\ f_1^{22} = 0.2$$

$$\hat{V}_0^1 = 2,\ \hat{V}_0^2 = 4,\ \hat{D}_0^1 = 1,\ \hat{D}_0^2 = 3$$
$$\hat{V}_1^1 = 2,\ \hat{V}_1^2 = 4,\ \hat{D}_1^1 = 1,\ \hat{D}_1^2 = 3$$

For the MC-simulation we need to specify the approximate market outlook time periods. Let the current period be 1 yr, and the next 2 yrs.

The real options are exercised according to the following simple decision rule that will reveal the effect of the real options on the profit:

1. if scenario A occurs, then exercise RO II if it is included in the investment portfolio – otherwise continue as usual;
2. if scenario B occurs, then exercise RO 0, *i.e.* continue as usual;
3. if scenario C occurs, then exercise RO I if it is included in the investment portfolio – otherwise continue as usual.

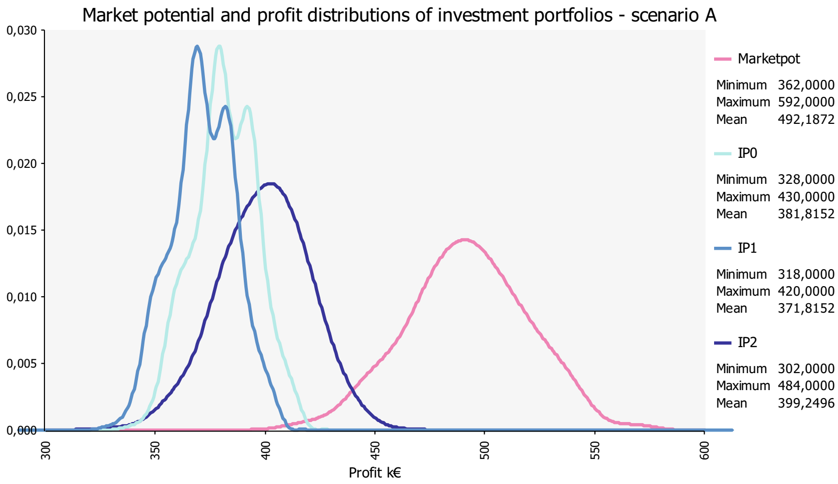
The MC results are displayed in Figures 6a–c. The 'Marketpot' lines shows the market potentials under the scenarios A, B and C, respectively. If capacity of production was inherently flexible without any limits, optimum capacity would track the demand exactly, and the uncertainty of profit would exactly follow the variability in the demand. As real options are coupled with finite discrete jumps in (effective) capacity, the profit distributions will reflect what can be achieved at best by exercising according to the decision rule.

It can be seen in Figure 6a that the investment portfolio 'IP 2' including the scaling option to increase capacity provides the best opportunity for higher profit in the case of the 'good' market outlook scenario A. IP2 has no hedging property and will therefore exhibit similar performance at the risky end of the market outcome. In scenario A, IP0 and IP1 perform similarly, the small difference determined by the option premium of the switch option in IP1.

In the case of scenario B in Figure 6b, the investment portfolio IP0 performs best, as should be expected as there are no market changes in this scenario. This is based on the assumption that the current capacity has been ensured by proper capacity investment in the previous decision cycle and is optimal also for the next period's demand levels which, in this scenario, is close to the current level.

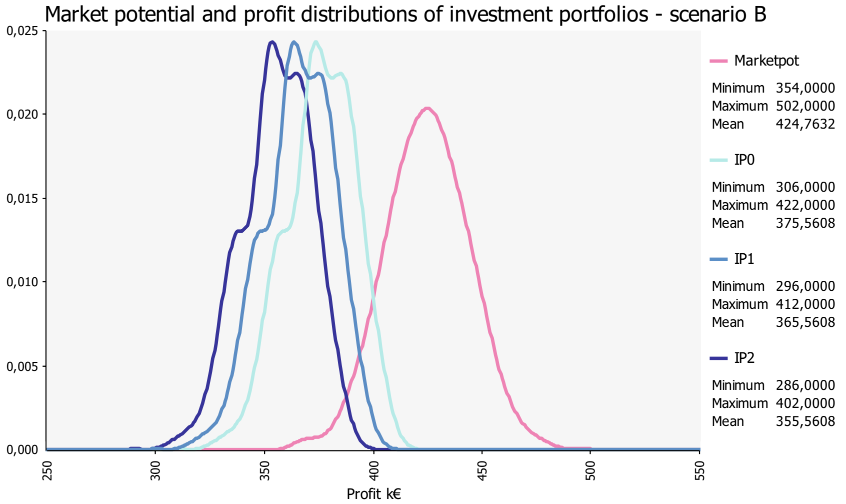
IP1 demonstrates the value of having a hedging option as shown in Figure 6c. IP1 outperforms the other IPs in the case of scenario C where the demand drops for product Q. The switch option can be exercised for increasing the capacity for another product for which the demand is not expected to fall in the next market outlook period.

Based on Figure 6 the inclusion of both RO I and RO II in the same investment portfolio would be the best solution as they can be exercised independently. These real options would together provide a hedging property as well as an opportunity-

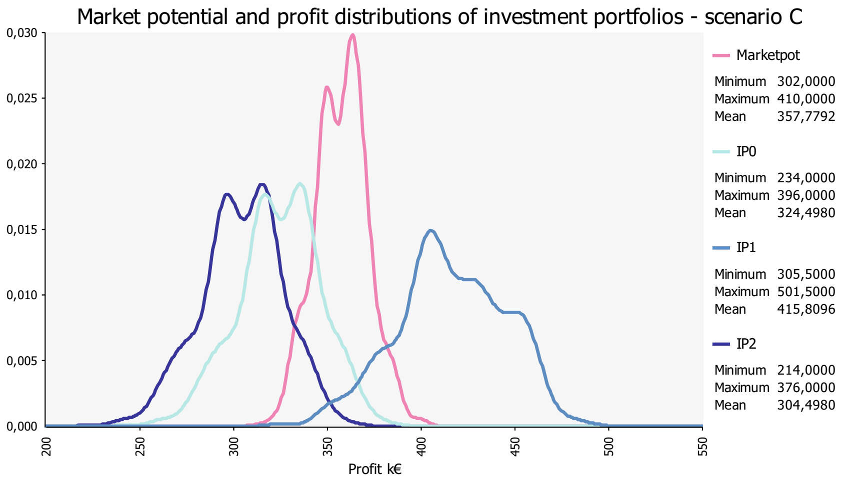


(a)

Figure 6 Simulated conditional profit distributions related to three investment portfolios for given market outlook scenarios: (a) scenario A 'market good'



(b)



(c)

Figure 6 Simulated conditional profit distributions related to three investment portfolios for given market outlook scenarios: (b) scenario B 'no market changes'; (c) scenario C 'market bad'

seizing property. (In the terminology of Trigeorgis [5], a multiple interacting option is a combination of a 'upward-potential-enhancing' option and a 'downward-protection' option).

In principle, we can compute the expected profit related to each IP by applying the Law of Total Probability in the case that the market outlook scenarios are assigned occurrence probabilities.

5 Discussion

In the above, the focus has been on developing a simple evaluation method of investment portfolios with real options for capacity management. Little has been said about the technology and knowledge underlying flexibility in manufacturing. Flexibility is partly inherent in the existing production system, partly contingent requiring some changes to be performed before it is utilizable. Exploiting this flexibility is never free and thus real options will always have a price. In this section, we will briefly review the basic types of manufacturing flexibility based on the notable paper by Sethi & Sethi (1990), and then link real options to these flexibilities, thus indicating that the evaluation method presented covers the particular flexibilities that are related to capacity management.

Of the above flexibilities, the expansion flexibility is related to the growing strategies of a company venturing into new markets and is thus more comprehensive than the other flexibilities focusing on the current market and its fluctuations. For more details on manufacturing flexibilities, and associated demands on the physical and human assets, the reader is referred to Sethi & Sethi (1990).

Table 5 Manufacturing flexibility with corresponding technology and knowledge requirements, as well as related real options (ScO = scaling option, SwO = switching option, StO = staging option)

Manufacturing flexibility	Technology and knowledge requirements	RO
Process flexibility *Process flexibility of a manufacturing system relates to the set of part types that the system can produce without major setups*	Material processing technologies and multiskilled workers handling fixtures and toolings into and out of the production system	SwO
Product flexibility *Product flexibility is the ease with which new parts can be added or substituted for existing parts*	Software modularity, part standardization, offline work station conversion skills, continuous learning programs for switching operation procedures	SwO
Routing flexibility *Routing flexibility of a manufacturing system is its ability to produce a part by alternate routes through the system*	Redundant, multipurpose equipment allowing work load balancing and load shifting in case of breakdowns, intimate knowledge of loading limitations and rerouting, work group cooperation	SwO
Volume flexibility *Volume flexibility of a manufacturing system is its ability to be operated profitably at different overall output levels*	Highly automated production system vs. multi-skilled labor for easy relocation (labor usually has higher adjustment costs than automation), subcontracting network	ScO
Expansion flexibility *Expansion flexibility of a manufacturing system is the ease with which its capacity and capability can be increased when needed*	Smart production system architecture, training programmes, focus on capability enhancement rather than just capacity enhancement	StO

6 Conclusions

The paper presents and demonstrates an application – oriented framework to specify, evaluate and decide on the 'Go'/'Kill/Defer' of investment (project) portfolios based on real options. Intuitively, the more real options we have in the investment portfolio, the more optimal capacity investments can be made in a volatile market, ensuring increased productivity and profitability. The context of applying real options is capacity management. The ultimate aim of the paper is to show that real options theory can be applied in a rather simple way for capacity management.

Basically, two properties of real options should be included in an investment portfolio for capacity management: one representing the opportunity to make greater profit, given that a favourable market situation is emerging; the other representing a hedge against losses in case of an unfavourable market situation.

The value of real options does not, however, come without costs *i.e.* option premiums that are essentially costs incurred by concrete project planning of the options. Moreover, exercising a real option incurs an additional project implementation cost, the exercise price.

The framework presented is based on

- two-period planning and exercising of real options in the investment portfolio (one decision cycle);
- expert panels for defining market outlook scenarios and investment portfolios including real options for hedging and seizing of opportunity;
- quantitative expert judgement on demand profile and rate of order;
- quantitative expert judgement on the effect of exercising of a real option with respect to production capacity (or capacities in the case of a product mix);
- quantitative expert judgement on the premiums (project planning costs) and exercise prices (project implementation costs) related to the real options;
- computation of the probability distribution of profit.

The approach is demonstrated in a worked example related to the capacity management of a plywood mill in Finland.

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Part IV
Scope (Asset Data and Condition Monitoring)

Business Rule Discovery Through Data Mining Methods

Jing Gao, Andy Koronios, Steve Kennett and Halina Scott

Abstract Engineering asset management processes rely heavily on input of data and also produce a large amount of data. Many asset management organisations need to manage their data for a long period of time (*e.g.* Water supply pipelines data will be kept for more than 100 years in utility companies). Due to the inability to access original data requirements and system design documentation, it is difficult for these organisations to redesign their asset management systems which often results in ongoing data quality problems. Our nation-wide data quality survey of 2500 Australian engineering management organisations and a pilot study have revealed that many of the data quality problems emanate from inconsistent applications of business rules that govern the behaviour of data (*e.g.* data management, data flow, system interactions and so on) within asset management information systems. Thus, this research will investigate the problems of business rule-based data and information integration from disparate sources in various forms found in asset management systems (*e.g.* Databases, Excel spreadsheets, *etc.*). This research aims at developing innovative methods to automatically discover undocumented business rules from disparate data sources and to use business rules for automated data integration in order to deliver quality asset data sets.

Keywords Data Quality, Business Rule and Discovery

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1 Introduction

Industry has recently put a strong emphasis on to the area of asset management (AM). In order for organisations to generate revenue they need to utilize assets in an effective and efficient way. Often the success of an enterprise depends largely on its ability to utilize assets efficiently. In other words, asset management is regarded as a set of business-capability building-processes within organisations. Thus, asset management has been regarded as an essential business process in many organisations, and is moving to the forefront of contributing to an organization's financial objectives. However, engineering asset management processes rely heavily on input of data and also produce a large amount of data during business operations. In many cases, the poor data quality resulted in severe impacts on asset management system performances – for example, an inability to determine the asset health status and predict the asset maintenance schedule.

Data Quality is becoming a critical issue for asset management. Modern organisations, both public and private, are continually generating large volumes of data. According to Steenstrup from Gartner Research (2005), each person on the planet generates an average of 250 Mbytes of data per annum, and this volume is doubling each year. At an organisational level, this results in incredibly large amounts of data, including structured and unstructured, enduring and temporal, content data, and an increasing amount of structural and discovery metadata.

Most organisations have far more data than they can possibly use; yet, at the same time, they do not have the quality data they really need (Levitan and Redman, 1998). Many information system studies indicate that the majority of the information systems contain substantial errors. Redman (1996) reports that organisational databases, with error rates up to 30 percent, are typical in industry. Klein, Goodhue and Davis (1997) indicate that mission-critical databases generally contain errors ranging from one percent to 10 percent. Similarly, the recent Australia-wide data quality survey (Gao *et al.*, 2006) has indicated that over 60 % of Australian public and private engineering management organisations have at least three different types of data quality problems (*e.g.* accuracy, completeness and consistency).

Therefore, it is believed that quality data sets will result in effective and efficient asset management. With this specific focus, this research investigated a new way to improve data quality by mining business rules from asset management systems log files. A pilot experiment was undertaken by using a web-based asset management system to demonstrate the possibility and potential values.

2 Research Problem and Importance

2.1 Relative Narrow Focus of the Current DQ Research

The field of data quality and data management has become an important and vibrant research domain. Numerous researchers have attempted to define data quality and to identify its dimensions (Kriebel, 1979; Ives, Olson, & Baroudi, 1983; Wang & Kon, 1993; Fox, Levitin & Redman, 1994; Wand & Wang, 1996; Wang & Strong, 1996; Shanks & Darke, 1998; Kahn, Strong & Wang, 2002).

Traditionally, data quality has been described from the perspective of accuracy. However, much of the research has indicated that data quality should be defined beyond simple accuracy, and they have identified it as encompassing multiple dimensions. In the literature, many authors have tried to explain the meaning of all relevant dimensions from several points of view (Strong, 1997; English, 1999; Ballou *et al.*, 1998; Orr, 1998). The four most frequently mentioned data quality dimensions in the literature are accuracy, completeness, timeliness and consistency (Liu and Chi, 2002; Naumann, 2002; Bouzeghoub and Peralta, 2004; Batini *et al.*, 2004; Strong, 1997).

Additionally, the majority of data quality studies focused on the accounting and customer-relationship management systems and failed in addressing the unique requirements of asset management. For example, many utility companies such as water suppliers need to record and use their pipeline data for more than 100 years. Due to the inability to access the original data and business requirements, it is difficult for these organisations to design their AM information system to utilise these data accurately and efficiently. In many cases, comprised solutions were decided (*e.g.* use dummy values, not migrate these data to the main data repository and so on), which often resulted in ongoing data quality problems. In other words, the ability of discovering the undocumented business rules will enable asset management organisations to improve their system design to better meet business requirements.

2.2 A Different Approach and a New Research Perspective – Business Rule Discovery

According to the Business Rules Group (2001), from the information systems perspective, a business rule is a statement that defines or constrains some aspect of the business. It is intended to assert business structure, or to contruct or influence the behaviour of the business. Weiden, Hermans, Schreiber and Zee (2002) further suggest that business rules are somewhat similar to integrity constraints in the database: they define some business invariants in a declarative manner. In this research, the investigators adopted the business rule classifications scheme (CommonKADS context-modeling framework authored by Schreiber *et al.* (2000) and published by MIT Press). This schema suggested that business rules can be categorised as

- Structural Rules: Concept structure, Persistency and History;
- Behavioral: Information Flow, Control Flow, Pre-conditions, Post-conditions, Frequency, Duration and Task Knowledge;
- Managerial: Goals & Values, Actor Competences, Responsibilities and Resources.

This research will primarily focus on the discovery of the first two types of rules from the disparate data sources.

Although business rule-based information data quality management has not appeared as a popular research topic, it is considered as a significant problem in practice. In accordance with the findings in the Australia-wide DQ survey (Gao *et al.*, 2006), the inappropriate application of business rules resulting in a serious data quality problem, has again attracted the Australian public's attention.

The Australian National Audit Office's (ANAO) report into the Integrity of Medicare Enrolment Data found a long list of serious, and sometimes bizarre, data quality issues associated with HIC. In fact, the ANAO has a long list of previous reports detailing federal data quality problems – data volumes are so vast now that a small error in the business rules governing data can lead to serious mistakes (Riley 2005).

Thus, it is believed that discovery of undocumented business rules from disparate data sources can lead to significant improvement of the information system integration process: pre-determine the optimal integration schema and ideal system interaction protocols; and in particular, ensure that the future integrated information systems support organisational goals. Moreover, the discovered rules can be applied to clean the current datasets and ensure that ongoing new data entries fulfil the quality requirements.

3 Business Rules Brief View

Business rule is a statement that defines and constrains the business's day-to-day operations to achieve the enterprise's objectives. A number of definitions of business rules have been found from distinct experts; Table 1 shows their unique understandings of business rules:

Table 1 Definitions of Business rules

Source	Definition
Entity Modeling: Techniques and Application, by Ronald G. Ross, 1987.	"… specific rules (or business policies) that govern … behavior [of the enterprise] and distinguish it from others … these rules govern changes in state of the enterprise …"
The Business Rule Book (First Edition), by Ronald G. Ross, 1994.	"… a discrete operational business policy or practice. A business rule may be considered a user requirement that is expressed in non-procedural and non-technical form (usually textual statements) …A business rule represents a statement about business behavior …"
GUIDE Business Rules Project Final Report, rev 1.2, October 1997, prepared by David C. Hay and Keri Anderson Healy.	"... a statement that defines or constrains some aspect of the business … [which is] intended to assert business structure, or to control or influence the behavior of the business. [A business rule] cannot be broken down or decomposed further into more detailed business rules … if reduced any further, there would be loss of important information about the business."

Table 1 (*Continued*)

Source	Definition
The Business Rule Book (Second Edition), by Ronald G. Ross, 1997.	"A term, fact (type) or rule …"
Business Rules Group, (formerly GUIDE Business Rules Project), 1998 (work in progress).	"… a directive that is intended to influence or guide business behavior. Such directives exist in support of business policy, which is formulated in response to risks, threats or opportunities."
BRSolutions, the BRS Business Rule Methodology, by Ronald G. Ross and Gladys S.W. Lam, 2000.	"An atomic piece of re-usable business logic, specified declaratively."

Source: Ross (2000)

4 Evolving Business Rule Expression

Similar to a computer programming language, business rules can be used to guide business operations (tasks and processes) in three different ways: sequence, selection and iteration. For example, the sequence of business rules determines the business process flows. However, in the research of business rules, the simplest expression is the selection rules, often represented as an IF-THEN-ELSE statement (or in a flow diagram). For example,

IF customers order five items
THEN give 5 % discount
ELSE provide 0 % discount

When dealing with complex business situations, advanced business rule representation languages (or notation systems) are useful. For example, Choi, Cho, Bae and Hyun (2000) propose an event based business rule notation language which depicts the business rules as events, conditions and actions. For example,

DEFINE RULE EngineeringChangeReflection
– rule name
Event AUTO_CAD.ModifyDrawing
– when will this rule apply?
Condition EBOM_DB.CheckDesign()
– Has the design been changed?
Action EBOM_DB.GenerateEngineeringAlert
– If changed, an alert needs to be issued to the manager
Manager.Notif y(``Adam' ',``Engineering change occurred' ')
END"

Although the above business rules are human readable, this way of expression is still not preferred by business managers when they need to deal with a large number of business rules. Thus, an open standard of business rule semantics was developed by the Object Management Group (OMG) in September 2005. The "Semantics of Business Vocabulary and Business Rules" (SBVR) by OMG defines the vocabulary and rules for documenting the semantics of business vocabulary, business facts, and business rules; as well as an XMI schema for the interchange of business vocabularies and business rules among organizations and between software tools. The SBVR business rules are represented in controlled nature languages. For example, SBVR Structural Business Rules use two alethic modal operators:

it is necessary that …
it is possible that …

The word "necessary" means that the future state (path) is a determined path under any circumstances, while "possible" provides flexibility for choosing the path based on further conditions or as a random selected result.

Discovering the business rules and creating new rules is essential to any enterprise. More and more companies now pay attention to the concept of business rules and try to identify an efficient approach that can extract the hidden implicit rules. This research tries to explore new ways of discovering business rules. The actual business representation is not the primary focus. Thus, instead of using advanced business rule languages, its simplest form (IF, ELSE and THEN) is used.

5 Research Aim

Much Data Quality research has focused on data quality dimensions (*e.g.* accuracy and completeness). However, a number of studies (*e.g.* Weiden *et al.*, 2002 Manila, 1994 and Klein *et al.*, 1997) have revealed that many of the data quality problems emanate from inconsistent applications of business rules that govern the behaviour of data (*e.g.* data management, data flow, system interactions and so on) within the information systems. Thus, this research investigated the problems of business rule-based data and information integration from disparate sources in various forms found in modern asset management systems (*e.g.* Relational Databases, Excel spreadsheets, *etc.*). In particular, this research explored the possibility of the dynamic discovery of undocumented business rules at databases and systems levels – rule discovering based on the user interface interaction capture (*e.g.* key logs), system log files (*e.g.* SQL statements to the backend database), network communication log files (*e.g.* request and reply to and from other systems) and database logs (read and write access).

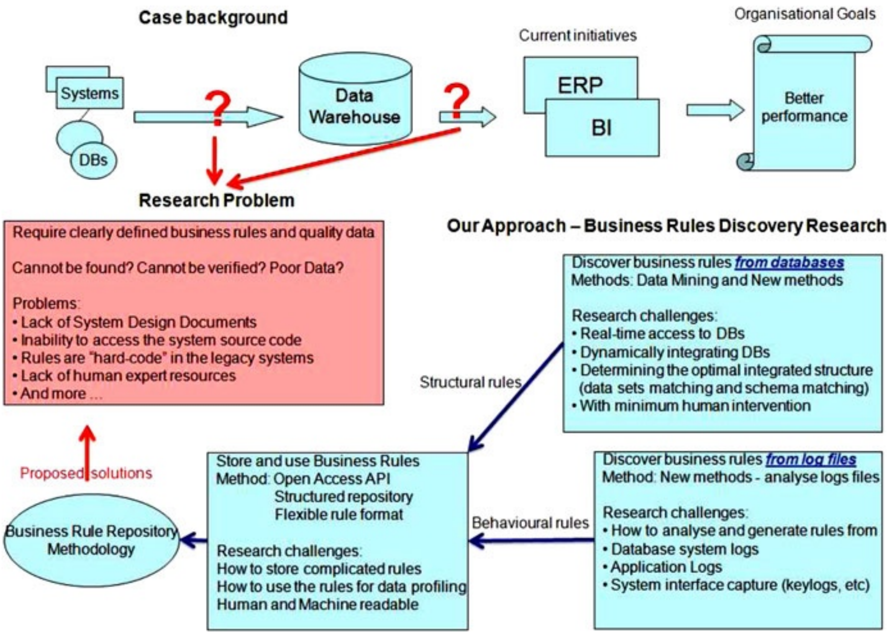


Figure 1 Research Approach Overview

6 Research Methods

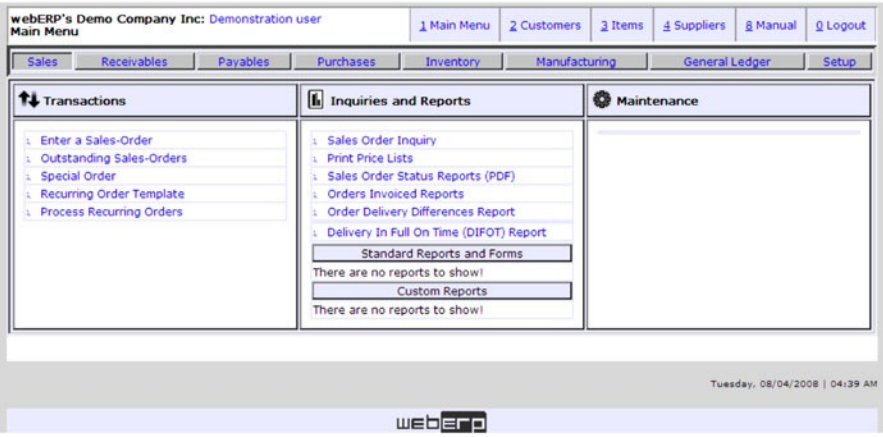
Business rules are significant when organisations are required to improve their legacy information systems. However, many engineering asset management organisations have experienced difficulties in collecting the existing business rules. In many cases, the original business rule documentation, system documentation, system source codes, database design documentation and so on are lost through time. Thus, the first stage of this research tries to explore the possibility of discovering business rules from the existing system and database logs (as the majority of systems have built-in log functions). It is thought the depicted business rules will be useful in redesigning the underlying database structure and current system business logics. It is believed that the improved design will improve the overall data quality of the organisation.

This research consisted of three steps:

- set up an asset management system;
- obtain the system and database logs for processing;
- parsing the logs and generating business rules (initially as a manual process).

The chosen system is an open source ERP solution which has inventory, financial and asset management functions. The underlying database is MySQL. This testing environment is very similar to large asset management implementation

(a)



(b)

Figure 2 (a) webERP login interface; (b) webERP user interface

systems (for example, SAP and Oracle database). Thus, if it is possible to discover business rules from the testing system setup, it is possible to apply this approach to other systems.

As discussed previously, this research will use the simplest expression of business rules (IF ELSE and THEN). However, this form of expression is difficult for readers who do not have a technical background to understand. Thus, the final results will be converted to a flow diagram, where a rectangle box represents an action, a diamond box represents a selection and the directional line represents a path.

The Software Parsing Method Basic Principle:

1. Typical login sequences were used to determine the action/transaction initialisation and completion (start/end). In modern asset management information systems, access control is included as a critical system function. Thus, each set

transaction performed by an individual often starts from the username selection statement and ends with another username selection statement. (It must be noted that the logoff function does not necessarily generate database entries.)

2. Although there are different versions of SQL Query statements, it is easy to create a SQL query command dictionary (and amended/modified based on the actual database program).
3. Each SQL statement always starts from verbs. The testing software uses the stringtokniser function to separate each key commands and actively searches for verbs based on a standard SQL query dictionary, and puts the verbs and nouns (tables, column names) into a tree structure.
4. The complex queries are handled by the recursive function. The parsing result was inserted into the tree structure as sub-branches.
5. Each selection statement (only at the top-level) is considered as a complete tree, which will be converted to the diagram.

   For example, the name of the column selected (*e.g.* SELECT username, FROM users, WHERE username="XXXXX"): suggests the action taken.

   SQL Where statement (WHERE userpassword= "XXXXX"): shows there could be a conditional check.

   The consequent SQL statements from the log files show the path: (if the SELECT username statement appeared again, it could mean the authentication failed previously or a new start).
6. Some human expert rules were added when creating the following charts (to make them more meaningful). For example, "select username …" is considered as login.

7 Preliminary Finding

A number of tests exploring the methods explained in the previous section, were conducted to examine various log contents, especially SQL related statements. As a result, the following business rules were extracted from the log files.

1. Login related SQL statements found in the log file

```
SELECT www_users.fullaccess, www_users.customerid,
   www_users.lastvisitdate, www_users.pagesize, www_users.defaultlocation,
   www_users.branchcode, www_users.modulesallowed, www_users.blocked,
   www_users.realname, www_users.theme, www_users.displayrecordsmax,
   www_users.userid, www_users.language
FROM www_users
WHERE www_users.userid='demo' AND
   (www_users.password='f0f77a7f88e7c1e93ab4e316b4574c7843b00ea4' OR
   www_users.password='weberp')
```

The business rule can be represented in the flow diagram:

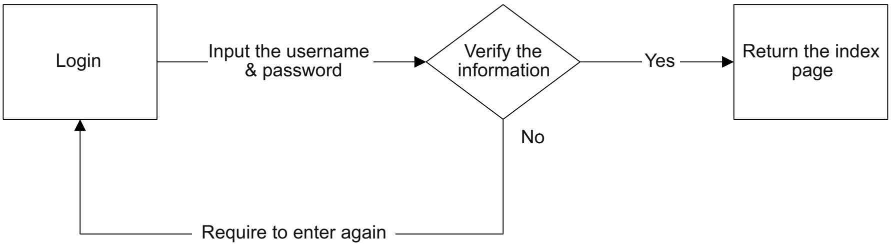


Figure 3 Flow diagram of Login

2. Create a new order

SELECT debtorsmaster.debtorno, debtorsmaster.creditlimit,
SUM(debtortrans.ovamount + debtortrans.ovgst + debtortrans.ovfreight + debtortrans.ovdiscount – debtortrans.alloc) as balance
FROM debtorsmaster INNER JOIN debtortrans ON
debtorsmaster.debtorno=debtortrans.debtorno
WHERE debtorsmaster.debtorno='001' GROUP BY debtorsmaster.debtorno.

SELECT prices.price, prices.debtorno, prices.branchcode
FROM prices, debtorsmaster
WHERE debtorsmaster.salestype=prices.typeabbrev AND
debtorsmaster.debtorno='001' AND prices.stockid = 'DVD-DHWV' AND
prices.currabrev = debtorsmaster.currcode AND
prices.debtorno=debtorsmaster.debtorno AND prices.branchcode='001'

SELECT categoryid, categorydescription
FROM stockcategory
WHERE stocktype='F' OR stocktype='D' ORDER BY categorydescription.

The business rule can be represented in the flow diagram:

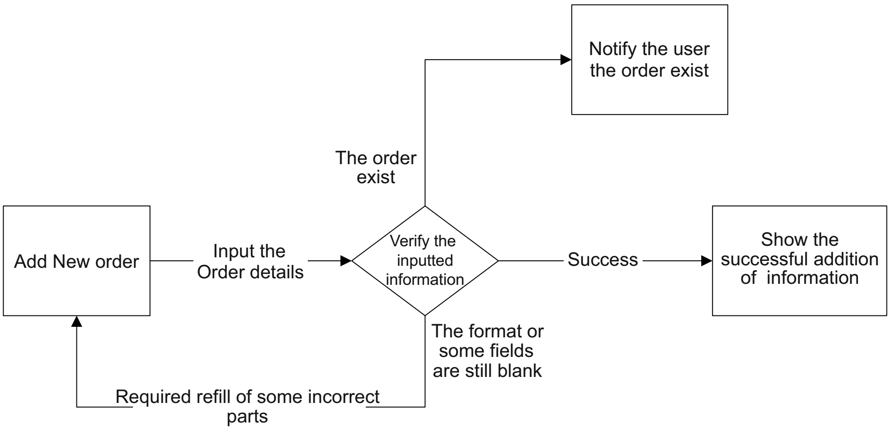


Figure 4 Flow diagram of Adding a new order

3. Add a new customer

SELECT currencydefault FROM companies WHERE coycode=1

SELECT debtorsmaster.name, custbranch.branchcode, brname, salesman.salesmanname, areas.areadescription, contactname, phoneno, faxno, email, taxgroups.taxgroupdescription, custbranch.branchcode, custbranch.disabletrans
FROM custbranch, debtorsmaster, areas, salesman, taxgroups
WHERE custbranch.debtorno=debtorsmaster.debtorno AND custbranch.area=areas.areacode AND custbranch.salesman=salesman.salesmancode AND custbranch.taxgroupid=taxgroups.taxgroupid AND custbranch.debtorno = '002'

The business rule can be represented in the flow diagram:

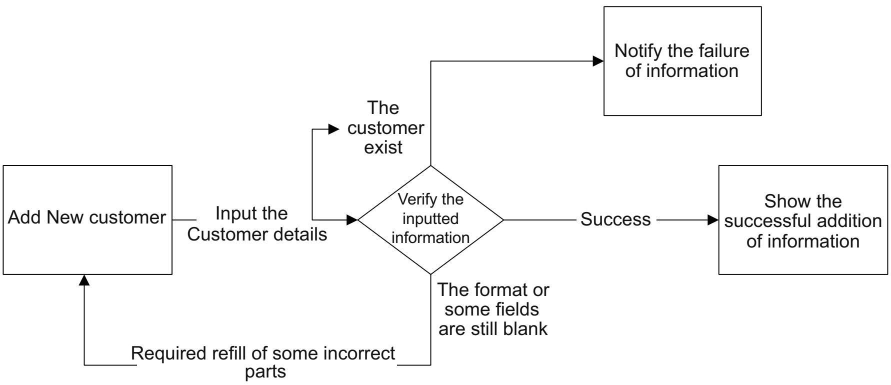


Figure 5 Flow diagram of Adding a new customer

4. Search purchase order

SELECT stockmaster.stockid, stockmaster.description, SUM(locstock.quantity) AS qoh, stockmaster.units, SUM(purchorderdetails.quantityord-purchorderdetails.quantityrecd) AS qord
FROM stockmaster INNER JOIN locstock ON stockmaster.stockid = locstock.stockid INNER JOIN purchorderdetails ON stockmaster.stockid=purchorderdetails.itemcode
WHERE purchorderdetails.completed=1 AND stockmaster.categoryid='DVD' GROUP BY stockmaster.stockid, stockmaster.description, stockmaster.units ORDER BY stockmaster.stockid

SELECT purchorders.orderno, suppliers.suppname, purchorders.orddate, purchorders.initiator, purchorders.requisitionno, purchorders.allowprint,

suppliers.currcode,
sum(purchorderdetails.unitprice*purchorderdetails.quantityord) as ordervalue
FROM purchorders, purchorderdetails, suppliers
WHERE purchorders.orderno = purchorderdetails.orderno AND
purchorders.supplierno = suppliers.supplierid AND purchorders.intostocklocation = '' GROUP BY purchorders.orderno, suppliers.suppname, purchorders.orddate, purchorders.initiator, purchorders.requisitionno, purchorders.allowprint, suppliers.currcode

The business rule can be represented in the flow diagram:

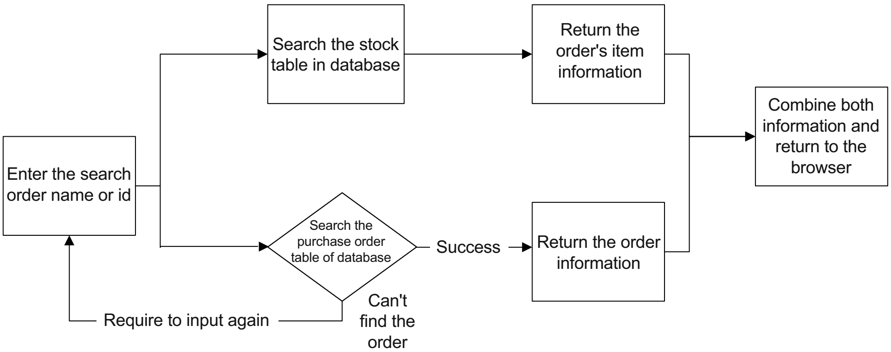


Figure 6 Sequence diagram of search purchase order

8 Conclusions

The above results are positive in showing how to discover business rules (even complex ones) from the database logs. By examining the discovered business rules, the system designer can improve the existing database schema (determine what data fields are currently unused or rarely used). A better database schema will help improve the overall data quality in organisations. In addition, the business rules can also contribute to the design of new systems (especially when the original design documentation cannot be found).

The current log data mining method is a manual process which requires the examiner having sufficient business knowledge (to understand business operations) and technical skills (to understand SQL queries). In addition, it also requires that the log file contains meaningful variable names (for example, username instead XYZ). It is also thought that the current method may not be able to cope with a large volume of log files. Nevertheless, using advanced artificial intelligence and sophisticated data mining methods may help automate this process.

Engineering asset management processes rely heavily on input of data and also produce a large amount of data. Engineering data itself is quite different to typical business-oriented data. It has unique data characteristics and complex data capture processes from a large variety of data sources. This large amount of data therefore can suffer from data quality problems. Due to the rapid change of business requirements, the evolving asset management system design needs to take these data quality problems into consideration. By incorporating both documented and undocumented business rules in the improved design, the engineering asset management organisation is able to obtain quality asset data sets for effective decision making. This paper has demonstrated the possibility to discover the undocumented business rules from the asset management systems log files. This approach is considered highly valuable for any asset management organisations who are seeking improvement to their existing information systems.

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Potential Uses of RFID Technology in Asset Management

Abrar Haider and Andy Koronios

Abstract Radio frequency identification (RFID) is a powerful data capturing technology that allows for electronic identification and tracking of the products, cases, or pallets that the RFID tags are attached to. As a result, the main thrust for businesses in adopting this technology has been on logistics and warehouse management. However, with the continuous development and emergent innovative use of technology, RFID is now being used for much more than just electronic identification of items. Particularly, for engineering asset management, RFID has the potential of taking workforce mobility to a higher level and allows for remote condition monitoring, failure follow up notifications, and embedding health history with the asset for its lifetime. RFID technology, therefore, has the potential of enabling a variety of applications spanning asset lifecycle. This paper presents the results of an evaluation study undertaken for the Cooperative Research Centre of Engineering Asset Management to explore the efficiency of RFID technology for Asset Management. The value profile of RFID technology in three areas were investigated. Firstly in remote condition and operating environment monitoring of asset operations. Secondly in defence supply chain management, where inventory consists of a variety of items; in order to alleviate capacity constraints where the flow of materials in the reverse direction is high, and the supply and demands factors are not as stable as compared to some other chains. In this case, the geographic end points of the supply chain are unstable and generally not static. The third area is automated configuration management, where constituent components

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Definitions, Concepts and Scope of Engineering Asset Management,

of large configurations can be identified automatically. This paper, thus, is significant across a variety of disciplines and professional areas such as, asset design, maintenance, logistics, and asset health management. This paper reports the results of three prototype projects carried out in controlled environments and provides an assessment of potential allowances and limitation of RFID technologies examined in this research.

Keywords Asset Management, Asset Maintenance, Asset Tracking, Condition Monitoring

1 Introduction

Radio Frequency Identification (RFID) has gained enormous popularity in the recent past, even though the technology has been around for a considerable period of time. Reasons for this trend is the ease with which RFID technology provides for item tracking and thereby inventory management, logistics management, and supply chain management. Wal-Mart and US department of defence have been leading the race in this regard, and in so doing are realising a novel relationship between items and information. Major advantage of RFID technology over bar code technology is that with RFID technology information exclusive to the item travels with the item throughout the life cycle of the item. For example, at any time it is possible to find out the current location of the item; its origin, such as supplier and date of manufacture; its existing use and intended use; and its future destination. This functionality provides for real time visibility of end to end supply chain. RFID has particular significance for defence supply chains where inventory consist of a variety of items; flow of inventory from consumer to supplier is high; and supply and demands factors in this situation are not as stable as compared to some other supply chains, and geographic end points of this supply chain are continuously moving. Location identification is just one area where RFID technology offers potential benefits; in fact it has the potential to address diversified issues concerning asset health management. Nonetheless, the proliferation of RFID technology is subject to the development of technology to overcome some of the issues such as, lack of standards, cost, data/infrastructure/systems implementation issues, data sharing and security. This paper reports results of evaluation studies that were carried out to assess the potential of RFID technology in supply chain management, configuration management, and management of asset condition and health. We conclude that although RFID technology is far from being pervasive, this technology is here to stay and its capabilities provide excellent grounds for various wireless applications in asset management. This paper presents leads to possible application of the technology in three areas; however the concepts could be applied to a variety of other application in management of assets throughout their lifecycle.

2 Issues in Contemporary Asset Management

2.1 Remote Condition Monitoring

Modern production or manufacturing environment demands an elevated degree of plant and equipment reliability involved in manufacturing process. Technological advances, on one hand have improved their efficiency, and on the other hand, have changed the ways these plant and equipment have traditionally been maintained. Information and communication technologies are fast taking over from the conventional practices of manual plant inspection and reliance of these practices on paper based information acquisition and management. These changes are aimed at inducing agility into the plant and equipment management process, particularly targeting continuous monitoring of the condition of the plant and equipment; so as to sense any malfunctioning in their operating conditions. It is important to discover a failure condition in its development, as manufacturing or production processes conform to a strict time scale and it is therefore important to plan ensuing plant shutdowns well ahead of time such that the production schedules are scheduled accordingly. Any change in the manufacturing or production schedule, accordingly, has a direct impact on enterprise resource planning, sales and distribution, and customer relationship management, therefore, a sound plant and equipment condition monitoring (CM) technique is extremely important for any manufacturing business. Nevertheless, the fundamental aim is to identify the factors hampering the smooth operation of assets. Contemporary diagnostic equipment, nevertheless, is ill equipped for the emerging e-intelligent maintenance paradigm. Mostly these equipment identify a failure when the situation is already out of hand, and therefore they serve as tools of failure reporting better than instruments for pre-warning the failure in its development. At the same time the information is mainly captured through sensors on an individual basis and there is no synergy with other sensors. Consequently, it is not possible to know what is causing the failure. For example, a rise in temperature provides no assessment on the condition of an asset, if it is taken in isolation from other condition parameters. In the absence of the complete picture it is difficult to find out what is causing the asset to malfunction and by the time the cause is pinned down the failure condition has gone from bad to worse. Therefore, there is a need for a CM apparatus that provides a comprehensive picture of an asset condition, through a single channel, so as to warn of a failure condition in its developmental stage. This is particularly important for remotely deployed assets, for example, a typical water pump station in Australia is located away from major infrastructure and has considerable length of pipe line assets that brings water from the source to the destination. The demand for water supply is continuous for twenty four hours a day, seven days a week. Maintenance labour at the water stations and along the pipeline is limited and spares inventory is generally not held at each station. Therefore, it is important to continuously monitor asset operation (which in this case constitutes equipment on the water station as well as the pipeline) in order to sense asset failures as soon as possible and preferably in their development stage. Furthermore, same information could be used to provide a complete prognostic report for asset health management at any point in time for effective asset utilisation and its lifecycle management. Such a CM mechanism is one that is responsive, technologically convergent, and information intensive, aimed at continuous monitoring of the operational environment of an asset, improving asset reliability through efficient prediction of asset failures, and reducing CM and maintenance costs.

2.2 Spares Supply Chain

Research in supply chain management (SCM) automation for managing the flow of materials and associated information flow has gained momentum in the last twenty years. However, issues relating to coordination of flow of inventory between different points of supply chain to plan, manage, and execute the processes of upstream and downstream inventory movement have only increased with time [1]. This is of particular significance to defence related supply chains, especially for assets deployed in operational areas. A good reference example is that of the autonomic logistics structure proposed for Joint Strike Fighters (Figure 1). This logistic structure is aimed at increasing the ground to air ratio of a fighter jet based at a carrier. While in operation, the fighter jet or what is also known as intelligent air vehicle continuously monitors its own condition through the monitoring sensors installed throughout the jet. This continuous prognostic is aimed at pre-empting failure condition rather than failure reporting, whereby the essential aim is to reduce maintenance time to increase operational time. The concept of the this prognosis is the same as there is for any fatal disease among humans, the earlier the prognosis is made the better the chances are to increase the operational life of an asset and its economical operation. Nevertheless, continuous prognostics are communicated to the base station on the aircraft carrier in real time and based upon these indications condition of the jet is assessed and analysed, which pre warns of any failure condition developing. This assessment generates recommendations for repairs and parts replacements that determine the type of spares required for carrying out maintenance activities. From this point onwards combat planning and the ground to air ratio of the fighter jet rests with the speed of the supply chain logistics of the critical spare parts required for maintenance of the jet.

In order to mange such maintenance regimes there are three important factors to consider. First, it is essential to maintain critical stock levels of essential spares on the ship; second, to order the repair stocks for major overhauls; and third to return the redundant spares to an onshore facility in order to alleviate capacity constraints on board. This supply chain also differs in its characteristics from

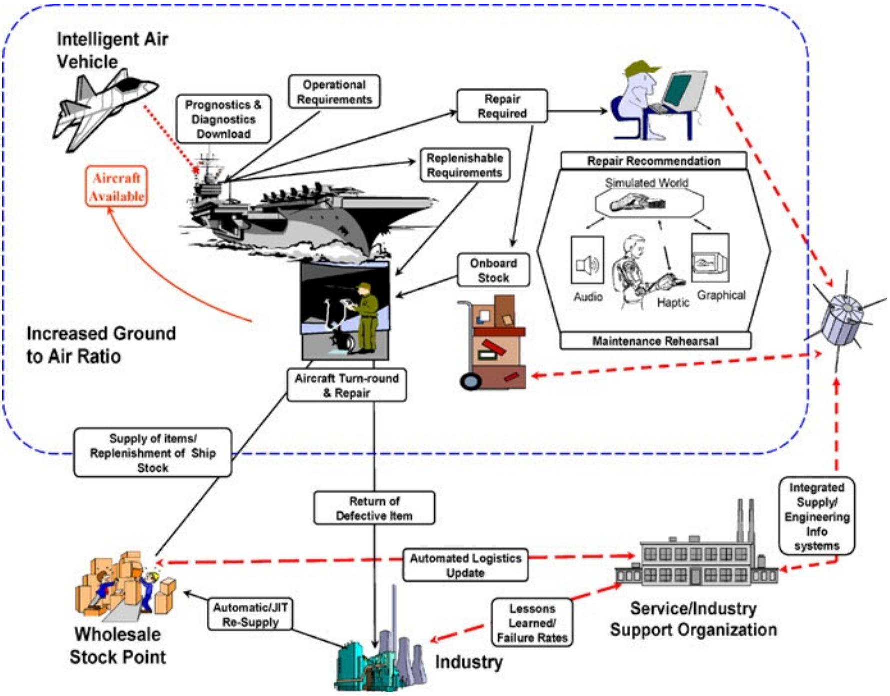


Figure 1 Autonomic Logistics Structure – Joint Strike Fighter, Source [2]

traditional commercial supply chains. In these circumstances inventory consists of a variety of items, the supply and demands factors in this situation are not as stable as compared to some other supply chain for consumer products, and the geographic end points of this supply chain are continuously moving. Conventional SCM strategies are therefore not able to cope with the challenges of such operational environments. Nevertheless, the effectiveness of maintenance processes in such stochastic environments depends upon the real time information about the flow of items at each major point in the supply chain, so as to facilitate maintenance planning and resource allocation.

2.3 Configuration Management

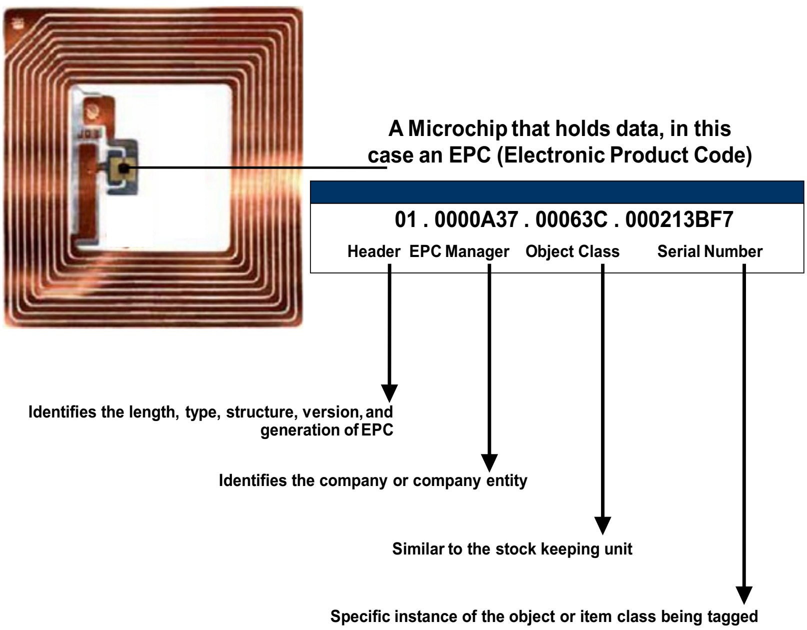
Configuration management focuses on ascertaining, preserving, and sustaining a system's functional and physical attributes according to their design and operational requirements all the way through the lifecycle of system. This process requires a large amount of data, as well as the correct attribution of this data with their respective components or configurations. Configuration management is a major problem in large engineering projects, where engineers from different disciplines work concurrently on their relevant designs. Particularly in overhauling of large sized engineering assets it is critical to maintain their design and technical integrity. Thus, a critical component of configuration management is the detection, notification, and resolution of design inconsistencies, and an early configuration will result in less engineering reworks. It is significantly difficult for older assets that were constructed or assembled in times when there was little or no digital information captured regarding their design and configuration. In these circumstances, access to and referring back to design drawing is a time consuming task. However, a mechanism to automatically identify individual components of any configuration would be of significant help to designers and maintainers.

With this backdrop, this study investigated the use of RFID technology with three objectives, firstly, to assess the capability of the technology in automatic identification of components; secondly, to evaluate the technology's strengths in facilitating logistics management for closed loop supply chains as illustrated in the autonomic logistic structure; and thirdly, to investigate the potential of RFID in providing foundational blocks for developing a proactive, cost effective, and efficient remote conditioning monitoring regime.

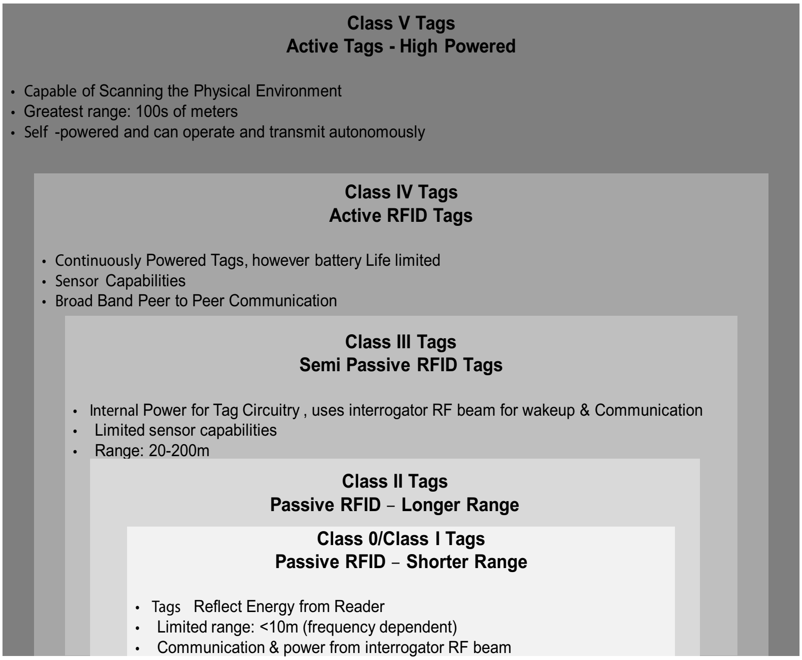
3 Fundamentals of RFID Technology

RFID technology consists of three components, an RFID tag, a reader, and a Tag/Reader management systems or a middleware [3]. RFID tags are made up of a small microcontroller and antenna available in many different packages. They provide a contact free form of identification through the use of radio frequencies. Each tag has an electronic product code (EPC) or an identification number embedded into the tag microcontroller that is used to uniquely identify each tag, which can also be termed as the RFID's version of a bar code [4]. When an RFID tag is placed close enough to the reader it is powered up through a magnetic field emitted by the reader thus powering the microcontroller of the tag, such that it transmits the EPC to the reader. RFID tags do not require line of sight between tags and readers for them to be detected and therefore make it possible for tags attached to items to be identified from a single point [5], [6].

The RFID reader is a mobile or fixed device, comes in a variety of shapes such as hand held or fixed mount, and emits electro magnetic waves. The reader activates the tags by sending tags out encoded interrogation signals. This signal creates a magnetic filed that the tag uses to power itself, the tag then sends its EPC to the reader. The EPC is decoded by the reader and sent to the middleware.



(a)



(b)

Figure 2 (a) Electronic Product Code; (b) RFID Tag Classification

The RFID middleware represents the hardware and software that is necessary to process data coming from the tags, coordinate communication to and from multiple readers, and send the captured information to legacy systems. It also segregates the vast amount of data before sending it onwards to legacy systems. In simpler terms it works as a traffic regulator and to some extent it also works as a communication moderator. Nevertheless, unlike bar codes that are only capable of identifying a class of items, EPC identifies each item uniquely. EPC provide a unique number for each item throughout its lifecycle. EPC is a coding scheme that identifies an item's manufacturer, product category and unique serial number. This standardisation guarantees interoperability and security, thereby aiding system and information integration. The 96 bit scheme has an 8 bit header and three other data partitions as shown in Figure 2a. The EPC identifies the manufacturer, product, version, and serial number or a product or item. There are two types of EPCs in common use, one supports 64 bit on board EPCs and the other supports 96 bit EPCs. A 96-bit EPC provides unique identifiers for 268 million objects [4]. Figure 2b illustrates the taxonomy of an EPC. Deciding which tags suit a particular application is a difficult choice. To do this, it is necessary to examine different tags and then evaluate their pros and cons.

RFID tags can be active, passive, or semi-passive tags, and are classified into five classes according to their capabilities and functionalities (Figure 2b). However, there are commonly referred to as either passive or active. Passive tags are interrogated by the reader for information contained in them, whereas active tags themselves transmit the data streams to the reader, hence the name passive and active. Passive tags are powered via the reader thus they do not require batteries to operate, whereas active tags have an onboard power. Passive tags can be detected from a distance ranging from a few centimetres to a few metres, whereas active tags, on the other hand, have an on-board battery, and therefore, have a far longer read/ write range and memory size. Class 1 and 2 tags are the most common and can be easily found in operation today. These tags are mostly used for item tracking and inventory management purposes. Class 3 tags are semi passive, which means that they are on board power available, but that power needs to be activated by the magnetic filed that the sensing beam of the RFID reader creates. They have relatively smaller read range, which means that the reader has to be placed in close proximity to the tagged item. Class 4 and 5 tags have on board continuous power available (usually a life span of 10 years) as they are fitted with a battery, in most cases have a microcontroller available on board, support on board memory, and also have sensing capabilities. These tags are usually able to sense the temperature or light. Active tags have external interface available that allows for interfacing additional sensors and devices. On the other hand, major advantage of the passive tags is their small size; consequently they can be used for many applications where size and weight are limiting factors. Extra features on a tag, however, do increase the size and cost of each individual unit.

4 RFID Applications

There are numerous applications of RFID technology currently being developed and a plethora of applications are envisaged by prospective users. At the moment major advantages that businesses gain from RFID are item tracking, warehouse management, reduced obsolete inventory, reduced material handling costs, supplier identification, authenticity of items, end to end visibility of materials flow, and supply and demand management support. Among these are applications like tracking a box, web luggage, smart shelves for pharmaceutical products, smart toolbox, and smart box etc [6], [7], [8], [9], [10], [11]. With regards to asset management, there are a range of applications for RFID technology spanning asset management particularly maintenance management. Active RFID technology can be of significant use for condition monitoring of an asset; the sensing capability of RFID technology is further discussed later in the paper. The tracking capability of RFID could be used for tracking assets such as railway tracks, and pipelines. Table 1 presents some of the RFID related initiatives under way in different agencies.

Table 1 Reported or Planned Use of RFID Technology, Source [12]

Industry/Service	Application
Defence	Logistics support; Tracking shipments; Tracking and identification; Monitoring weapons
Energy	Detection of prohibited articles; Tracking the movement of materials
Health and Human Services	Physical access control
Homeland Security/Immigration and customs	Border control location system; Smart containers; Tracking and identification of assets; Tracking and identification of baggage on flights
Law and order	Tracking offenders and prisoners
Transportation	Fleet management, Electronic screening
Finance and Treasury	Physical and logical access control; Records management (tracking documents)
Environment Protection	Tracking hazardous material
General Service Administration	Tracking and routing carriers along conveyor lines; Identification of contents of shipments; Warehouse management

5 Making Use of the Uniqueness

It is clear from the discussion of the technology that in most cases the RFID tags can only hold the EPC and no other information. However, in all the applications being investigated in this paper require significant amount of information to be captured. Figure 3 illustrates a framework that could be used for capturing large amount of data about the items attached with RFID tags. In this framework items are tagged with an RFID tag; either active or passive, depending upon the nature of application. When the tag comes near the reader, the radio frequency field generated by the reader powers up the tag and causes it to continuously transmit its EPC by pulsing the radio frequency. The reader passes the EPC to the middleware, or what is also termed as a savant. A savant acts as a buffer between the reader and other organisational information systems, and consists of various modules or sub programs with each module performing specific functions. The savant remains connected to the readers, and behaves as a router of the RFID network with the primary functions of EPC related data smoothing, data forwarding and data storage; along with reader coordination, and task and event management. These savants use algorithms that take care of the reader collision, such that each tag is identified uniquely and is read each time it is attempted to be read.

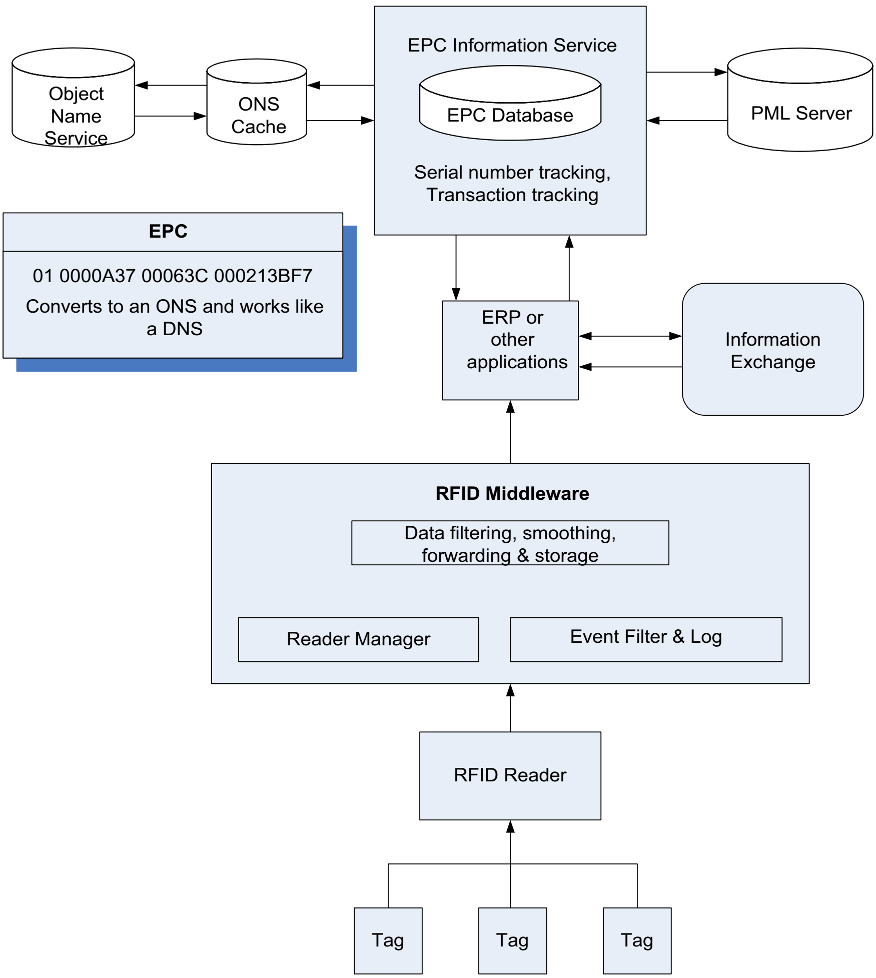


Figure 3 Framework for RFID Based Prototype Applications for Asset Management, Source [13]

Since the EPC is the only information stored on the tag, it has to be used in such a way that it provides additional information about the item that the EPC is attached to. The savant interprets the EPC into a unique address of an object naming service (ONS), which points to a physical mark-up language (PML) server. PML is a version of the popular XML meta-data language. The server stores PML files that contain information about the item that the RFID tag is attached to. The whole process works like a user accessing a website on the Internet, where a user types in the unique url (in this case the EPC), this url is interpreted into a DNS, which points to the service that is hosting the website pages and associated information. Using this framework, any amount of information exclusive to an item can be stored and retrieved in real time.

6 Evaluation of RFID Technologies for Asset Management

In our evaluation we examined RFID Technologies, for configuration management, item tracking, and for condition monitoring. We chose Texas Instruments Midrange Evaluation kit and Chipcon CC1010, since both these technologies offer valuation packages which include all the hardware and software required to begin developing specific applications. This also allowed us to explore both the passive and active tags. Examination of active tags led us to believe that RFID technology could be used of a much enhanced scope of applications in engineering asset management.

6.1 RFID for Configuration Management

The Texas Instrument midrange evaluation kit is equipped with one reader and a selection of Tags in different packages. It operates at 13.56 MHz capable of reading tags at a range of 7 inches from the reader. The reader unit is a similar size to a paperback novel (13 cm * 3.5 cm * 18 cm), the unit is encased in a black plastic box which roughly doubles the necessary size of the unit. A variety of tags are supplied with the reader unit they can be categorized into two different types which come in different sizes. The Tag-it transponder inlays with 256 bits user programmable data, the estimated data retention time is 10 years and can be programmed typically 100 000 times. The evaluation kit also comes with Tag-it ISO transponder inlays also available in a range of different sizes the main difference is they have 2000 bits of programmable memory and a larger unique identification number for future expansion. The inlay style tags are a cost effective solution for tracking and inventory control type applications. As this technology becomes used on a larger scale it is expected the tags will be available for (USD) $0.10 each or less. However they are limited in the fact that they can only provide location information in conjunction with a software application. We developed a simple application as an introduction to the hardware components and how to collaborate between software applications and RFID tags. The purpose of the application is to provide a management system which can locate individual components of a configuration, record their current location, and keep a record of their history. This information can then be displayed to the user through a software application (software flow shown in Figure 4).

For proof of concept we assumed a box attached with RFID tag to be the main asset configuration and tagged items inside the box to be the constituent items of the configuration (Figure 5). Thus there are two types of items we have used in our design, items (configuration items) and container or assets. An item is the lowest level of the two and only has knowledge of its own existence. Containers on the other hand can hold items within themselves. Our aim is to monitor the location of each configuration item as well as that of the overall asset. In the application that we developed, when an tag is first read at a location the user is asked to enter a description and define the type of item that it is attached to, *i.e.* whether it represents the overall configuration or is its constituent component.

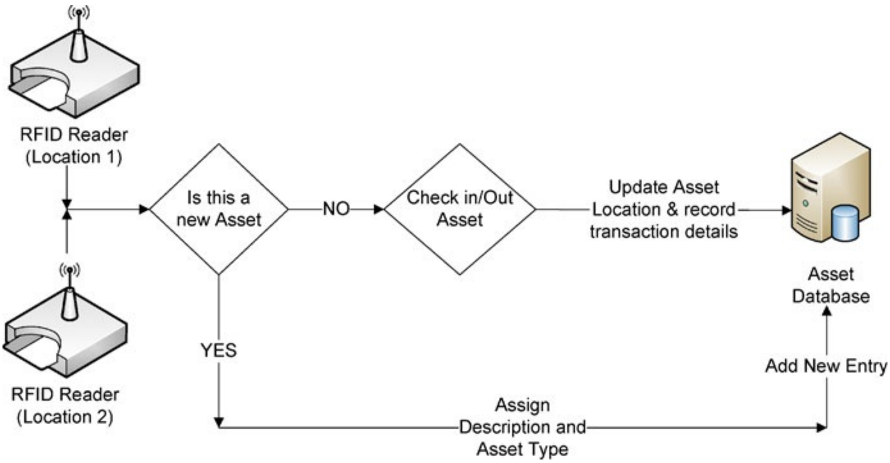


Figure 4 Software flow for Configuration Management

Figure 5 Inlay RFID Tag attached to container

Now as an item leaves and enters the configuration (in our case the box) it is read by the reader which in turn adds transactions to the database. Each transaction records the location of the tag and the time the transaction occurred. When a container type is selected the operation is similar to that of an item with the exception an item may be placed within a container (Figure 6). This allows us to keep track of groups of related objects as one entity or assets when querying the database (Figure 7).

One of the limitations which should be considered is the material in which tags are attached to as well as the materials in the environment. When the tags are attached to metallic surface the tag malfunctions. Texas Instruments have released

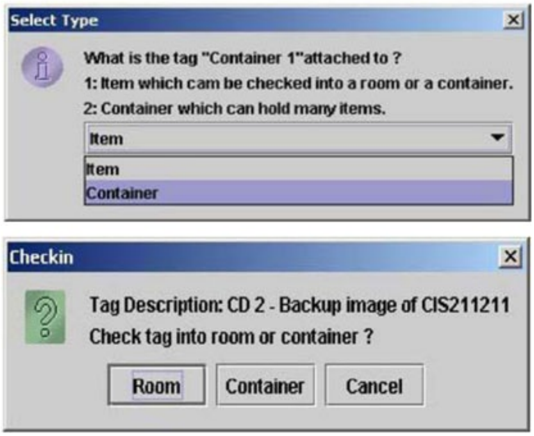


Figure 6 Container and its constituent items check-in

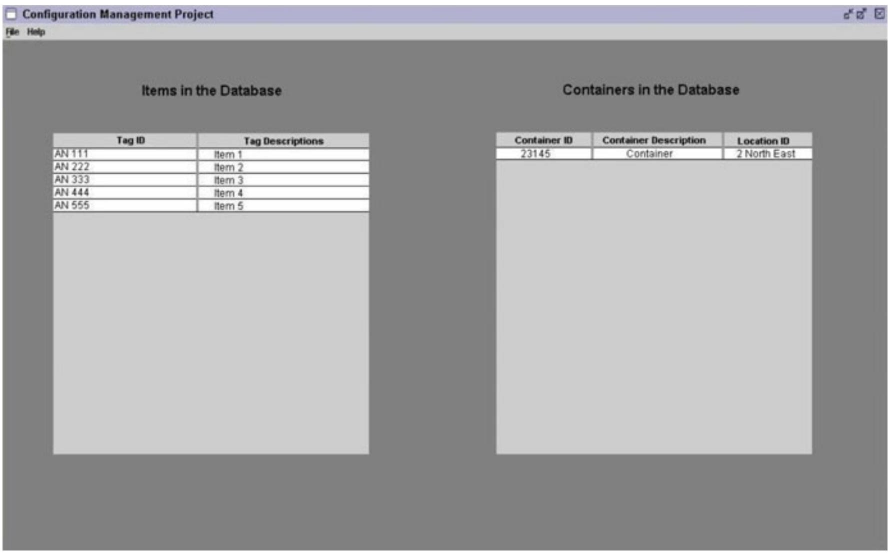


Figure 7 Configuration Database

a range of tags designed to be mounted on metallic surfaces. However their reading range is reduced by 30 % and their size is much larger than the inlay variety. It appears that in highly metallic assets such as railway tracks, rolling stock, or military hardware existing RFID tags, especially the inlays, may not function. It is therefore, necessary to investigate how a robust tag can be developed that is able to provide the same functionality in a variety of environments. In addition to this, the issues regarding RFID technology working on different frequency spectrum will remain, particularly when assets are moved between international borders.

6.2 RFID for Supply Chain Management

Using the methodology described in Figure 3, we examined the Texas Instruments Series 6000 – HF-I Midrange technology. The midrange evaluation kit consists of one reader and a selection of tags in different packages. It is a high frequency kit, which operates at 13.56 MHz. The reader is capable of reading tags at a range of 7 inches and its plastic housing integrates an antenna and an RS232 interface board. The reader is able to communicate with Tag-It as well as any ISO 15693 compatible tags. We used two readers in this scenario, with the other reader being S251B, which is a low frequency reader operating at 134.2 kHz and is able to communicate with TIRIS Low Frequency tags. It automatically tunes a standard antenna to resonance and keeps it tuned during operation. It is able to communicate with tags at ranges up to 1m (using a large size gate antenna). The reader decodes the signals emitted from transponders into identification numbers, performs error checking and translates the signals to standard serial interface protocols (RS232, RS422/485). It also contains a buffer, which can store up to 909 reading transactions. Communication with a PC can be performed over a serial interface (RS232) using ASCII commands.

The prototype asset spares inventory and logistics management application was developed using the Series 6000 – HF-I Midrange technology, mimics the scenario of movement of assets or items between an Ordnance depot and field store. The application displays two warehouses with each containing six sections. If each section was equipped with a reader, thus, we could easily locate the section containing an item at any time. The two readers are installed at entrances to the warehouses, thereby allowing for tracking movement of tagged items, Figure 8.

When an item enters Forces Distribution Centre for the first time, the user is asked to enter item details (Figure 9). After entering item details, the item is displayed in the system, as shown in Figure 10.

When an item is moved out of the depot, it displays the status of the item as in transit, till the time it is checked in another location/store/depot (Figure 11).

Figure 12 illustrates that history of an item's movement along with the time and date of each movement. Thus, providing complete details of each item from the moment it was purchased/acquired to its current location or deployment.

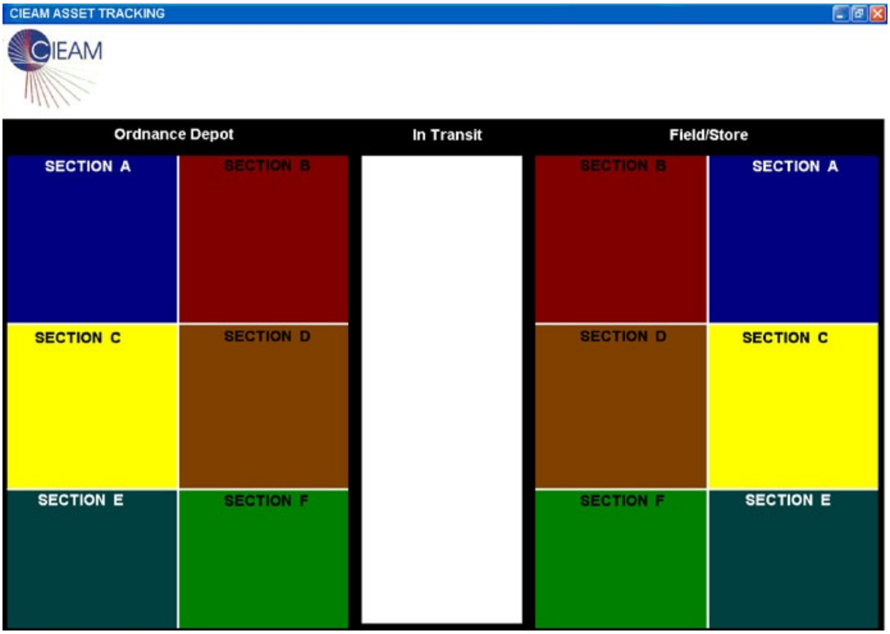


Figure 8 Asset Tracking Application Interface

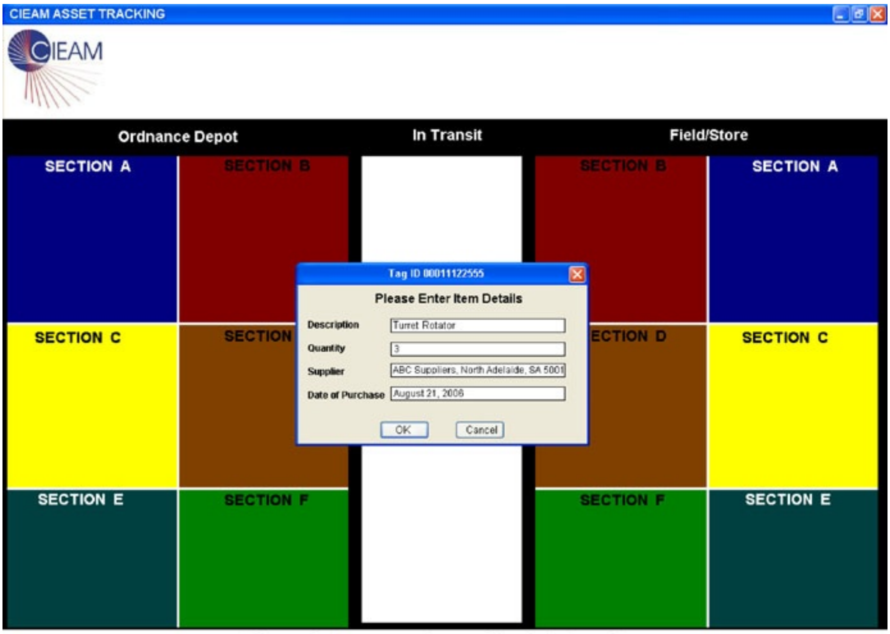


Figure 9 Inventory Items Check-in Interface

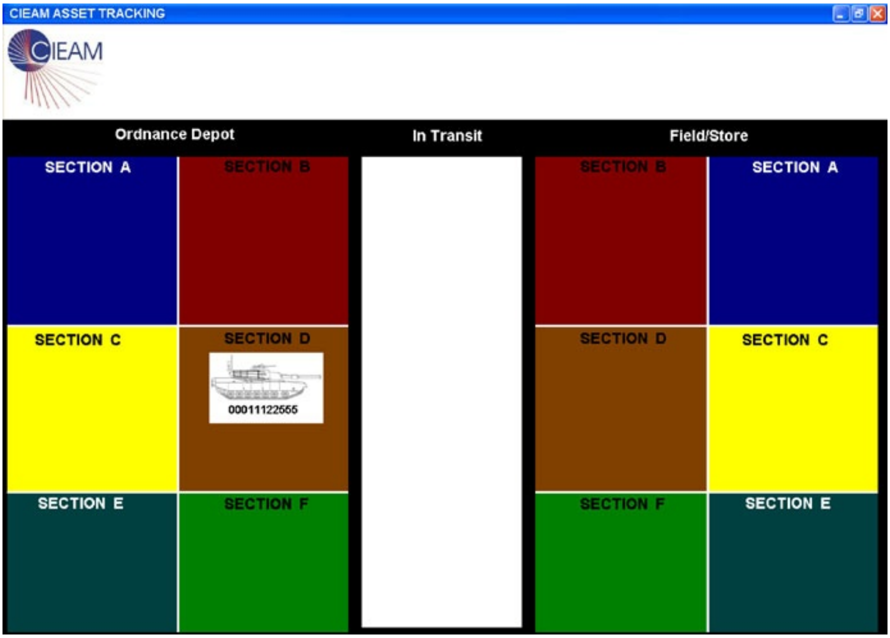


Figure 10 Inventory Item Checked in

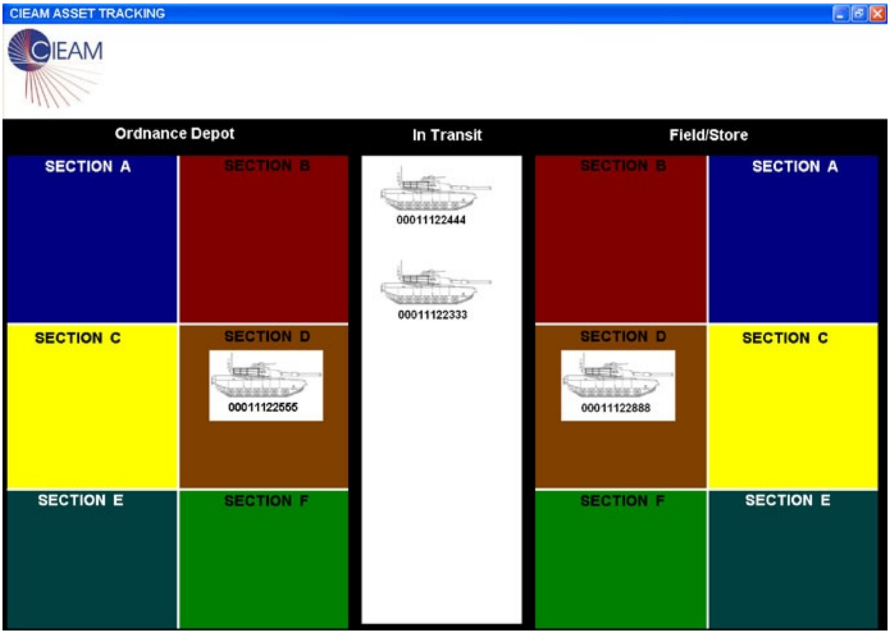


Figure 11 Inventory held in Depots and in Transit

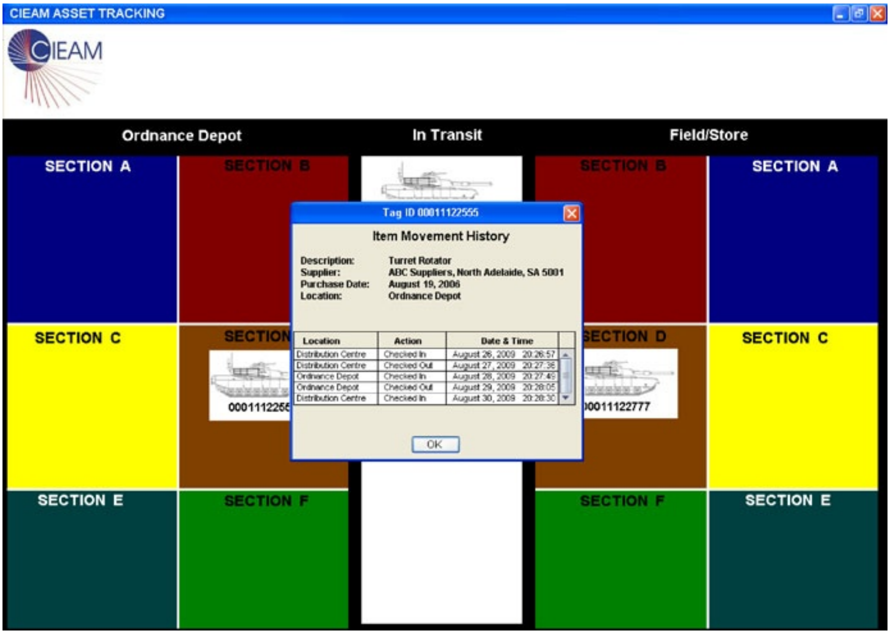


Figure 12 Asset Tracking Application Interface

However, it must be pointed out that the prototype was tested in laboratory only and did not have the chance to test it in field. Nevertheless, some of the issues that we faced using this technology were the malfunctioning of the technology in high magnetic fields, and in environments where other high frequency based equipment was in operation. Apart from these, a major issue that we encountered for item tracking was the real time monitoring of an item when the same is in transit. RFID tags have a limitation and require the reader to be in close proximity of a tag, which means that they work well within the warehouse or a defined space, however it cannot be used to track items moving out of the range. We considered GPS tags; however GPS technology cannot work in in-door environments. Therefore, in its existing state RFID technology can be used for item tracking between different staging sections and within those staging section; however it cannot be tracked in real-time when the item moves out of the staging sections and is being transported. Further research is required in resolving this issue.

6.3 RFID for Condition Monitoring

We used Chipcon's CC1010 evaluation kit for the proof of concept for condition monitoring. The kit includes an evaluation board (CC1010EB) and two evaluation modules (CC1010EM). CC1010EB provides access to all of the analogue and

Figure 13 Left CC1010 module, Right CC1010 development board with module attached

digital pins on the CC1010, along with two serial ports, a parallel programming port, RF network analysis ports, and other peripherals. Each evaluation module features CC1010, an antenna port, and an analogue temperature sensor. CC1010EM includes an RF transceiver that can run from 300 MHz through to 1 GHz. It has an onboard 8051 8-bit microcontroller with 32Kb of flash for code and non-volatile data, 2 K of RAM. CC1010EB supports three ADC (analogue-to-digital converter) channels, a Universal Asynchronous Receiver Transmitter (UART), and 26 I/O pins. An important feature of CC1010 is that it can be read and written from distances in excess of 100 meters. At the same time, the tag supports a serial peripheral interface, and a hardware Data Encryption Standard chip for secure communication. Its flash RAM is divided into 256 pages with programmable protection flags that prevent unauthorized downloading of internal programs and data. All these features make the CC1010 a versatile platform for applications where we want to add external sensors to the modules. The general purpose I/O pins can be connected to temperature, humidity, pressure and a whole range of external sensors. The two hardware UARTS are used to communicate between serial devices, this may be a PC other RFID modules or and hardware device using serial communications.

We envisioned the framework presented in Figure 14 that utilizes CC1010 tags. In this framework each asset is attached with a CC1010 tag or a collection of it, such that all tags collectively form a wireless mote network with the provision of a gateway tag that provides for communication of data captured by the network. The gateway tag serves as the liaison between the database server and sensor network and delivers data captured to condition monitoring database. Apart from unique identification of the asset, the availability of serial ports in CC1010 provides for interfacing digital as well as analogue sensors. This means that it allows a connection with any amount of sensors used for condition monitoring of an asset. This framework highlights continuous streaming of data without having to have any

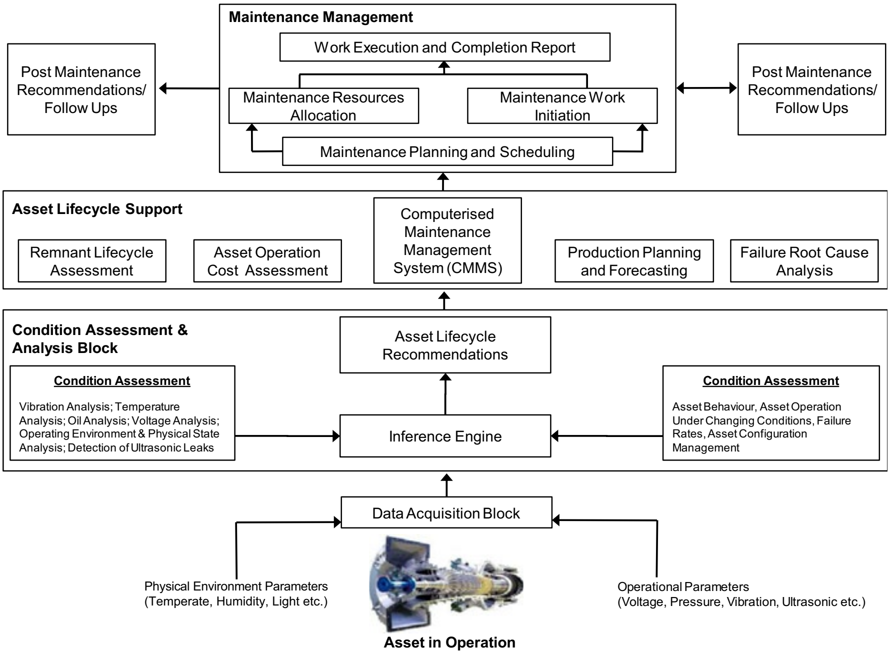


Figure 14 Integrated Condition Assessment Framework

human intervention for data logging or recording. Obvious advantages of this type of CM are reduced labour cost, better fault detection, and identification of dangerous or hazardous areas without incurring risks to maintenance crew. Most significant advantage of this framework is that it makes possible economical remote condition monitoring. The framework captures data from different channels simultaneously and processing the same immediately, thereby achieving greater accuracy in failure prediction. At the same time, it is also useful in isolating the area where the fault may be developing.

In this proposed framework, the condition assessment block represents a series of decision support indicators, analyses and trend projections of assets operation. Using these comparisons and behavior assessments of asset operation useful deductions could be drawn for asset lifecycle support. The inference engine acts like a watch dog and compares the probabilities and possibilities before generating recommendations concerning asset life cycle support and other associated processes. Using RFID for prognostics poses significant advantages for engineering enterprises, and proves to be an important building block towards e-intelligence based maintenance and asset management. This framework allows for a technologically convergent and miniaturized device that bears most of the features of a SCADA systems at a fraction of its price. For proof of concept we used the technologies presented in Figure 15, and an external humidity sensor and the temperature sensor that is embedded in CC1010. The raw information captured from the sensors was communicated through the gateway to a transition database. The

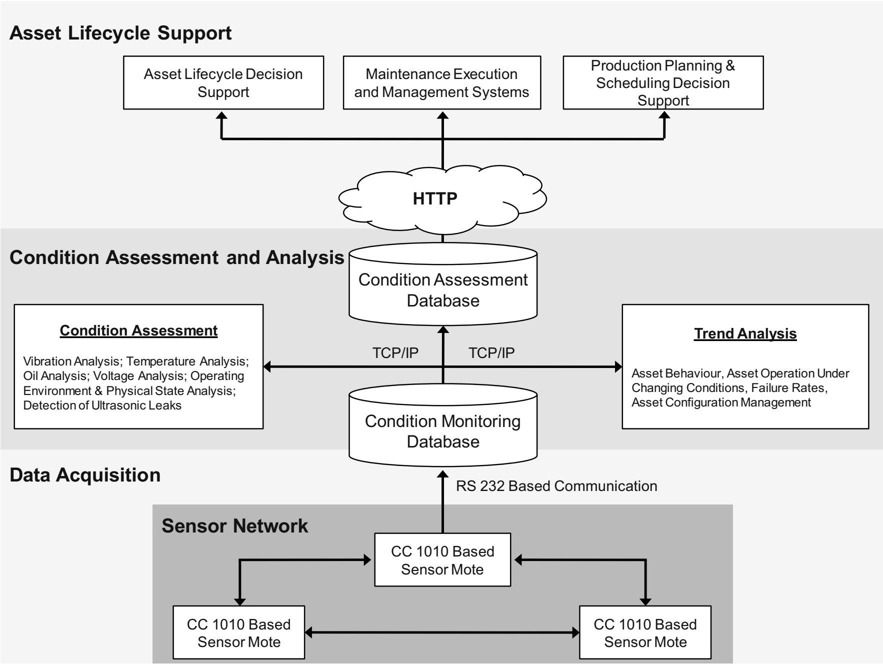


Figure 15 Integrated Condition Assessment with CC1010

interface allowed for viewing this information as graphs or simple readings over a period of time. However, this information could easily be fed into a condition database with time stamp and tag ID, where it could be analysed further. The TCP/IP based connections allowed for a distributed server model, which means that using this framework remote condition monitoring is also possible. Apart from providing advances such as consolidation of condition information and single channel communication, another advantage of this framework is fault detection. An essential characteristic of RFID tags is their ability to identify themselves, therefore when the information captured from each asset is analysed, it provides important indication on exact location of the asset under investigation. For example in case of a failure condition developing or any malfunctioning it can point that at site number 1, pump no 2's vibration pattern is unusual. At the same time, this information together with information on other variables will provide for the exact nature of the fault and indications on its maintenance demands. The onboard memory provision of CC1010 could be used to store information, such as asset health and maintenance record, which could be updated after each maintenance execution.

Using RFID for prognostics poses significant advantages for engineering enterprises, and may prove to be an important building block towards e-intelligence based maintenance and asset management. This methodology allows for development of a technologically convergent and miniaturized device that could easily be mounted on an asset and realise centralized data acquisition. It reduces monitoring costs significantly and improves asset reliability through efficient prediction of asset failures. We tested the technology for two sensors; it will be interesting to see how the RFID tag behaves when more sensors are attached. Other area of research is of making the technology more efficient, as the on board power supply of CC1010 has limited life span. Once these issues are resolved, it will be worth while to investigate the ways of integrating the inference engine on the gateway sensor mote.

7 Challenges Posed to RFID

Since the modern wave of RFID technology is still evolving and the technology can best be described as emergent, there are many issues and challenges associated with the technology. As mentioned before, one of the issues associated with RFID is the lack of uniform frequency spectrum. Different standards organisations and governmental legislations are under way to address this issue. Standards development efforts also include developing standards for hardware and software used in RFID technologies. However, there is another issue that emerges from standards development, which is regarding the multiple efforts towards developing standards for RFID operation. This means that in the presence of multiple standards there is no guarantee that the technology will embrace uniformity at a global scale. A corollary to the issue of multiplicity of standards is interoperability. This is, however, not to say that this problem does not exist at the moment. The issue of interoperability includes readers as well as tags, as presently the tags and readers have fixed operations and it is not possible to read high frequency tags with a low frequency reader. Acceptance of RFID technology will require it to be of low cost, and to be of low cost this issue of interoperability needs to be resolved. Cost effectiveness of RFID technology is actually an issue that small business and SMEs are facing at the moment, as they have limited budgets and limited expertise available at their disposal. Security and privacy are two other issues that are catching the attention of consumers as well as the general public worldwide. With the existing nature of technology (primarily passive RFID tags) it is possible to read tags without any problem, which means that anybody could identify tagged items and could track their movement. A solution often proposed to address this issue is to encrypt the message, however as yet there is no solution on market that could provide this functionality and security.

8 Conclusions

The primary aim of this evaluation study was to test RFID technology for possible uses in asset management. We were able to successfully test the technology for three different applications. Nevertheless, the proliferation of RFID technology is subject to the development of technology to overcome some of the issues identified in the paper. These issues and challenges include robustness of technology, operation of technology in different environments, lack of standards, cost, data/infrastructure/systems implementation issues, data sharing and security. Nevertheless, with further research into these areas it is anticipated that large scale implementation of RFID will occur in the next few years.

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Wireless Condition Monitoring and Embedded Novelty Detection

Christos Emmanouilidis and Petros Pistofidis

Abstract Wireless sensor networks are increasingly employed in a range of applications. Condition Monitoring in particular can benefit from the introduction of distributed wireless sensing solutions, operating with a high degree of autonomy. Wireless condition monitoring can extend the toolset available to the lifecycle management of engineering assets, offering ease of installation, flexibility, portability and accessibility. A significant hurdle for the adoption of wireless condition monitoring solutions in industry is related to the extent that such solutions can operate over long time periods, while providing adequate monitoring. At the application level of sensor nodes, recent programmable wireless modules are able to host intelligent services exhibiting some form of smart behavior that enables them to recognize events that deserve further attention. Thus, engineering assets equipped with embedded novelty detection capabilities exhibit some level of self-awareness, much needed to support enhanced and sustainable operation. Investing in sensor logic and its software implementations upgrades wireless modules to small model building agents capable of providing strategic advantages over static sensing infrastructures. The configurability and the programmable nature of recent maintenance management techniques and their decision support algorithms can now be ported to software agents hosted on tiny devices right in the operating environment of each asset. In this paper we review current enabling technologies, with respect to implementing ubiquitous maintenance solutions, and we study the design requirements for developing Novelty Detection techniques, as intelligent

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middleware components embedded on a single sensor module. On the basis of the identified design requirements, a conceptual architecture for the development of wireless sensor – embedded intelligence is outlined.

Keywords Condition Monitoring, Wireless Sensor Networks, Novelty Detection, Smart Sensors

1 Introduction

Industrial needs for mass customization and increased manufacturing competition exert more pressure on enterprises to improve their operational efficiency in order to preserve their long-term sustainability. In the pursuit for rapid adaptation to the ever changing production demands and manufacturing paradigms, a sustainable manufacturing organization should be supported by a versatile maintenance engineering infrastructure. The maintenance management, execution and operations framework should have goals that lay beyond the horizon of simply preserving the operating condition of isolated process equipment at a desired level. Instead, a holistic view of maintenance is required, from the operations level, wherein monitoring of critical machinery parameters is taking place, all the way up to the level where strategic decisions are taken, influencing production process planning and imposing targets and constraints to production machinery operation. High-level maintenance planning can only succeed insofar it is based on valid operational-level data and reliable machinery operation. Within a lifecycle engineering management approach, condition monitoring emerges as a key enabling factor to support sustainable operation of machinery, engineering structures and production, units (Kiritsis 2010).

Most modern industrial manufacturing processes utilize condition monitoring systems that rapidly adopt and benefit from technology innovations. These advancements provide upgrades for the system's technical infrastructure or operating logic. The former include device architectures that may include system-on-a-chip (SOC) designs or isolated advanced circuits, while the latter chiefly refer to supporting logic and software tools – such as novelty detection, diagnostics & prognostics, enhancements in computerised maintenance management systems and remote services. Wireless sensor networks offer easy and customizable deployment of several sophisticated agents of small form-factor Within an e-Maintenance approach (Liyanage *et al.* 2009; Muller *et al.* 2008), these monitoring agents are able to host automated computational and data storing operations that scale from elementary sample filtering to complex data processing (Monostori *et al.* 2006; Moyne 2007). The current vision is that such programmable features of the latest wireless sensor modules, coupled with their wired counterparts, can fuel the development of on-line maintenance management systems that rely on processed data-streams from intelligent services hosted on dynamically formulated monitoring subnets. These dedicated subnets, populated by capable software components, will be able to monitor, model, diagnose and become calibrated to the operating behaviour of each specific machine installation. Sustainability in such systems is essentially supported by a virtual technician who samples and smart-processes the machines parameters on a 24/7 basis. This virtual technician's efficiency can be easily upgraded by simply adding more wireless agents or updating their embedded software.

Presently, maintenance service providers are not limited to static solutions of wired infrastructures controlled by complex software suites. Utilizing an isolated server as the sole point-of-access for machinery information in a monitored environment, does not constitute anymore the most efficient approach. Data relevant to condition monitoring and equipment maintenance can become ubiquitously available to technical personnel, via mobile and handheld devices, or remotely via the internet by simply coupling to services residing directly in the sensing infrastructure. In the medium to long term, this approach opens up the potential for the creation of a new market niche, wherein condition monitoring and maintenance service providers will be offering highly efficient and customisable software solutions, with increased interoperability to operate seamlessly on top of various wireless sensing modules. Key to this radical innovation is the ability to perform reliable condition monitoring tasks, based on flexible, portable and easily deployable systems, making extensive use of wireless and miniature-devices (Arnaiz *et al.* 2006). With industrial equipment increasingly being treated as asset whose value needs to be managed, an important research edge is to embed self-awareness features, both in stand-alone machinery, as well as in complex equipment configurations or production lines and units (Emmanouilidis and Pistofidis 2010). This paper deals with issues pertaining to the development of wireless sensor network-based condition monitoring. Current hardware/software platforms and applications are reviewed and we take a look at the design features, the architecture and the implementation issues that involve the development of sensor-embedded intelligence. That is a set of functions and services, able to deliver efficient local processing of condition monitoring data, which can be exploited for novelty detection & diagnostics and can be ported to wireless sensor networks. Our approach places machinery self-awareness as a key feature for achieving sustainable machinery and therefore production operation. We argue that the first step towards machinery self-awareness is embedded software implementing novelty detection. The discussed research can lead to platform attributes able to significantly widen the range of sensor-embedded software functionality, allow rapid development of the proper middleware components and ensure efficient novelty detection performance. Novelty detection is a key first level of processing for condition monitoring, which in turn holds the key to enhancing and extending sustainable machinery operation.

This paper is organized as follows. Section 2 reviews wireless condition monitoring applications. Section 3 takes a closer look at some of the current wireless sensor network platforms and their characteristics, with a view to their potential benefits to wireless condition monitoring. Next, the available sensor operating systems and middleware are discussed, upon which the development of an embedded – logic novelty detection and condition monitoring architecture can be based, as discussed in Sections 4 and 5, respectively. The targeted industrial pilot case is briefly presented in Section 6, followed by the conclusion.

2 Wireless Condition Monitoring

Wireless sensor networks are increasingly deployed as flexible alternatives to wired instrumentation systems. Their ease of installation & operation, scalability and topology flexibility are seen as their main advantages over wired solutions. Recent advances in microprocessors and board integration methods have provided the means to produce potent, richly-featured and considerably cheap sensor board architectures. Current sensor boards contain powerful 32 bit CPU architectures, several MB of flash memory, and diverse RF connectivity, *e.g.* Bluetooth, WiFi or ZigBee. Research utilizing these architectures has made possible the transition of sensor board logic from simple protocols and algorithms printed on bare metal, to complex multi-tier middleware platforms. Such middleware can effectively sit on top of various dedicated sensor operating systems and provide interfaces for pluggable application components. On the down side, they have a limited battery life used to support their low-consumption tiny scale SOC integrations, while they can be susceptible to interference and noise. Extending battery life is sought by means of optimising the sensor node power management through energy-saving protocols and energy-aware profiled operation scheduling. Alternatively, research efforts have been devoted to convert sensor nodes from passively powered components to active systems that seek to balance power consumption with power management and harvesting, in the form of self-powered sensors. This is the prime objective of the recent EnOcean initiative, targeting primarily the building monitoring sector[1], Power management is still very much an issue open to research, seeking to identify adequate trade-offs between capable wireless sensor modules and energy-saving implementations.

Condition monitoring was from the outset an early adopter of emerging sensor technology. Soon after wireless technologies started to mature in modular designs and implementations, advances in hardware integration of wireless circuits and embedded programming of wireless protocols lead to the concept of wireless sensor networks. The mass availability of small wireless devices and their applicability to industrial automation enabled access and transmission of sampled data or processed information anytime and anywhere. Wireless sensor networks can scale up to compose large monitoring environments, since expanding a network is as easy as simple node placement/addition. The main advantages brought by wireless sensors include:

- Ease of installation: sensor positioning is freed from the constraints of cabled installations.
- Accessibility: every point of measurement becomes accessible. Each individual wireless sensor node can be mounted to various positions on the monitored machine. The small size and autonomy of these devices allows extensive placement customisation, including locations that would be harder to consider for wired instrumentation. Furthermore, it is also possible to retrofit sensors onto equipment after the latter has been installed, with minimal intervention.

[1] www.EnOcean.com

- Simplified network design: dynamic topologies for fault tolerant networks allow redeployment, traffic rerouting and network robustness to deal with possible interference. Mesh sensor networks provide dynamic self calibration and embedded diagnostics that constantly calculate optimal reconfigurations. Such features are essential for all wireless deployments, especially when they have to utilise congested bandwidth for their communication.
- Scalable, large and yet maintainable infrastructures, as new nodes can easily be added to the network. Upgrading, maintaining and restoring wireless sensor nodes results in near zero down-time for the monitoring system. Reconfiguration of the topology is instant, while any new nodes are automatically accepted by the network and directly utilised to serve the monitoring process. Thus the network is tolerant to faulty nodes and can always adjust to deliver monitoring services. Wireless sensor networks are by nature a versatile and easy to maintain infrastructure.

Wireless sensor network deployment and applicability may nonetheless be constrained by the limited battery life of the sensing node, its higher costs and susceptibility to damage when the node is not offered in a relatively ruggedized enclosure. Furthermore, relatively high powered interference, electromagnetic scattering and noise may cause additional problems, reducing the reliability and effective bandwidth of the deployed network (Conant 2006). Wireless technologies have been used in condition monitoring systems, bringing in considerable benefits. With wireless sensors rapidly evolving in multiple engineering disciplines (both in terms of hardware components and their embedded logic), there currently exist a significant number of different academic and commercial wireless sensor platforms. New alliances and vendors have been formed around the technology, producing building blocks and prototype systems that serve low duty-cycle monitoring environments for applications such as commercial buildings, public infrastructures and industrial plants, as long as radio transmission is relatively robust. These set of 'early adopters' are gradually creating initial success stories and know-how, preparing the ground for a much wider adoption of wireless condition monitoring. Thus, in the last five years, WSNs have made a growing impact serving mainly non-manufacturing application areas. A second wave of adopters is currently growing in the manufacturing area, where large installations of wireless condition monitoring systems move from their infancy to more robust deployments with accurately defined functionality and effective co-existence and connection with previous maintenance subsystems and infrastructures. Early research efforts have given rise to evaluation testbeds, piloting installations and device prototypes, gradually leading to more efficient and upscaled condition monitoring tools and solutions. Based on the extent and results of the active research and the recorded number of end user deployments, two broad application areas have already emerged for wireless condition monitoring systems:

A. *Structural Health Monitoring (SHM)* – The structural health of large scale constructions, such as highway and railway bridges and utility infrastructures, constitutes a problem space where maintenance is translated in large annual expenditures and high-risk manual inspections. Since accurate multipoint measurement is the rule here, wired deployments tend to limit the infrastructure's sensing capabilities merely to its first installation placement configuration. Moreover, routing wires on a structure, to implement a sophisticated placement plan tends to contribute to any degrading process that undermines its solidity. Maintaining the monitoring infrastructure adds one extra reason for a technician to conduct visual inspection of wires and devices. In the context of SHM, wireless sensors do not operate as sampling simple endpoints. Their capabilities and complexity designates them as autonomous data acquisition nodes to which traditional structural sensors (*e.g.* strain gages, accelerometers) can be attached. In such wireless condition monitoring processes the sensor network is viewed as a small scale platform in which mobile computing and wireless communication elements converge with the sensing transducer. A platform with a layered embedded logic:

- The Operating System – it provides an abstraction layer, hiding the hardware control mechanisms from higher level software components.
- The Middleware Applications – hosting the implementation of methods and algorithms designed to autonomously process and store structural response.

Examples of such monitoring deployments are analysed in (Chintalapudi *et al.* 2006), where a two-tier hierarchical architecture (resource constrained sensors/computationally potent sensor modules) is used to compose a highly responsive and robust wireless sensor network for vibration monitoring and analysis. In (Lynch and Loh 2006) a detailed review of various wireless sensing modules is conducted surveying their hardware features and testing their ability to fulfil the required complexity of structural history analysis and data processing. Wireless condition monitoring has been widely adopted by systems supporting civil infrastructures such as bridges (Kim *et al.* 2007) (Wang *et al.* 2007) or pipeline network (Stoianov *et al.* 2007) where the size of the deployment area requires placement specification only met by the versatility of wireless sensor networks.

B. *Equipment or process monitoring* – Industrial plants constitute the second largest and most significant application domain for wireless condition monitoring. Wireless sensor networks have been primarily piloted and tested in non-critical industrial environments and manufacturing processes (Alhetairshi and Aramco 2009). Application examples include condition monitoring of rotating machinery (Lee 2008; Son *et al.* 2009), machine tools & machining processes (Tan *et al.* 2009; Wright *et al.* 2008b), Condition monitoring involves analysis and processing of high-resolution sensor samples, using intelligent, statistical and pattern recognition techniques to estimate the condition state of a component, machine, or process. A condition monitoring system enables the implementation of a condition-based maintenance strategy, whereby maintenance decisions are taken on the basis of the actual monitored entity condition, with clear benefits:

- Predictive maintenance applications have benefited from automating the traditional manual process for the collection of machine state data through visual inspection and instrumentation. Wireless condition monitoring systems allow multiple samples to be flexibly acquired, while their nodes' processing units can execute single-node or even collective algorithms effectively driving smart prognostics and diagnostics closer to the machine's operating environment (optimal responsiveness) (Ramamurthy *et al.* 2007).
- Condition monitoring has benefited from the fact the wireless condition monitoring facilitates the sampling of far more sensing points and parameters than any wired solution. The ability to reconfigure sensor placement or even re-distribute the number of sensor modules among the wireless network's subgroups (each dedicated to one monitored equipment), offers limitless calibration potentials for the network deployment and topology.

Many wireless deployments that serve industrial condition monitoring, focus on the operational behavior and the condition state of a single critical machine. Such an example is presented in (Chan and Tse 2009) where a motor-driven equipment is monitored by wireless vibration sensors embedded with a data compression algorithm that uses empirical modelling to identify instantaneous changes in non-linear and non-stationary signals, caused by anomalous machinery operation. Another example of critical-machinery monitoring is described in (Discenzo *et al.* 2006) where self-powered wireless vibration sensors are employed to monitor the state history of a large shipboard pump. An evaluation of WSNs, and their supporting platforms, to provide tools for research in predictive maintenance and condition-based monitoring of end-milling is also reported in (Wright *et al.* 2008a). In a plant-scale application example, the deployment of an extended WSN to support quality control operations in a water plant is reported in (Shah 2007), featuring aspects of a "Smart Factory" concept. The flexibility and versatility offered by wireless technologies enable an increased level of self-awareness about the state of individual machines to be attained. In doing so, they pave the way to more widespread implementation of condition-based maintenance (CBM) policies. CBM itself has been defined to be implemented at different layers by the Open System Architecture (OSA) for CBM (Thurston 2001), adopted under the ISO-13374 standard for Condition Monitoring and Diagnostics of Machines and the MIMOSA Open Systems architecture for CBM (www.mimosa.org). Although much development effort has been devoted to the definition of related standards and to the development of appropriate operating systems and middleware for WSNs, much more research effort is needed in this area to reach a maturity level that will enable rapid application development and engineering solutions for industrial condition monitoring. In all cases, wireless condition monitoring based on WSN should offer smooth data acquisition, processing and transmission. To achieve this aim, WSNs must be supported by the availability of adequate WSN operating systems and middleware. Based on the availability of such operating systems and middleware, several different application modules and services can be built and integrated within a mobile maintenance management architecture (Arnaiz *et al.* 2006; Emmanouilidis *et al.* 2009).

3 Wireless Sensor Networks

A typical wireless sensor network comprises several sensing nodes deployed to cover an area of interest. Each sensing node is typically a miniature device comprising a board with sensing/actuating elements, a power unit, local CPU, memory, and an RF communication component comprising an antenna and a transceiver, while it may also incorporate other application specific modules (Figure 1). A wireless sensor network is a system largely characterised by (Sohraby *et al.* 2007):

- its topology, mesh, star or hybrid, with mesh being more applicable to large scale outdoor deployments and star or hybrid being preferable choices for more controlled flow of information in short range areas, including industrial sites;
- its communication protocols, such as 802.15 (http://www.ieee802.org/15/);
- the type and physical characteristics of the employed sensors (*e.g.* temperature, vibration, light);
- the operating environment (indoor/outdoor, harsh, hostile, office/industrial, *etc.*);
- the energy availability (limited/unlimited, rechargeable);
- the nature of the sensing nodes operation (cooperative/non-cooperative);
- the sensor network operating system and middleware.

The successful implementation of sensor network solutions depends on the maturity, functionality and expandability of the corresponding sensor network middleware and operating systems. These may deal with the way sensed data is ag-

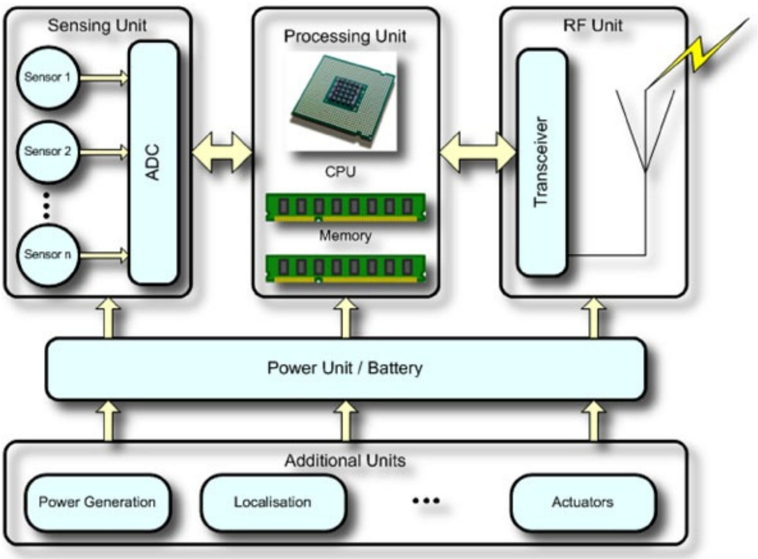

Figure 1 A Wireless Sensing Node

Table 1 Wireless Protocols Features

Protocol Features	Bluetooth	ZigBee	802.11x
Maximum Bandwidth (lower in practice)	Up to 3 Mbps for Bluetooth 2.1.	Up to 250 Kbps for 802.15.4	Up to 54 Mbs for 802.11g, over 100Mbps for 802.11.n
Operations	Data transfer between devices, cellular phone peripherals	Wireless sensor networks, industrial and home automation	Individuals, wireless internet service providers (WISPs), wireless intranets
Operating Band	ISM 2.4 GHz unlicensed	ISM 868 MHz, 915 MHz and 2.4 GHz	ISM 2.4 GHz or 5 GHz for 802.11.a and 802.11.n
Range	10 m maximum in best conditions (100 m for high powered devices)	Typically up to 10 m	100 m maximum in best conditions
Battery life	Hours to days	Days to years	Minutes to hours
Size/Cost	Small/Low cost	Very small/ very low cost	Medium to large/ medium

gregated or disseminated, as well as the way information routing is implemented. The latter can be done in a number of ways, such as data-centric, hierarchical, hybrid or by placing emphasis on sensor location or on Quality of Service (QoS) and performance issues. Sensor management (naming, localisation, maintenance, fault tolerance), authentication, registration, tracking and session establishment issues are largely dealt with by the WSN operating system and middleware. Our focus here is not on the sensor technology itself, but on issues related largely to the WSN operating system and middleware, to the extend they impact on the practicalities of implementing wireless condition monitoring. WSNs offer diverse characteristics, based on the adopted technology and protocol (see Table 1). They can be based on protocols, such as Bluetooth (www.bluetooth.org), WiFi (www.wi-fi.org), WirelessHART (Highway Addressable Remote Transducer) (Foundation 2007) and even proprietary ones, yet it is the ZigBee protocol that has emerged as a de facto industry standard for employing WSNs in industrial automation and conversely in wireless condition monitoring (Baronti *et al.* 2007; Gungor and Hancke 2009; Moyne 2007; Wheeler 2007).

Indeed, the market forecast for ZigBee nodes was to reach half a billion by the end of 2010, exceeding a market value of $ 7 billion (Sohraby *et al.* 2007), although more moderate estimates were suggested by other market studies[2,3], with figures reaching a peak at around 2013, partly due to an expected drop in prices. This market increase is fuelled by a the technology push leading to lowering the

[2] ON World WSNs for Smart Buildings, 2009
[3] IDTechEx ‘Active RFID and Sensor Networks’ report, 2007

cost and size of wireless sensing units, while increasing their capabilities, as well as by a market pull, encouraged by the growing maturity of the offered solutions and a real demand across application domains. The main reasons for the increasing adoption of ZigBee in industrial automation is its low cost and energy consumption, its small memory footprint, its relatively long range and the support for a large number of connected nodes. The initial application markets for ZigBee are energy management, industrial, home and building automation, supported by the development of public ZigBee profiles offering standardisation of interfaces between ZigBee compliant devices. More recently, ISA standardisation efforts are targeting at the development of the ISA100 family of standards for industrial automation, including IEEE 802.15.

3.1 Smart Sensor Networks

A *smart* sensor is a term advocating the presence of sophisticated sensor functionality. Smart transducers are defined in the IEEE 1451 family of standards. These outline a set of protocols for wired and wireless distributed monitoring and control applications. IEEE 1451 smart transducers are expected to have capabilities for self-identification, self-description, self-diagnosis, self-calibration, location-awareness, time-awareness, data processing, reasoning, data fusion, alert notification (report signal), standard-based data formats, and communication protocols, supported by the so called TEDS (Transducer Electronic Data Sheets) (Song and Lee 2008). Smart sensor behaviour may vary from simple signal amplification to advanced data modeling techniques for condition monitoring (Boltryk *et al.* 2005). The characteristics and functionalities of a smart sensor are listed below (Vadde *et al.* 2004).

- They include the processing capacity and the proper software routines to process data locally.
- They can make efficient use of the network infrastructure through complex protocols and distributed communication patterns. Smart sensors are able to implement policies that enhance the network robustness and flexibility, and lessen the burden on centralized nodes.
- They can support the execution of advanced distributed processes. These may include collective decisions, node task allocation and workflow management for the entire network.
- They should be able to classify the data according to its criticality, in order to avoid unnecessary data processing during a critical stage of the monitoring item. Smart sensors can evaluate situations and configure sensing frequency enabling better monitoring performance when identifying a critical state.
- They should be capable of self-diagnosis and self-calibration and be able to periodically prompt on coordinating sensors to collect and process network sta-

tistics. Such processing can result in network self customizations that balance topology and upgrade sensing performance. Faulty sensors can be easily identified, while the deployment of new nodes can be estimated based on sensing coverage maps and algorithms.
- They can be re-programmed and facilitate the network to receive remote software updates. Additional processing techniques can be downloaded to a smart sensor. This feature eliminates the down-time of the network for updates.

Inside most condition monitoring systems the sensor node constitutes the end-point component that lays closest to the machine. In the past, the main role reserved to the monitoring sensor was that of simply measuring parameters and transmitting (through wire) the samples to a data acquisition unit for further processing. The first step towards "smart sensor behaviour" is that of having nodes capable of conditioning and processing the monitored signal, before transmission. This upgrade is enabled by the introduction of hardware & software components (microcontrollers, memory, and basic processing software), into a sensor-scale board. These sensors moved from sensing end-points to "sensor nodes" and their device level architecture has been rapidly evolving. More sophisticated network-scale wireless sensor node architectures implement and support the second leap towards sensor intelligence for condition monitoring systems. Typical sensor-node designs now provide the basis application-oriented embedded software, addressing specific monitoring needs, thus enabling the wireless modules to perform:

- Intelligent Sensing – Decide when to send machine parameters, by local evaluation of their novelty, significance, as well as confidence in reaching a first-level decision. The decision at this level should be merely focused on whether the monitored signals and parameters are 'of interest', so as to trigger further processing (*e.g.* transmission, diagnosis).
- Intelligent Sustainable Monitoring Tools – Constantly monitor the sensor network and adapt its topology and operation to new parameters, conditions and events (i.e node failure). Network self-diagnostics and self-calibration can now be placed inside the tool (sensor nodes) and no longer constitute a responsibility of the instrumentation technician.
- Intelligent Diagnostics – Warning/Critical level measurements automatically invoke local execution of simple or complex diagnostic procedures. Embedded databases can effectively store reference history samples or previously processed machine state models. The technician can correspondingly access and respond to the reports or alert signals, while further development can lead to systems that self-trigger data transmission and remote services.

Such a WSN architecture can constitute a key tool to support sustainable machine operation, as instead of sophisticated handheld instruments, connections to remote data centres, or printed machine history, the only needed tools are simple handheld devices able to wirelessly connect and couple with the service software components residing inside the sensor attached to the audited machine. The above smart sensor behaviour allows great potential for local data processing, upgrading the value of each sensor according to:

- What has it been stored and recorded up until now, such as machine state parameters and events history.
- What has it been modelled and learned up until now – reference parameters and models, capturing the machinery normal/abnormal behaviour. Profiling separately each machine or even each point of measurement, is becoming feasible, while still allowing for jointly considering multiple measurement data for modelling more complex behaviour.
- What has it been diagnosed and reported up until now – correct/false alarms, confidence & novelty detection, efficient reporting and suggestions for further actions.

Smart sensor networks are a form of programmable sensor infrastructure. Their role is not confined to monitoring a single unit. Their programmable nature enables deployment to serve different condition monitoring tasks, with minimal reconfiguration, thus forming a flexible and easy to customise tool that can support sustainable machinery operation.

3.2 Enabling Hardware Components

The technological edge of the most recent wireless sensor designs and architectures is reflected to their increasingpenetration in monitoring systems. Their programmable nature offers huge potential of customization and configuration adjustment. Their ability to quickly adopt the cheap processing power and memory capacity constantly strengthens their place at the device-level of system components hierarchy. Some of the best performers, in terms of balanced capacity and energy efficiency, are powered by 8bit (Crossbow IRIS/Micaz), 16 bit (Shimmer, Quax MS-Pro) or 32 bit (SunSPOTs (Simon *et al.* 2006), Crossbow Imote2) processors. Memory capacity (RAM/EPROM/Flash) can scale from several kb (Crossbow IRIS/Micaz, Shimmer, Quax MS-Pro) to several Mb (SunSPOTs, Crossbow Imote), or even external storage (Shimmer). Table 2 presents details of specific wireless sensor node hardware, whereas more comprehensive listings can be found in dedicated web resources[4,5,6].

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[4] The sensor network museum, available at http://www.snm.ethz.ch/Main/HomePage, as of 16/4/2010

[5] WSN mini hardware survey, available at http://www.snm.ethz.ch/Main/HomePage, as of 16/4/2010

[6] Body sensor networks, available at http://ubimon.doc.ic.ac.uk/bsn/m206.html, as of 16/4/2010

Table 2 Smart Wireless Sensor Modules Classification

Wireless Sensor Module		Microcontroller	Memory Capacity	Wireless Connection	Operating System	API/Middleware
Crossbow (IRIS/MICAz)	 IRIS  MICAz	ATmega1281 8-bit	8KB SRAM (IRIS), 512 K (Ser.) FLASH, 128 K (Prog.) FLASH	2.4 GHz IEEE 802.15.4/ZigBee compliant	TinyOS Based, Contiki (IRIS)	MoteWorks/TinyOS Nesc
Crossbow (Imote2)	 Imote2	Intel PXA271 32-bit	256KB SRAM, 32MB FLASH, 32MB SDRAM	2.4 GHz IEEE 802.15.4/ZigBee compliant	TinyOS, Linux and SOS	MoteWorks/TinyOS Nesc, Microsoft.NET Micro Framework
Sun (SunSPOTs)	 SunSPOTs	ARM920T 32-bit	512KB RAM, 4MB FLASH	2.4 GHz IEEE 802.15.4	Java Squawk	Java APIs
PrismaSense (Quax MS-Pro)	 Quax MS-Pro	MSP430 16-bit	10KB RAM, 40KB FLASH	2.4 GHz IEEE 802.15.4/ZigBee compliant	ISOS	Microsoft.NET Micro Framework
Shimmer (Shimmer-Research)	 SHIMMER Sensor	MSP430 16-bit	10KB RAM, 48 KB FLASH, Micro SD	2.4 GHz IEEE 802.15.4 and Bluetooth	TinyOS	TinyOS Nesc/Labview

3.3 Energy Issues

Managing and minimizing the energy consumed during the operation of a wireless sensor based system, is a major concern. The main driving force for this effort is the resulting increased energy lifetime of the system. To be able to make solid steps towards such a goal, one should have a clear picture of the energy behaviour and the energy needs of each subsystem comprising a part of the sensor node architecture. This power analysis is extremely important to identify power bottlenecks in the system, which can then be the target of aggressive optimization (Raghunathan *et al.* 2002).

Though tiny in size, as sensor nodes make the transition from labscale test-devices to real-world assets, they offer increasingly complex architectures with demanding energy schemes. To facilitate this transition, research done on the node platforms has identified promising techniques that can yield significant energy benefits. The most efficient method to ensure energy optimization in a sensor network is to customize the design of the sensor-node platform itself. Ultimately, it is the sensor-node hardware that consumes the energy, so if the platform itself is not developed on an energy-oriented pattern, no amount of higher layer management can produce the desired energy behaviour (Raghunathan *et al.* 2006).

In the majority of wireless sensor networks deployments, the target event or amount that needs to be sensed and/or measured does not require constant sampling. Environments and situations, where continuous and permanent sampling and monitoring is essential (*e.g.* for integrity assessment, time-of-action or other reasons), are application areas where wireless sensor networks are inherently in disadvantage. The prime reason for that is that wireless sensor nodes are devices limited by the lifetime of their battery/energy source, while on the other hand real time performance are not strictly guaranteed. Their sampling/sensing activity is best characterised as periodical or on-demand, as every energy-aware activity does. The primary energy-saving behaviour has each node spending the majority of its time in a state of sleep. Waking up, to sample-compute-communicate, is programmed in predefined time slots or invoked when probed by external sources. To provide high-energy efficiency in this paradigm, a sensor-node platform should provide:

- ultra-low power-sleep mode;
- rapid wakeup capability to minimize the power management (duty-cycling) overhead;
- an embedded mechanism for controlling the transition between the sleep and awake modes and vice versa.

While awake, apart from sampling, a sensor node may perform a considerable amount of computation and communication activities. Both research testbeds and deployment feedback have proved that computation is far less expensive than communication, in terms of energy consumption. As VLSI designs advance, sensor nodes gain processor and micro-controller complexity while keeping a low level of energy consumption. Since computation cycles are cheap, sensor network lifetime is significantly enhanced when the system software, including the operating system (OS), application middleware, and network protocols, are all designed to be intelligently energy-aware. The exploitation of these sophisticated platforms has given birth to the concept of smart wireless sensors. Such sensors allow the development of innovative energy-balancing components that are embodied in the node's OS. This pattern has created a fruitful cycle of research that constantly upgrades wireless sensor energy behaviour in a number of ways:

- Efficient management of available energy.
- Energy saving hardware empowers high level computation.
- Smart behaviour can be computed based on intelligent models.
- Better tools and software components for sensor energy management are being developed. (*i.e.* Topology Management, Traffic Distribution)
- Greater efficiency in energy management.

The communication hardware in sensor nodes has only undergone small energy optimizations, not sharing the evolution steps of other subsystems. Though essentially serving communication interoperability and standardization, the mature state of 802.15.4/ZigBee protocol is promising controlled data transmission costs, by minimising the energy consumed in the Radio subsystem. Research conducted on the full range of communication layers proposes various energy-aware techniques (Raghunathan *et al.* 2002):

- Low Traffic Packet Forwarding – The use of intelligent radio hardware enables packets that need to be forwarded to be identified and redirected from the communication subsystem itself, allowing the computing subsystem to remain in sleep mode, saving energy.
- Power Management of Radios – Techniques such as dynamic voltage and frequency shifting are used to reach an optimal balance between transmission energy consumption and transmission latency.
- Modulation schemes – Higher modulation levels might be unrealistic in low-end wireless systems, such as sensor nodes. In these scenarios, a practical guideline for saving energy is to transmit as fast as possible, at the optimal setting.

Most of the discussed techniques have been widely used in real life deployments, in order to extend the network operating lifetime. Nevertheless, they often ignore a crucial aspect of the sensor node functionality, namely, the energy supply system (most commonly consisting of batteries). Whatever method a system might use for energy management, its batteries can only provide a limited amount of energy and thus place an upper bound to the network lifetime. To overcome these limitations, research has turned its attention on energy-efficient management of the nodes operation and energy-harvesting. In order for these approaches to present an attractive solution to the energy problem, two main design principles must be followed (Raghunathan *et al.* 2006):

- Extract the maximum power from the energy source, at each time instant dedicated to this process (since solar panels are essentially a “use it or lose it” power source).
- Minimize any energy overhead associated with the energy harvesting, storage, and transfer components.

Existing sensor-node platforms are unable to simultaneously satisfy all the above requirements. Their architecture and components can only be designed and developed, accordingly, to serve a small subset of the available power-saving methods. For example, an ultra-low-power sleep mode and an energy-efficient high-active mode represent conflicting objectives. As in every energy-oriented problem, WSN energy-management too, is an issue open to research, clearly in need of optimising energy-aware algorithms. The answer is nor trivial nor unique and lays in accepting the design rules of carefully balanced trade-offs based on best-performance practices. In summary, despite the fact that the WSN research community has made some progress on energy optimization, substantial research effort is still need in this area.

3.4 Supporting Technologies – RFID

RFID technology is used for identification purposes in a similar but more flexible way compared to barcodes. Reading is done via RF readers rather than direct and close optical scanning required by barcode readers. At the same time RFID tags can locally store limited information, for example history data readings and can facilitate structured and decentralised data keeping. The business case for RFID technology is strong, particularly in Supply-Chain Management (Angeles 2005). Using RFID technology, asset tracking and handling can easily become computerised, facilitating the integration of maintenance and asset management with the ERP and the overall O&M activities of the enterprise. RFID adoption has to overcome certain challenges both of financial as well as technical nature. The key technical challenge is how to achieve reliable operation in a wide range of operating environments, as RFID operation can be hampered by the presence of metal surfaces or liquids (Apel and Strömdahl 2008). Other issues are related to the larger effort needed to establish the infrastructure required to support the RFID tracking, as well as to customise the solution to the specific industry needs (Wu *et al.* 2006). However these concerns can be alleviated if the expected return of investment is shown to justify the extra cost and effort.

The combination of WSNs with RFID technology brings in functionalities of rapid asset, equipment and component tracking. This in turn enables linking collected information to the data collection point. This link provides the right context for the measured signals. The integration of WSNs, portable computing devices and RFID technology makes the shop floor machinery information available to the networked enterprise authorised users, irrespective of location and time. In order to maximise the advantage of combining several wireless technologies together (WPAN, WiFi, RFID), a system architecture must be in place to integrate sensors, RFIDs, specialized embedded system units for equipment data collection, processing and transmission tools, handheld computing devices, display and touch screen panels and storage devices, as well as a central or distributed server system, accessible via wired or wireless connections. A typical application scenario in such a system is that of ubiquitous information mediation, which may be contextualized too, *i.e.* relevant to specific user profiles, locations or asset (Spaccapetra *et al.* 2005). Mobile technologies can also be used to offer Location Based Services (LBS). For example, RFID technology can be employed for the identification of components or assets. A system that is aware of the location of its monitoring assets can exploit this information to indirectly identify the user location.

4 WSN Operating Systems and Middleware

Sensor research & development has been effectively serving diverse applications. Research focused on sensor embedded software engineering has produced implementations that include programmable APIs and versatile toolkits, able to provide a rich base for the developers to utilize and extend many sensor module's functionality. Energy-aware transmission protocols and sampling algorithms were the first to upgrade their computational complexity in order to trade the significant cost of data transmission for cheap processing cycles. This trade-off was possible through the development of dedicated software components utilizing advanced methods and approaches on data acquisition, data modeling and data interpretation. The level of computational complexity that characterizes the operations embedded on a sensor board is only limited by the processing and storing abilities of the board's implementation. Promising implementations that effectively manage to fully utilize the capabilities of the latest state-of-the-art smart sensor modules have now evolved into pioneering software embedded components such as fully featured sensor operating systems, flexible tiny-scale databases, and even service-based platforms. Taxonomy and evaluation of these implementations provides valuable feedback that supports standardization initiatives and software architecture research (Akyildiz *et al.* 2002; Heinzelman *et al.* 2004; Sugihara and Gupta 2008; Tilak *et al.* 2002):

- Abstraction of underlying hardware – Sensor level operating systems (TinyOS (Levis *et al.* 2005), SOS (Han *et al.* 2005), Contiki (Dunkels *et al.* 2004)) and middleware that can operate as the base logic of a range of sensor board architectures and integrated circuits. Multi-tier operating systems with software drivers which can efficiently handle and control sensor module-components: integrated sensors, ADC, memory modules, microcontrollers, RF/Wi-Fi/BT (Figure 2).

- Support of standards, specifications (*e.g.* MIMOSA, SensorML (Botts and Robin)) and communication protocols (802.15.4/ZigBee) that ensure software interoperability and efficient coupling in diverse wireless sensor networks.
- Extensibility and customisation options – Versatile middleware supported by rich APIs and SDKs can interconnect and communicate with various sensor operating systems. It allows programmers to build software applications and services, implementing advanced internal functions or extend sensor connectivity. Third party applications and services can be hosted, inside the sensors logic, with customised functionality like a tiny-scale system.
- Intelligent tools – Tiny complex database along with optimal small-footprint implementations of modelling techniques currently allow the development of small-scale intelligence within the sensor. Properly sized datasets and distributed implementations of statistical algorithms can be easily embedded inside wireless sensor modules to offer intelligence balanced by various parameters like energy-efficiency, network awareness and task prioritisation.

As RF operation is much more power-consuming compared to CPU operation, a key challenge for smart wireless condition monitoring is to make optimal use of the RF operation, by transmitting only when and what is absolutely necessary, rather than sending a whole time series of measurements. The key to this is reliable and efficient Novelty Detection, ie the ability to track process deviation from known patterns of behaviour. However, this process can be computationally intense and resource-consuming. Such real time data processing involves signal conditioning, filtering & other pre-processing, as well as modelling for novelty detection and diagnosis via machine or statistical learning methods. Typically these processes are performed on remote collection servers or to some extent on hand-held devices. Smart sensor nodes in WSNs can now accommodate online data processing supporting them with proper middleware routines. This does not resolve the other key questions: to transmit or not to transmit; what to transmit; when and how often to transmit. Sensor-embedded novelty detection is the first

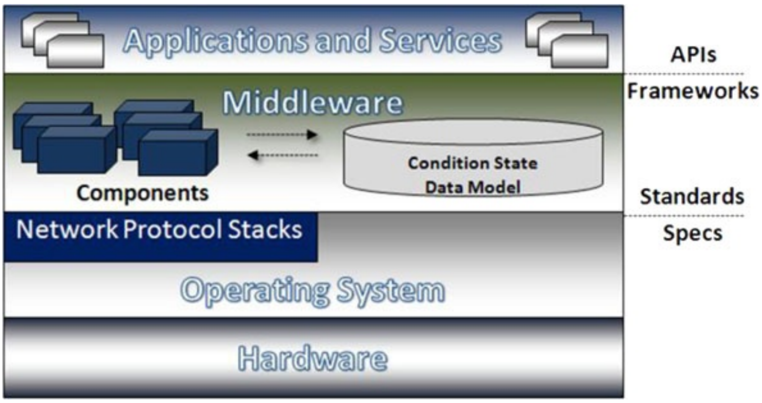

Figure 2 Smart Sensor Embedded Logic

step to answering these questions. It makes no sense for a sensor to transmit, if it is not polled to do so or if it has nothing new to transmit. Therefore, sensor-embedded novelty detection is a key feature for energy-aware operation of WSNs.

4.1 WSN Operating System

Overall, the functionality of a WSN is indeed similar to that of a distributed system. However the form factor of the sensing nodes and the constrained resources require different treatment compared to a network of desktop computers. In particular, a sensing node requires an operating system that takes care of hardware control while abstracting the hardware from the higher level network layers and offer adequate services to the applications, much the same way as a typical operating system does. Nonetheless, due to the limited resources available to a sensor operating system, the management of resources by such a system has considerably different requirements, compared to standard operating systems. In particular a sensor operating system must (Sohraby *et al.* 2007):

- have a very small memory footprint and low CPU requirements;
- provide some (though not full) real time support, as WSN are expected to be deployed at the operational level of an enterprise;
- employ efficient and reliable code distribution among sensing nodes, occupying as little bandwidth as possible;
- support efficient energy management, switching of nodes between sleep, awake and receive/transmit modes;
- provide application interfaces to the sensor middleware and application levels, making hardware accessible for system performance optimization.

Among the various operating systems that have been developed for WSNs, including TinyOS, Contiki and SOS, perhaps the most widespread in its use is TinyOS. The latter has been designed with two prime aims, namely to guarantee simultaneous data flows among hardware devices, while providing as little processing and storage overhead to sensor nodes as possible. TinyOS is a compact operating system that does not employ stack-based threading but employs an event-driven model of operation. Both TinyOS and Mantis employ static memory and can be ported in a small size ROM. Contiki switches between static and dynamic memory and has large ROM requirements, while SOS entirely employs dynamic memory allocation and has the highest memory requirements. TinyOS execution is entirely event-based, while Contiki employs both event-driven and threaded programming and SOS executes in modules which are independent binaries that implement certain tasks or functions. Although popular, TinyOS has its drawbacks, namely the lack of support for priority scheduling, multitasking, fault tolerance, real-time guarantees. Recent effort in WSN operating systems are focusing on making them handle a larger set of real application requirements, while providing expanded toolsets for application development.

4.2 WSN Middleware Design

Currently available middleware solutions include MiLAN (Heinzelman *et al.* 2004), IrisNet (Gibbons *et al.* 2003), DSWare (Li *et al.* 2004), Impala (Liu and Martonosi 2003) and Dfuse (Kumar *et al.* 2003). The various middleware platforms have different priorities. Depending on their priorities, they can be characterised as data-centric, Quality of Service (QoS) driven, agent-based, web-based. Some can be considered as event-based, others as agent-based and some of them are known to employ a more conventional centralised approach (Sohraby *et al.* 2007; Molla and Ahamed 2006). Conducting a more development-oriented survey, a classification of present middleware solutions can be done. WSNs have been surveyed in terms of the programming model and design principles of each project (Hadim and Mohamed 2006). Since application development is crucial for the utilisation of wireless sensor networks, many recent middleware initiatives are designed to constitute small footprint virtual machines with runtime support (Mate (Levis and Culler 2002), SensorWare (Boulis *et al.* 2003)). This runtime support extends the functions provided by the underlying OS for processing, communication and storage management, in order to offer a well-defined execution environment for applications and system programs. In this context, MagnetOS (Barr *et al.* 2002) is an example of middleware that constitutes a single-image virtual machine. Unlike other sensor-focused virtual machines, MagnetOS integrates the OS functionality rather than interfacing with an independent OS layer. Such an approach, although limits the middleware interoperability and modularity, it ensures the efficiency of internal processes.

Several recent projects, addressing the need for local data handling on sensor devices, have managed to fit their middleware functionality into the architecture of a tiny-sized database management system (Cougar (Yao and Gehrke 2002), SINA (Shen *et al.* 2001), DsWare). This approach fails to introduce complete standalone middleware solutions, since the architecture of a database system is tightly organised to focus on resource management efficiency. On the other hand, the majority of these platforms can easily interface and serve larger architectures acting as sophisticated component modules and services for data dissemination and data aggregation (TinyDB (Madden *et al.* 2005)). The distributed nature of sensor networks and the need for intelligent sensor behaviour has lead to the quick adoption of mobile agent technologies for WSN middleware components (Impala). Projects like Mires (Souto *et al.* 2004) are building on-top of the widely adopted TinyOS a publish/subscribe mechanism for efficient service discovery. EnviroTrack (Abdelzaher *et al.* 2004) is another example of middleware utilizing TinyOS to offer application-focused tracking services. The novel concept behind EnviroTrack's architecture is the introduction of object entities and functions. It is worth mentioning that unlike traditional middleware implementations that sit between the application and the operating system, there are projects like MiLAN which have an architecture that extends into the network protocol stack. Recently, considerable research effort has been devoted to studying the principles of macroprogramming abstractions in WSN applications. This line of research aims to provide the developer's community with adequate guidelines for developing versatile middleware components and APIs (Kairos (Gummadi *et al.* 2005)).

Even this brief overview of the different architectures and designs that provide the development guidelines for wireless sensor software, clearly displays the level of diversity that characterises this context. In Table 3 we summarise the key design concepts and features for each middleware platform and operating system. A basic set of principles has been derived from studying the development stages and the design decisions of the above WSN implementations (Yu *et al.* 2004):

- The middleware should provide data-centric mechanisms for data processing and querying within the network. Data are distributed across the entire sensor network, and so are hard to use. Communication between sensor nodes requires the expenditure of energy, a scarce commodity in most WSNs. Making effective use of sensor data will require scalable, self-organizing, and energy-efficient data dissemination algorithms.
- Application knowledge can be used to tailor the design and implementation of software. Detailed knowledge of the WSN application's functional requirements can significantly speed up the development of the services to be offered through the platform middleware. Making early application-focused decisions about the services design pattern is important for ensuring the middleware efficiency on top of different sensor operating systems.
- Localized algorithms should be used to collectively achieve a desired global objective. Due to the distributed, dynamic, ad-hoc, and energy-constraint nature of wireless sensor networks, these algorithms can provide scalability, robustness and energy-effectiveness advantages. They are able to support intelligent task assignment methods for the sensor nodes (sensing, tracking, and reasoning). Flooding the network with useless or redundant data is avoided, and thus the lifetime of the sensor network is extended.
- The middleware itself should be lightweight in terms of the computation and communication requirements. Though it is very tempting to adopt the paradigm of smart sensors software modules, it is quite hard (conflicting objectives) to develop energy-aware, memory-efficient or data-centric intelligent behavior. Sometimes simple and lightweight implementations can offer greater benefits.

It is necessary for the middleware to smartly trade the QoS of various applications against each other. It is very likely that the performance requirements of all running applications cannot be simultaneously satisfied. A dynamic balancing based on predefined application criteria should be performed by the middleware QoS component services.

Table 3 Wireless Sensor Software Classification

Wireless Sensor Network Operating Systems			
Project	**Design Rule**	**Main Advantage**	
TinyOS	Event Based	Small Memory Footprint	
Contiki	Event Driven	Multi-Threading	
SOS	Kernel Based	Dynamic Modules	
MANTIS OS	Multi-threaded	Time-sliced Multithreading	
MagnetOS	Virtual Machine	Java VM – Easy Code	
Wireless Sensor Network Middleware			
Virtual Machine oriented approach			
Project	**Command Language**	**Programming Level**	**Underlying OS**
Mate	Byte code	Low	TinyOS
SensorWare	Tcl scripts	High	TinyOS
MagnetOS	Java language	Higher	MagnetOS
Database oriented approach			
Project	**Querying & Tasking Language**		**Data Collection**
Cougar	XML data format, SQL-like language		Enquire
TinyDB	ACQP language		Enquire/Event Driven
DSWare	SQL-like Language		Event Driven
SINA	Queries formatted in SQTL Scripts		Enquire
Other approaches			
Project	**Programming Paradigm**		**Abstraction Level**
Mire	Message Oriented – Pub/Sub Services		Local
Milan	Extends of the network protocol stack		Local
Kairos	Macroprogramming Based		Global
Impala	Mobile Agent Based		None
Enviro-Track	Object Based		Global

4.3 Sensor Embedded Application/Service Development

In order to equip WSNs with sensor-embedded operations, adequate software components need to be built. Various software architectures have been proposed and developed to drive the behaviour and functionality of WSNs. The latest and most promising ones adopt modular service-based patterns (SOA) that allow flexible and extensible development of sensor applications (diagnostic tools, prognostics, decision making, reporting) and/or middleware components (data handling, network management, energy-awareness). These are supported by (a) open/board-independent or (b) proprietary/board-specific development tools, such as programming APIs, SDKs, emulation environments and software libraries. Wireless sensor intelligent software components in general follow three major programming paradigms:

- Java (Java Squawk) – Due to the large java-community and the available tools and frameworks, java monitoring middleware has grown in availability and maturity, featuring easy portability to various java-based platforms. This fact has lead to significant research for Java sensor APIs and middleware in the last few years. Java monitoring agents and services rapidly evolve, offering extensive customisation options and efficient integration with higher level software populating online condition monitoring systems and CMMS. On the down side, most sensor embedded java virtual machines have significant consumption profiles and require considerable computation and memory resources. Additionally, most java sensor components have been designed and implemented as stand-alone all-in-one platforms, integrating the role of operating system, middleware components and application services in a single virtual machine. This usually leads to poor support for more hardware sensor circuits and limited interoperability potential.

- Microsoft.NET (Micro/Compact Framework) – These rich and extensible frameworks offer rich integration options with high level.NET application-suites and environments, such as CMMS and other remote control services. .NET Sensor software components exhibit fast performance and good control over hardware, thus appropriate for efficient execution, synchronisation and scheduling of monitoring tasks and events. Backed by well-structured libraries and tools, and by a constantly growing community.NET based wireless sensor modules allow rapid application development. As in Java,.NET also requires potent hardware components in terms of processing capacity and memory. Utilisation of such hardware is almost always characterised by high energy consumption profile.
- NesC Programming Language (TinyOS) – NesC is an open C-like language. A large pool of components has been produced, currently driving the processing logic of many wireless condition monitoring systems. TinyOS, which is currently progressing to its 2nd stable version, offers a solid and reliable OS to host processing components that range from simple data/event handling mechanisms to complex statistical modelling for measurement classification. Its wide adoption both by research and industry lead to the present extensive availability of software drivers and frameworks for many different wireless sensor integrated circuits and their applications. NesC is lightweight enough to support balancing computational efficiency with network communications and hardware utilisation. From its birth, NesC was aimed to act as the programming language that will efficiently program low-featured wireless sensor modules participating in energy-aware communication networks. Today, TinyOS effectively populates the lower layers of multiple NesC developed middleware that commercially provide sophisticated modelling routines and diagnostics.

5 Architecture for Novelty Detection and Condition Monitoring

We now turn our attention to the design of an innovative architecture able to support intelligent on-site, as well as remote maintenance management. This effort introduced a wireless infrastructure that manages to interface and connect the latest implementations in low cost wireless devices (sensor, RFID, PDAs). Benefiting from the advantages of each technology serving its architecture, the proposed system presents a practical and easily deployable monitoring and maintenance management platform. In order to draw a clear picture of the systems's targeted problem space, we describe the Use-Case scenario that acted as the guiding rule for extracting the platforms functional requirements: A typical user of the system will be equipped with a PDA device while operating at the shop floor. The PDA device carries a RFID reader so when the user approaches a tagged component or machine, the system recognises the user position in the operating environment and identifies the 'active' monitored component. The monitored machinery may have attached to it one or more sensing nodes. The user can wirelessly communicate with these nodes via the PDA or via the central computer system. In this way he can retrieve contextually relevant information, initiate or execute relevant work orders or receive visual or acoustic aid for his task at hand. The sensing nodes themselves are acting as sensor agents and can send and receive data back and forth to the central computer system via dedicated wireless gateways. The back office comprises a central database and a series of web services for communicating with the wireless sensor network, or for managing work orders and other maintenance related activities.

The architecture comprises two blocks of maintenance – related services, operating on the operations and tactical level respectively (Figure 3):

- Generic condition monitoring agents with embedded local sensing board (vibration, light, temperature, humidity, while other sensors can also be incorporated), signal processing, condition monitoring and diagnostics.
- Generic mobile maintenance management support, which will bring to the shop floor instant support for engineering personnel, providing services such as access to equipment information, work planning & orders, shop floor monitoring data, service history and spare parts data.

Next, we focus on the condition monitoring agents.

5.1 Condition Monitoring Agents

Considerable research effort has been devoted to condition monitoring and fault detection. The operating behaviour of each machinery class, along with its special attributes, have led to the development of intelligent modeling approaches, such as knowledge-based systems, fuzzy logic, machine learning, neural networks and genetic algorithms. However, in most cases intelligent condition monitoring, assigns the execution of data analysis and modeling tasks away from the actual sensor and thus from the monitored machine. This denotes that data acquisition schemes and their response-actions may suffer from transmission delays between sensor nodes and gateways or gateways and the central server. Any failure of the server that hosts the analysis software results in a transition to a manufacturing process with zero support for diagnostics and prognostics. Even when backup servers are invoked, data synchronization delays, sample-records gaps and reconfiguration routines make milliseconds or seconds seem like ages of unsupervised operation for critical machinery.

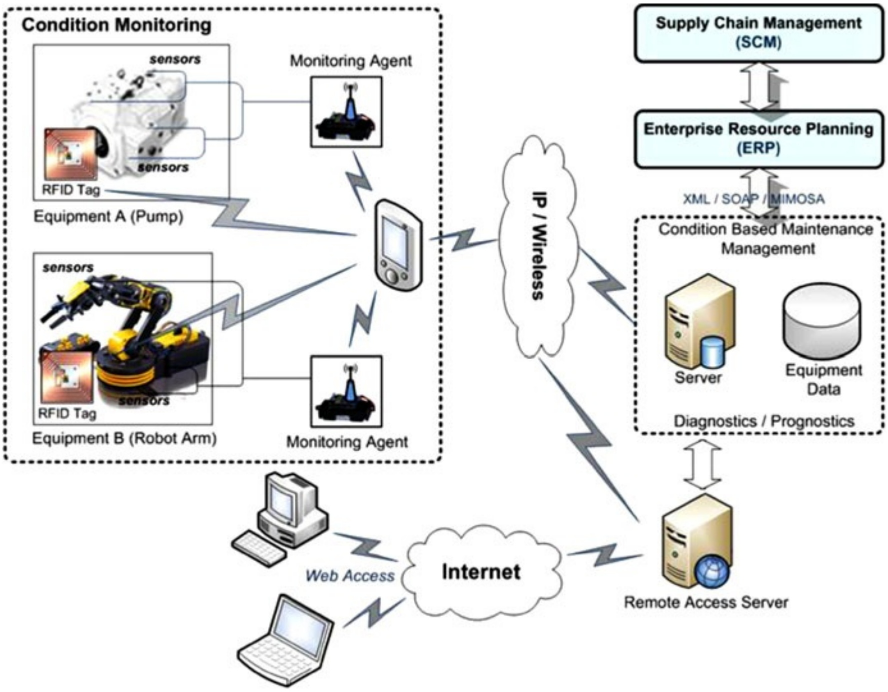

Figure 3 The System's Architecture

As a more efficient, scalable and reliable alternative, this paper advocates decentralization of data analysis and its porting to a sensor network distributed paradigm, within a wireless sensing infrastructure that performs distributed constructive novelty detection and diagnosis (Figures 4 and 5). Increasing the granularity and the distributed character of a computationally intensive process is a paradigm that has been followed by most disciplines in order to maximize utilization and performance while offering reliable (code migration, data replication) and scalable (over-the-air programming) processing infrastructures.

The first level of processing of any condition monitoring agent is the ability to detect deviations from expected behaviour, often referred to as anomaly or novelty detection. Several anomaly detection techniques are reported in the literature, usually performed at the single sensor reading or component level, but sometimes also collectively in a distributed manner (Chandola *et al.* 2009; Rajasegarar *et al.* 2006). We propose a sensor-embedded novelty-detection that upgrades the monitoring system's flexibility and responsiveness to faults. The sensor network that monitors machinery behavior constitutes the part of the system that resides closest to the source of any fault or degradation process. Developing sensor-embedded diagnostics can instantly signal alarms or schedule critical maintenance actions, directly after detecting the novelty in sampled machine parameters. By investing in a sensor embedded distributed intelligence, we aim to build a constantly upgrading constructive knowledge system tailored to each machine. Instead of a static sensing infrastructure supplying a central station with training data, we use sensor embedded novelty-detection to train and enrich a dedicated model for each machine's condition state. Population-based computing paradigms such as evolutionary computing or swarm intelligence are strong candidates to implement the adaptive and distributed nature of this emergent learning behaviour pattern.

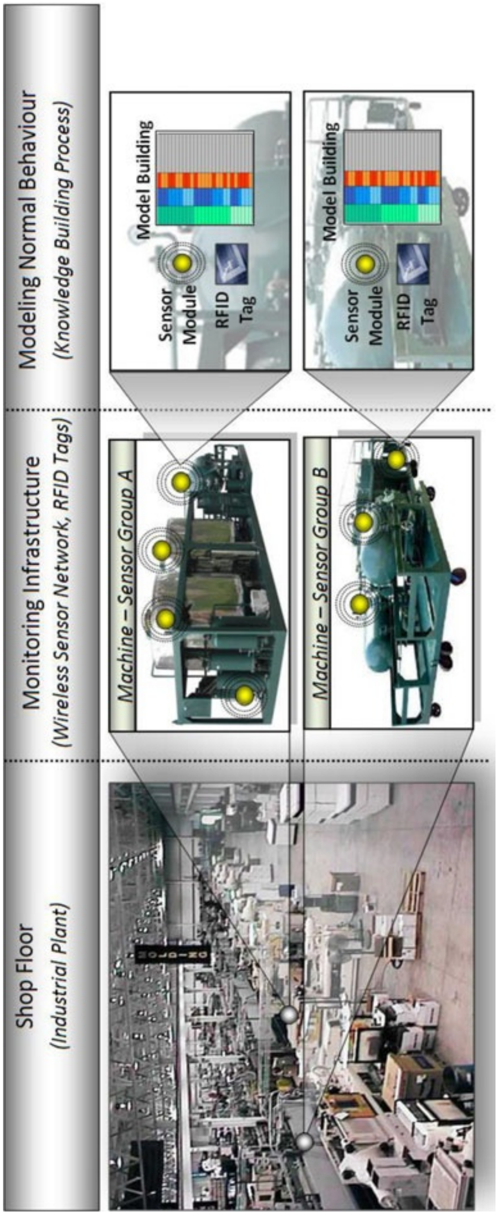

Figure 4 Sensor Embedded Novelty Detection Concept

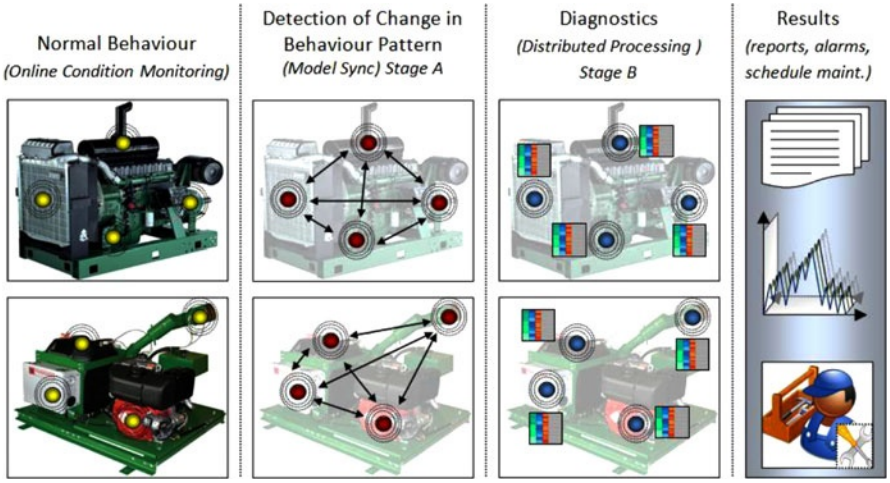

Figure 5 Distributed Novelty Detection Engine Concept

Scalability and portability are among the benefits that WSN bring in to condition monitoring. This allows maintenance engineers to design modular architectures, which can easily scale from machinery-based networks up to plant-wide deployments. The efficiency of formulating computational groups, or larger sensor grids by sensor nodes, is mainly defined by the distributed pattern of the embedded software intelligence. It is therefore necessary to focus in the first instance on the machinery-level monitoring, before moving on to implementing a plant-wide monitoring infrastructure. The focus therefore is on defining a Service Oriented Architecture to populate the nodes' embedded logic. This architectural pattern is currently driving the majority of web-based and grid platforms. The coupling between service-based components is aimed at providing a dynamic synthesis of computational resources and data collections. The resulting distributed data model and processing capacity constitute the means for implementing efficient Novelty Detection. Focusing on modular (service-based) patterns for embedded logic, WSN condition monitoring systems can scale from few nodes to few thousand nodes. Such a scalable and programmable infrastructure can be customised and tuned to meet diverse condition monitoring and diagnostics needs, using the same infrastructure to monitor different machines or even different plants.

5.2 Novelty Detection Engine

In order to address the design issues of embedding learning methods within the sensor logic, a reference, component-based architecture is proposed. The reference architecture is an advancement of the concept of constructive modeling for novelty detection, redesigned for embedding it within a sensor board (Emmanouilidis *et al.* 2006). In this constructive modeling setting, empirical process models are built and expanded to exploit newly acquired data. Each subtask of the novelty detection process is associated with an application or a service module according to its role and functionality. Inter-process communication and synchronization aspects are also addressed. The proposed architecture is modular by design and is based on a multi-tier sensor platform. It supports component interaction via appropriate interfaces. Subsequent analysis points at the need of standardizing these interfaces. Possible communication patterns and synchronization paradigms need to be studied. In our modular design, we assume that the components implement their intended functionality. Naturally, any alternative algorithm versions can be employed for the same functionality, thus the architecture can benefit from algorithmic improvements in terms of performance, computational efficiency and memory usage. For every subtask of the learning process a balanced decision must be made to prioritize and define the trade-off between performance and resource allocation.

Sensor-level novelty detection aims at identifying *unusual* or *unforeseen* sensed behaviour based on features extracted from the monitored equipment. Any measurements which significantly deviate from the sensor-embedded process model are judged to be novel. It is important to make this clarification as in practice a measurement collection can be marked as novel not in the case that an expert user would consider it so but insofar as the built-in model recognizes it to be so. By the very nature of the approach, it is possible to expand the sensor-embedded novel to accommodate additional data and therefore expand its ‘receptive’ field, a process consistent with the concept of constructive model building. In the context of a smart sensor’s logic, this process can be implemented as a Novelty Detection (ND) subsystem constituting a part of its software middleware. In order to design a proposed architecture for this subsystem, we first describe its step-by-step functionality and then assign execution to software components that can be included inside the sensors resource-limited logic. The functionality of the novelty detection system should include the following steps (Figure 6):

1. *Initial setup*. This step involves the initialization of the novelty detection subsystem. Parameters and processes are initialized and reset. During this step, ND database can be initialized to default data. This enables initial sensor-logic initialization to utilize previously built knowledge.
2. *Initial data acquisition*. A first set of samples are acquired, to capture the monitored machine’s normal behaviour. This information is utilized to build the initial model that reflects the normal operation state. In the case that the initialization process did not discard previously stored knowledge in the database, this step can be omitted.
3. *Set-up refinement*. The initialization step is executed again. This second initialization is configured by the normal state knowledge residing in memory (step 2). The goal of this repetition is to achieve the best initial calibration of the real-time monitoring and processing stage that follows. The benefits of utilizing any pre-existing data during initialization can prove to be much more im-

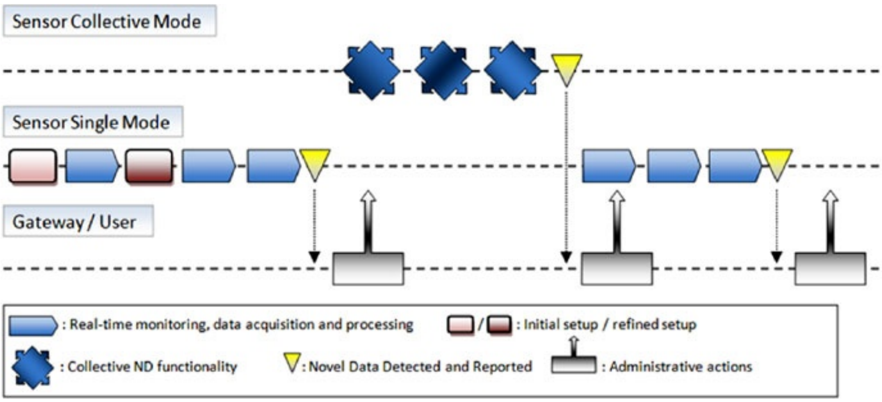

Figure 6 Novelty Detection Subsystem modes and steps

portant than hundreds of processing cycles that try to compensate for a badly configured training process.

4. *Real-time monitoring, data acquisition and processing*. This step can be characterized as the ND subsystem's core phase. It includes the real time knowledge building through empirical model learning. The data acquisition should be carefully synchronized with processing and signaling operations. The processing includes the execution of the employed learning algorithm, while the signaling operations need to define and drive the sensor's response and reaction to ND subsystems findings (sensor single mode).
5. *Collective ND functionality (sensor collective mode)*. This step is also associated with an ND subsystem's core phase. In order for the sensor's logic to participate in the execution of distributed processing, it must switch to a different operation mode. This mode is characterized by communication based on preconfigured patterns and processing based on special components of the ND subsystem's architecture. During this stage/mode the sensors' subsystems communicate to synchronize their models and collectively train them, either as individual models or as one synthesis deriving from their fusion. Collective ND is a significant feature of the proposed architecture. Many processes need multiple-sources data acquisition, involving measuring the same physical quantities from different locations, or different quantities from the same location, or different quantities from different locations. The ability to perform novelty detection based on the fusion of all these quantities is termed collective novelty detection. Novelty detection based on a single sensor or single sensor-node readings are a trivial case of collective ND, when additional data sources are nullified.
6. *Asynchronous independent functionality*. This step is essentially executed in parallel to the previous core phases. It includes externally invoked processes that support the ND subsystems task. Their goal is to allow network users execute administrative and customization actions. These actions may include database management, labeling novel data or configuring the ND subsystem.

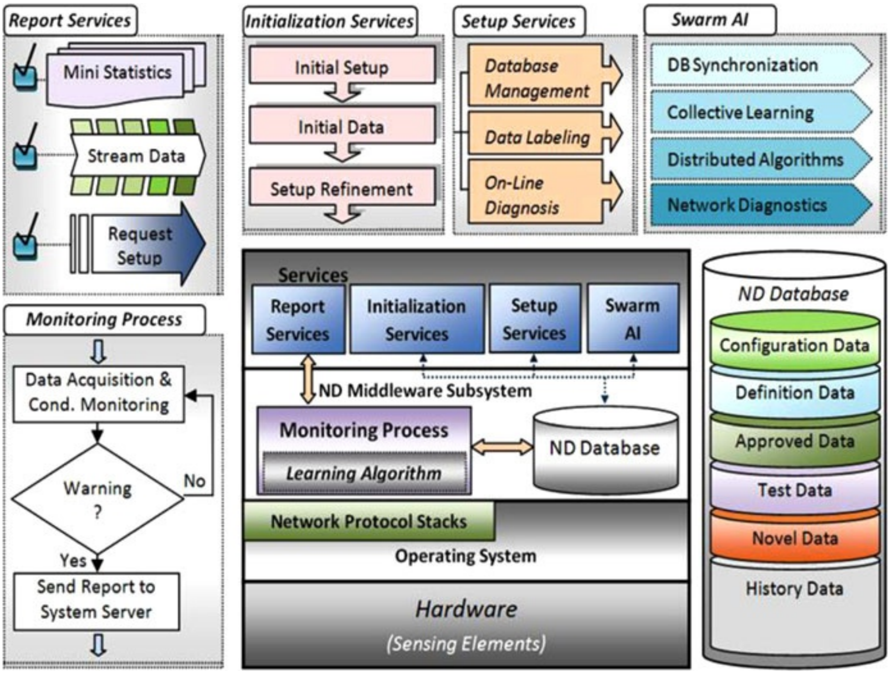

Figure 7 Sensor-based ND Subsystem

The overall functionality of the described above process is that of progressive model building (Emmanouilidis *et al.* 2006). The ND subsystem design should be versatile and customizable enough, in order to serve the knowledge-building needs of various monitoring applications. The main advantage of this approach is the full utilization of the energy-cheap processing and storing abilities provided by recent smart sensor modules. Thus, investing in the development of advanced sensor logic better exploits the sensor network's infrastructure. Such an architecture has the additional advantage of bringing sensor software one step closer to standardization. In Figure 7 we illustrate the proposed ND subsystem's software architecture. Deriving from the previously mentioned generic functionality steps and stages, this conceptual architecture is based on design decisions that involve component role designation, component implementation characteristics and component interaction and interfacing. To assign roles and properly place each component in our architecture, we divided each step and stage in a number of subtasks that constitute the components core functionality. A component's implementation can be classified as:

A **Service Component** – Service components follow publish and subscribe paradigms to register their functionality and their point of contact. Administrative and supervision tasks that involve network-user's interaction with sensor-level information are implemented as services. Tasks that include data exchange between sensor nodes (distributed processes) or a sensor node and the data gateway (reporting tasks) constitute sensor interconnecting behaviour and they should also be implemented as services. Open and widely adopted standards should be followed to assure scalability and interoperability.

A **Middleware Component** – Middleware layer is mainly populated by processes that need to utilize stored data and interface with the underlying operating system. Instead of outgoing communications links, these components are focusing on core functionality and aim for performance and efficiency. Functions that handle and process significant amounts of data (considering the sensor level memory) naturally reside in the middleware tier, implemented as components that can directly connect to organized memory structures without the need of complicated interfaces. Middleware components should be implemented with board specific SDKs or Toolkits in order to maximize performance and make optimal resource utilization.

The ND Systems Database

A learning-based Novelty Detection system should be supported by a model that undergoes successive training cycles. This model has to reside in some kind of organized memory space, supported by the proper access mechanisms of the underlying sensor operating system. Various projects are currently offering advance data handling techniques as sensor-level middleware components. SQL-like languages support these tiny scale Database Managements Systems (DBMS) and allow efficient filtering of sensor data. In our architecture, the database component plays a critical role in every step of the desired functionality. Implementing a ND subsystem, to train a model that resides in a DBMS middleware component, creates a strong dependency between the subsystem's and the component's performance. The database (DB) schema must include proper data records to assist the model training. It should also include detailed settings to allow extensive subsystem customization. In order to efficiently configure the ND subsystem and model sampled data, the DB includes:

- The **"Configuration Data"** table where various operation profiles for the ND system can be stored, as a set of configuration parameters and settings.
- A **"Definition Data"** table that lists and describes the application specific parameters and factors that can be monitored and used for the monitoring task at hand. A subset of these parameters will be selected to define the record structure of the rest of the DB tables.
- **"Test Data"** is a set of predefined data used to test the models ability to effectively identify a number of important condition states.
- **"Novel Data"** is a table where the system stores sensed data, whose processing could not associate them with a previously known state.
- The **"Approved Data"** table includes previously identified novel data that have been cross-examined and revised by an expert and, in turn, have been labeled

as indicators of a certain state (through administrative actions). Data populating this table compose the model that drives the training process.

- Finally, **"History Data"** acts as a legacy data repository for backup purposes and rolling back self-correcting operations. Its size and type should be carefully configured, in order not to waist valuable memory space.

Advanced DB management actions may include setting up "Definition Data" for the monitoring application, inserting, deleting and revising "Approved Data", examining, re-classifying and labeling of past data, as well as appending them to the pool of "Approved Data".

ND System Middleware Components

A design decision is made to implement the monitoring process as a middleware component. The essential role of the learning process is to compare new incoming sampled data against the data model's profiled clusters and evaluate its participation to any previously profiled condition state. According to the employed learning algorithm, data representing thresholds, central points and other cluster information are stored inside the DB. When a new sample cannot be associated to a previously recorded or known state, then an interrupt flags novelty and instantiates a reporting service to alert the network administrator and/or provide additional information. This component essentially executes the training procedure, and thus requires fast and synchronized DB access for the periodic processing and updating of the data model. In order to achieve such a balanced synchronization, the operating system's data handling mechanisms can be utilized to execute advanced memory actions (DMA). The monitoring process calibrates the data processing cycles according to the sampling frequency and the DB access delays. Any charted time overhead is available in DB and assists in refinements aiming to achieve optimal training rate.

The ND Systems Middleware Services

The Service layer of the proposed architecture includes four groups of services, each delivering different type of sensor node behaviour and connectivity:

Initialization Services – A set of services for booting the ND subsystem by initializing settings values and table records in the DB (definition data, test data). If the initialization service detects the absence of a stored knowledge model, it invokes the monitoring process and executes one cycle of data acquisition and processing (Figure 8). The resulting instance of the data model is processed by a refinement service that calculates enhanced values for a second subsystem initialization.

Report Services – This group of services allow the ND subsystem to alert the network user on the identification of novel data and prompt for their classification through data labeling. Simple trending functions are also available as services, providing mini trending reports on parameter escalation and history of changes. Such reports along with streams of the corresponding data history, accompany alert messages to support the technician's diagnosis for qualitative classification.

The examination of this feedback may lead to the identification of a 'hidden' pattern of abnormal behaviour that causes a slow paced degradation.

Setup Services **–** The ND Subsystem can be on-line reconfigured through a set of setup services. These services enable network users to access the data stored in the DB and modify critical settings that define the learning process. Database management services allow the user to revise and tailor the approved or history data table. The user can translate, label and classify data previously identified as novel. If this classification is not possible due to uncertainty, then further processing can be initiated (compare against updated data model) to refine the results and support a new decision.

Swarm AI Service **–** The presence of these services can turn a single ND subsystem into a smart agent operating in a network of collective intelligence. The learning process is encapsulated in a distributed service envelope, allowing connection

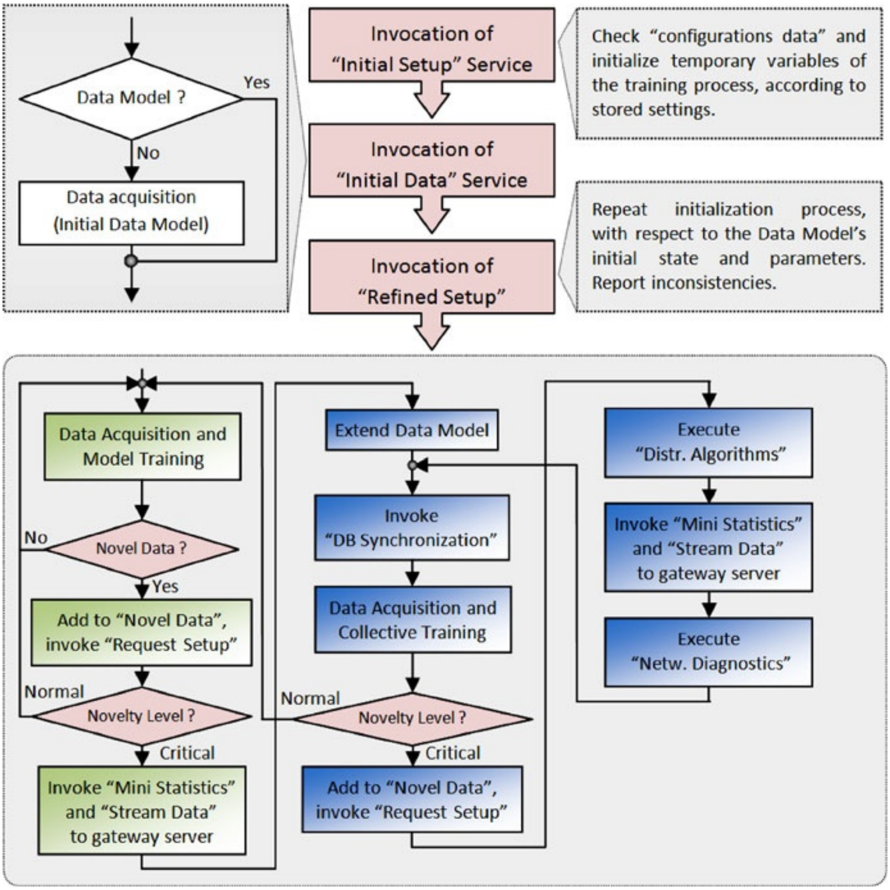

Figure 8 Novelty Detection Subsystem Flowchart

and coupling with other similar services. As displayed in Figures 7 and 8, these services implement DB synchronization techniques (replication, migration) and execute algorithms for collective decisions (collective-based Novelty Detection). Streaming variables' history, data model's characteristics (clusters' central points, thresholds and dimensions), or even profiled state, allow data fusion functions and provide advanced reports on trends and data classification. Any type of collective decision algorithms can be embedded in this service with a prime choice being swarm intelligence (Engelbrecht 2005).

6 Testbed and Application Development

Porting smart wireless sensing to industrial condition monitoring applications requires a careful consideration of a number of factors, which are likely to influence the efficiency of any implemented solution. Setting other factors aside, the ability of a sensor node in the first instance and that of a network of sensor nodes collectively, operating to deliver condition monitoring services, may be severely limited if a sufficiently long operational autonomy cannot be secured. Battery life itself can only be prolonged insofar as the need to initiate and execute RF transmissions is minimal, as power consumption associated with RF operation is a scale of magnitude higher than that of CPU operation. This is incompatible with condition monitoring practice, typical in cabled condition monitoring, that accommodate regular data transmissions of the time series of measured data or of a set of monitored parameters. Instead, RF operation should be initiated only when needed. This need is translated to a deliberate policy of ceasing data transmission for as long as the taken readings do not constitute useful data. That is when the observed machinery behavior follows known and anticipated behavior patterns, which do not have implications for the production or maintenance planning. In WSNs, this is equivalent to a careful and optimized control of the sensor node operating state transition between sleep, awake and transmit states. In a condition monitoring application it is hardly an energy efficient practice to leave this mechanism to be controlled only by the inherent sensor operating system mechanisms. Instead, the mechanism should also be tailored to the very nature of the application domain, ie condition monitoring. This implies that adequate middleware components need to be designed and implemented, which will achieve to effectively drive the sensor node operation, on the basis of the actual observed machinery operation patterns, rather than by built-in machinery state-'agnostic' WSN mechanisms.

Following the introduced design architecture, our research therefore focuses on the design and implementation of the proposed component and novelty-detection engine. Our initial priority is to define adequate computational structures, algorithms and software components that are likely to exhibit adequate novelty detection performance, when embedded in wireless sensor devices. To this end we are not initially interested in a large-scale deployment but rather seek to explore the implications of applying smart wireless sensing at the single machinery level. This single-node sensor intelligence is the precursor to the larger-scale collective node condition monitoring architecture, which is our ultimate target but is out of the scope of the initial testbed and application development. Only upon ensuring adequate performance at this level, will we move to implement the collective wireless sensor node operation, to be deployed at a larger scale. However, we seek to develop the single-node computational architecture by taking into account not only laboratory-based conditions and constraints, but also real-plant conditions, in order to progress step-by-step in an overall efficient architecture that is of industrial relevance.

Our goal is to study the level of intelligence that can be embedded in a wireless sensor module when this module serves as a node in a condition monitoring infrastructure. When employing constructive model building for novelty detection, one has to tune the employed techniques to serve the specific application functional requirements. To this end, our case study was selected to provide the basis for testing the validity of our assumptions on machinery-level novelty detection in an industrially-relevant setting, before attempting to port the new WSN-based novelty detection architecture to larger – size installations.

Having defined a modular architecture for sensor-based novelty detection, we process the condition history of industrial equipment to decide the level of complexity for the modeling function that will drive our sensor-level novelty detection engine. This engine will identify *unusual* or *unforeseen* sensed behaviour based on features extracted from the samples. Any measurements (training data) which significantly deviate from the embedded data model are judged to be novel. It is important to emphasize this, as in practice a collection of samples can be marked as novel not because an expert user examined them and decided it, but the built-in model recognizes it to be so. The first step in this direction is to experiment with the implementation of constructive model building for novelty detection and diagnosis based on real data, before embarking on porting the architecture to the field. The testbed is situated at the Phosphoric Fertilizers Industry compound of Kavala (Greece) and involves two pumps operating around the clock to supply water and Ammonium Nitrate to critical manufacturing components of the plant (Figures 9 and 10). Pump P-451 A is a Feed Water Pump for two boilers, while pump P-503 A is an Ammonium Nitrate Supply Pump for

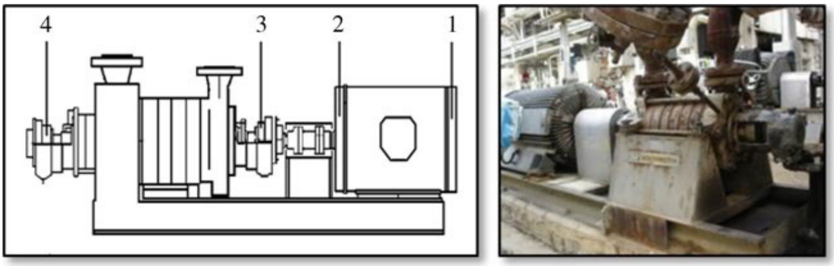

Figure 9 Photo and Measurements Schematic for Pump P-451A

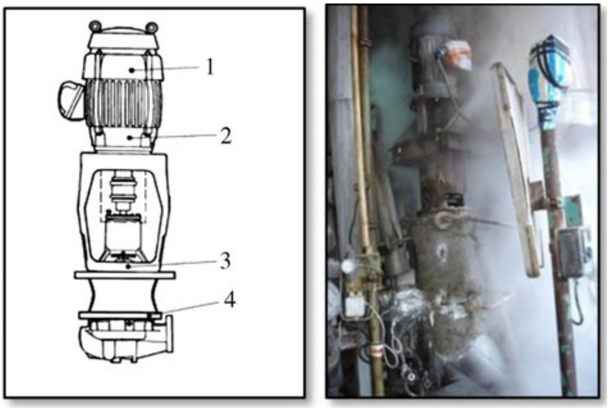

Figure 10 Photo and Measurement Schematic for Pump P-503A

a granulator. They are both included in a visual inspection program that performs tactical multi-point measurements of vibration velocity, while an online monitoring system constantly records the vibration peak velocity (single-point). The plant harsh environment and multi-level structure make permanent cabling almost impossible, while some hazardous material could easily corrode such a deployment.

The measurement history (4-point Axial/Vertical/Horizontal velocity readings) of both pumps was processed and modelled through simple heuristics to assess the classification quality of a simple to compute novelty-detection engine. Our goal is to gradually enhance the engines' efficiency in modelling and identifying novelty, while maintaining a low-to-medium computation profile. Data accuracy, volume and complexity are significant factors in balancing memory requirements and computational efficiency. We utilised this to build a heuristic constructive modelling process. We employ distance-based novelty estimation and a nearest neighbour technique for machinery condition classification. Pump 503 A went through repeating operational failures which resulted into multiple "Critical" conditions.

Our model training process used a small subset of the provided measurements as an initial set of Approved Data History. This subset comprised of samples which profiled two condition states (Normal, Critical). At each processing step (evaluation of a new measurement), any novel or missclassified measurements were automatically flagged out for future labeling and addition to the Approved Data History, in order to gradually enhance the models ability to correctly classify future measurements (Emmanouilidis *et al.* 2006). After a few processing steps the result was that all other measurements were correctly classified, providing evidence of successful constructive model building. However, the high performance rate is attributed to the limited data set upon which we experimented and cannot be expected to be achieved in all tests in this real application scenario.

Figure 11 displays the classification results of two cases: (a) Evaluating Test Data using a static initial set of Approved Data and (b) Evaluating Test Data

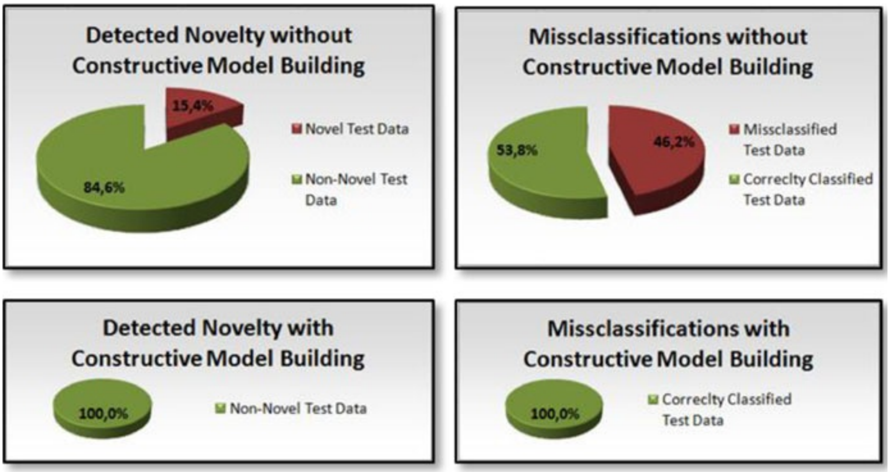

Figure 11 Constructive Model Building Efficiency

through Constructive Model Building. The former approach flagged many novelties and has produced a significant number of misclassifications, while the latter's utilisation of constructive model building created a dynamically trained model which managed to correctly classify the total set of Test Data. Furthermore, no novelty was flagged in constructive modelling, effectively eliminating uncertainty for the machines condition states. These early results clearly attribute superior classification abilities to any dynamic model that constantly learns from the machine's state history. Our goal is to define and optimally balance the implementation of this learning process, allowing its computationally efficient execution on top of sensor-level resources. Upon completing this stage of the work, our research will focus on more extensive evaluation both at the laboratory and industrial plant settings. The final single-sensor level subsystems will constitute modular components for the larger scale implementation.

7 Conclusions

Condition Monitoring can greatly benefit from the introduction of distributed wireless sensing solutions. Wireless condition monitoring is a flexible alternative to wired condition monitoring that has the potential to become a powerful toolset that can be exploited to enhance the lifecycle management of engineering assets. This has looked in key aspects of wireless sensor technology, with a view to its applicability in condition monitoring. Rather than designing the structure of a complete wireless sensor network middleware layer, we identify the need for proper module containers inside a sensor's logic. Containers host services that respond to network requests, or application components that respond to internal calls and invocations. Such a wireless sensor network software architecture can have a significant impact in various aspects of condition monitoring:

1. It supports an emerging new level of software development; the sensor-device development. The sensor device software is a promising market that needs specifications and tools to drive its solutions. Sensor services and applications move closer to becoming a product unit. A sensor-logic component that employs a learning technique for novelty detection is no longer a simple function to perform an elementary sensor task; it constitutes an advanced application executed at runtime.
2. Condition monitoring systems serving industrial plants will significantly upgrade their performance and cost savings, by utilizing sensor level novelty detection:

   – There is no need for a multi-core collection server, when there is a multi-agent collective network. Sensor level resource allocation and task allocation services will ensure data availability, network robustness and efficient processing. One step further from sensor embedded novelty is the sensor collective novelty, scaling down and porting the benefits of a grid architecture to a wireless sensor network. The practice of grid or clustered processing offers solid proof of the significant reliability and performance upgrades when moving to a distributed model. A collective of smart sensors can more than adequately fulfill the processing needs of most condition monitoring processes.
   – The need for pre-scheduled visual inspections, maintenance actions and data readings is reduced when a group of smart sensors is able to identify critical events from fused novel data and automatically produce reports that can drive the scheduling of maintenance tasks. On-demand visual inspections mean fewer personnel on the shop-floor, which in turn, means less risk in the case of personnel working in harsh environments. Sensor embedded novelty can detect faults in the sensing infrastructure, while at the same time monitoring the state of the application environment. The same advanced detection method will be utilized to model, monitor and self-configure the sensor network itself. Sensor embedded novelty can serve as the basis for multiple network targeted functions: (a) scheduling sleep, (b) tuning sampling, (c) detect environment resource for energy harvesting. Self calibration and energy savings are directly translated in less time spent by personnel to check, configure and maintain the engineering assets infrastructure.
   – Finally, there is no need for top-to-bottom condition monitoring with overloaded software suites and black-box sensors, when programmable sensors with open software can be purchased and subsequently populated with services and applications able to drive and compose the desired monitoring process. Instead of full-scale suites, the provision of sensor services and sensor components will emerge offering a much greater variety, customization level and control over the features and the potentials of the final condition monitoring system. Thus engineering assets can be monitored by carefully

tailored sensors equipped with the proper software modules to power its detecting capabilities.

This paper has looked into how Novelty Detection and Condition Monitoring functionalities can be embedded in wireless sensor nodes and networks. A reference architecture for sensor-embedded novelty detection has been defined. This architecture supports basic and advanced novelty detection functionalities in a modular approach, defining individual components and services that can be embedded at the sensor board level. Promising though it may be, the concept of sensor embedded novelty has significant limitations and constraints. Implementing model training tasks by utilizing the resources of a sensor board is challenging and bounded by the processing and memory capacity of small-devices. Novelty detection is a process that occupies many clustered and grid infrastructures. A smart sensor's logic can only support the execution of simple and less sophisticated approaches, and thus the least efficient ones. The sensor's small memory size poses serious constraints to the complexity and the magnitude of the dynamic data model. Low CPU resources will bound the amount of the sampled data that can be processed on-line, thus making the training rate low and the produced model non-qualitative. From a collective perspective, network-level intelligence can provide a more parallel-capable processing capacity with enough distributed memory to exploit and execute recent and more advanced novelty techniques. The performance of these implementations, ported for sensor middleware, will suffer from: (a) the overheads from non-standardized wireless and inter-process communication links, (b) the low-speed CPU-memory bus of the clustered sensor nodes, (c) fixed-to-OS implementations, bounded by their specific features for distributed functionality and lack of cross-OS portability. Currently, an increasing number of sensor middleware projects are utilizing a multi-agent paradigm for their implementations. These implementations do not share anything in terms of underlying OS, middleware interfaces, data formatting, process definition, agent architecture, thus making their fusion and collaboration, to form scalable sensor collectives, almost impossible. The next steps in our research involve the detailed definition and development of individual modules and services. The aim is to abstract the wireless sensor hardware and operating system as much as possible, so as to make the developed modules as platform-agnostic as possible. Then, on the basis of the single – node level development, the focus will be shifted towards the collective-node implementation, which in turn will be of relevance to larger scale wireless condition monitoring applications.

8 List of Abbreviations

ACQP	– Acquisitional Query Processing
ADC	– Analog-to-Digital Converter
API	– Application Programming Interface
CBM	– Condition-based Maintenance
CMMS	– Computerised Maintenance Management System

CPU	– Central Processing Unit
DBMS	– Data Base Management System
DMA	– Direct Memory Access
EPROM	– Erasable Programmable Read Only Memory
ERP	– Enterprise Resource Planning
ISA	– International Society of Automation
ISM radio bands	– Industrial, Scientific and Medical radio bands
LBS	– Location Based Services
MIMOSA	– Operations and Maintenance Information Open System Alliance
ND	– Novelty Detection
O & M	– Operations & Maintenance
OS	– Operating System
OSA	– Open System Architecture
PDA	– Personal Digital Assistant
RAM	– Random Access Memory
RF	– Radio Frequency
RFID	– Radio Frequency Identification
ROM	– Read Only Memory
SCM	– Supply-Chain Management
SDK	– Software Development Kit
SDRAM	– Synchronous Dynamic Random Access Memory
SRAM	– Static Random Access Memory
SHM	– Structural Health Monitoring
SOA	– Service Oriented Architecture
SOAP	– Simple Object Access Protocol
SOC	– System on a Chip
SQL	– Structured Query Language
SQTL	– Sensor Query and Tasking Language
TEDS	– Transducer Electronic Data Sheets
VLSI	– Very-Large-Scale integration
WPAN	– Wireless Personal Area Network
WSN	– Wireless Sensor Networks

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Integration Through Standards – An Overview of Internal Information Standards for Engineering Asset

Daniela L. Nastasie[1], Andy Koronios and Abrar Haider

Abstract Contemporary engineering organizations are increasingly becoming reliant on advanced computing technology and information systems to ensure the effective management of their engineering assets. Ensuring the reliability, maintenance and management of assets is dependent on the integration and interoperability of their information systems. A plethora of standards have emerged to assist the horizontal and vertical integration of such systems. Within the asset management field several leading bodies and consortia are focusing on standards development. MIMOSA and ISO are two of the leading standardisation bodies that are active in the development of such standards. Although a number of 'open' standards have been developed such standards are not being taken up as rapidly as expected due mainly to the significant investment required in adoption and inertia to change. This not only has implications for interoperability as assets become more complex and difficult to maintain, but also the storage and retrieval of quality data over its lifecycle. This paper provides an overview of information standards relevant to the integration of asset management systems, discusses the direc-

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tions of the development of these standards and comments on the implications of these advances.

Keywords Asset Management, Interoperability, Standards

1 Introduction

Standards are common agreements that enable communication across a range of systems for a variety of user requirements with the goal to increase economic efficiency by detailing specifications, processes, formats and procedures so that the quality and safety of processes can be monitored consistently [1–3]. One way to categorise standards is by their ownership, who created them and under what Intellectual Property rights. From this point of view, standards can be classified into *open standards* (free for public use, development and inspection) and *proprietary standards* (protected by Intellectual Property laws). The purpose of *open standards* is to support common agreements that enable communications open to all [4]. Krechmer [4] questions the very term 'open standards' and argues that Standards Setting Organisations (SSOs) rarely meet the criteria of an open standard and those that do are at varying levels of support. Kemmerer [5] calls for a methodology for the evaluation, testing and validation of open standards from the perspectives of conformance, interoperability and implementation is required. Proprietary standards, on the other hand, can lead to financial losses for vendors when multiple proprietary systems target a single market *'... multiple proprietary systems catering to a single market often lead to financial loss for vendors in that space'* [6].

Standards are generally defined at a national or international or company level, but in the last decade there has been a clear movement towards international standards [1] – Figure 1:

> *Only when buyers and sellers actually use the standards to conduct day-to-day business can they realize the competitive advantages of the standards ... Standards adoption, in fact, can transform industries, and often signifies the maturation of those industries as a whole* [6].

A further method of classification of standards is by *their originating body*, into '*de jure*' *standards* – created by authoritative standardization bodies and '*de facto' standards* – standards that arise from particular industries or market places and become widely implemented and used.

Standards could also be categorised *by the level of detail* they present. Bloomberg and Schmelzer [6] classify them into *LCD (Least Common Denominator) standards*, describing standards that include only those elements that all parties manage to agree upon, and at the other end of the spectrum, the *'kitchen-sink' standards*, those that contain all the suggestions of all the parties usually '*too large for everyone and not specific enough for anyone*'.

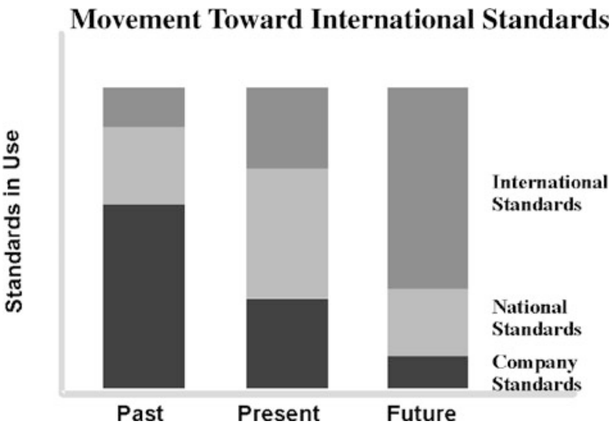


Figure 1 Movement toward International Standards – Source: [1]

Bengtsson [7] provides an insightful perspective into the role of standards, defining the purpose of standardization as reaching 'the optimal technical and economical solution to recurrent problems' and suggesting that standards are an important environmental and energy saving tool

> *Standardization should be looked upon as a tool for a rational, environmentally sound and energy saving development of production, distribution and utilization of commodity, processes, systems and services* [7].

This paper presents an overview of international standards of relevance to Engineering Asset Management (EAM) focusing in particular on standards of relevance to the integration of asset management information systems.

2 Integrated Engineering Asset Management

After a time in the 1980s when building the physical infrastructure had a high priority and the funds to support these efforts was easily available, the government focus changed to maintaining and increasing the life expectancy of the existing infrastructure, escalating the demands on agencies to be more accountable and provide cost justification before further money allocation. As a consequence, agencies now recognise the need for a more systematic approach to the management of assets and the asset managers rely more and more on information systems, knowledge databases and asset registers to make better informed business decisions [8]. At the same time, effective and efficient data analysis has become essential for integrated resource planning based on a more strategic understanding of infrastructure assets and their role in the provision of community services [9].

The Cooperative Research Centre for Integrated Engineering Asset Management, (CIEAM) is an organisation created with the main purpose of optimising asset management systems, study innovative technologies, processes and programs in order to enhance the infrastructure cost effectiveness, productivity and longevity of the Australian engineering infrastructure.

CIEAM defines Asset Management as

> *... the process of organising, planning and controlling the acquisition, use, care, refurbishment, and/or disposal of physical assets to optimise their service delivery potential and to minimise the related risks and costs over their entire life through the use of intangible assets such as knowledge based decision-making applications and business processes.*

Tangible assets such as buildings, roads, machineries, and hardware, are distinguished in the CIEAM definition from *intangible assets* such as knowledge, software, intellectual property, and financial assets [10], and the two types of assets are considered to be connected, as presented in the assets structure in accounting systems where *intangible assets* are considered a subclass of *physical* (*engineering*) *assets* at the same level as *tangible assets* [11]. This connectivity is the foundation and motivation for the concept of *Integrated* Engineering Asset Management, which emphasises the role of *intangible assets* in the management of *tangible assets*. In this context, issues related to the *integration of information* from various engineering asset management systems to better inform the decision-making bodies constitute a main topic of research in the Engineering Asset Management literature [11].

3 The Engineering Asset Core Lifecycle (EACL)

Asset Management definitions depend largely on the perspective from which the analysis of the assets is made and the purpose of the study.

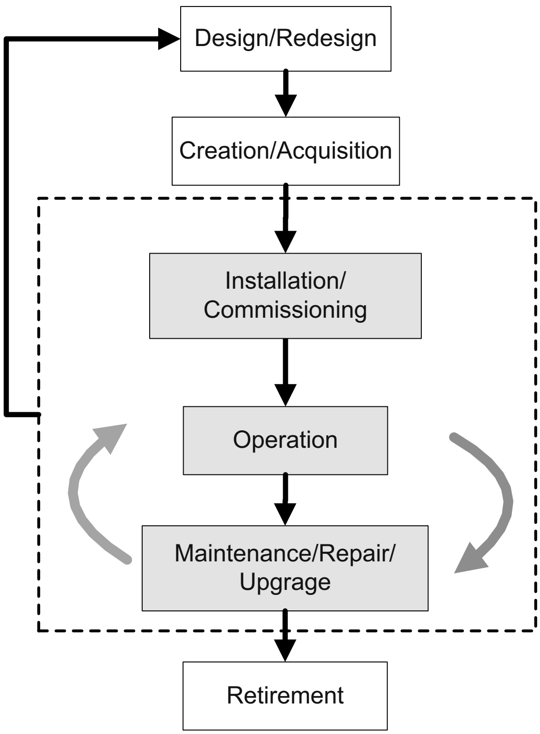
Woodhouse [12] promotes a strategic business approach towards Asset Management when he defines Asset Management as

> *the set of disciplines, methods, procedures and tools derived from business objectives aimed at optimising the whole life business impact of costs, performance and risk exposures associated with the availability, efficiency, quality, longevity and regulatory safety/ environmental compliance of an organisation's assets* [12]

while Haider [13] invokes a lifecycle approach to the assets in his definition of Asset Management, arguing that

> *asset management entails preserving the value function of an asset during its lifecycle and maintaining it to as designed or near original condition through maintenance, upgrade, and renewal until sustainable retirement of the asset due to end of need or technology refresh* [13].

Figure 2 Simplified View of Engineering Asset Lifecycle (EACL). Source: Developed by the authors



This paper will combine these two perspectives, by considering the management of assets as part of the strategic view of organisations, as well as following the lifecycle stages of the asset management process. An abridged view of the lifecycle of an engineering asset is presented in Figure 2.

The EACL (Engineering Asset Core Lifecycle) diagram presented in Figure 2 will be used in this paper to anchor the discussion on the activities and processes related to the lifecycle of an asset and as a pattern for analysing the standards required throughout the asset lifecycle.

The asset lifecycle begins with design and creation/acquisition stages, moves into operation and maintenance stages, and finally into its eventual divestment or retirement stage. An area of particular interest in the lifecycle of an asset is the Operation and Maintenance block, represented in the EACL diagram by a rectangle, where most of the effort is concentrated with some organisations reporting that up to 70 % of the total cost of ownership of an asset is consumed at this stage. The maintenance block is important, but communication is required along the whole lifecycle of assets and standards to regulate these interfaces (the design, creation, retirement) as well as operation and maintenance, need to be considered in order to facilitate the interoperability and integration inside the lifecycle of the asset.

Assets also depend on other assets or they constitute parts of a bigger ensemble, so when discussing interoperability between assets the external as well the internal connections between assets are considered (For example when managing a road asset, the sub-ensembles of lighting or signage on that road need to be also considered, but also we need to integrate the road into the bigger picture of how it fits into the infrastructure network of the whole area).

Therefore, from a *business perspective*, Asset Management refers to attributes such as: assets health, availability/reliability and performance (HARP) and the aim is to reduce costs, increase reliability, performance and return on investment (ROI) in order to increase customer satisfaction [14]. Asset Management in the Business arena deals with the dynamic impact of HARP values on to each other and is mainly interested in the financial value of the assets [15]. Business Asset Management mainly uses data from business, financial, human resource, inventory and maintenance systems, such as Facility Management Systems (FMS) or Financial Systems (FS). These systems store usually *static data* about the physical assets and cannot acquire or use dynamic data relevant to the operation or performance of the asset. ERP (Enterprise Resource Planning) systems are also included in this area, which will be called the *Business Management* area.

From a *technical point of view*, Asset Management refers to gathering critical (very often real-time, dynamic) data, along the life-cycle of the asset, monitoring the assets and collecting data in order to perform intelligent diagnosis to support their maintenance and performance. This part of Asset Management is based on systems like system control, data acquisition, condition monitoring and condition maintenance management. This area will be called the *Engineering Management* domain.

From an *information perspective* Asset Management refers to collecting and storing data about the assets using various application software and integrating them into Information Management systems, storing them into Data Warehouses and retrieving information as needed for various purposes. These systems could include critical and/or non-critical data, could be either fully developed systems or particular technologies designed with a specific focus in mind (such as systems used to record dynamic snapshots for control and monitoring – *e.g.* SCADA – Supervisory Control and Data Acquisition). This area will be called the *Information Management* domain.

One issue with all these systems from various domains is that they do not communicate with each other, they use different technologies, store data in separate databases, and use different data structure formats. It comes as a consequence that efforts are now aimed at designing Integrated Asset Management systems, and to be able to achieve this goal, open (international) standards need to be created and implemented. Referring to the current status of systems integration MIMOSA president, Alan Johnston, remarks that

> *what organizations have not done is to establish proper systems integration between their real-time oriented plant floor systems and their transaction-processing oriented business systems* [16]

Johnston uses the concept of *vertical and diagonal integration of data* into information systems and considers that the integration should start with collaboration between key standards organizations in order to ensure efficient, effective, and interoperable standards [16]. The "*Theoretical Framework for Integrated Asset Management*" designed by CIEAM [17] distinguishes 12 functions (modules) pertaining to an Integrated Asset Management Framework, as presented in Table 1.

For the purpose of having a generic view of engineering asset management standards, we will group the CIEAM asset management modules into three main areas as per the layers identified above (*Business Management*, *Engineering Management* and *Information Management*) and create a graphical representation of an Integrated Asset Management system, with the following components (Figure 3).

1 *Business Management* – Strategic Planning, Risk Management, Financial Management, Budgeting and Costing, Asset Ownership;
2 *Engineering Management* **–** Assets Usage Life Cycle, Performance Measures, Tactical Planning, Condition Monitoring;
3 *Information Management* – Information Systems, Data Management, Human Resources.

The *Information Management* domain has a special role in the IEAM diagram. The IM is the support layer of integration between the EM and the BM domains, and its role increased in time with the evolution of Information Technology discipline (Figure 4). Initially, the Information Management was concerned with

Table 1 Integrated Asset Management functions – Source: adapted from [17]

1	Strategic Planning	7	Tactical Planning
2	Asset Ownership	8	Human Resources
3	Risk Management	9	Asset Usage Life Cycle
4	Budgeting and Costing	10	Performance Measures
5	Data Management	11	Information Systems
6	Condition Monitoring	12	Financial Management

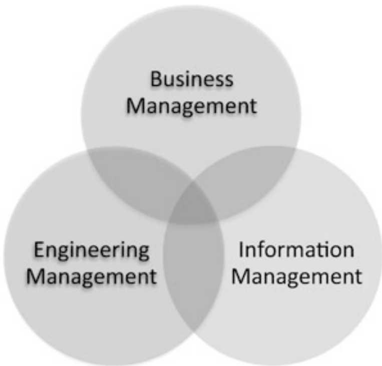
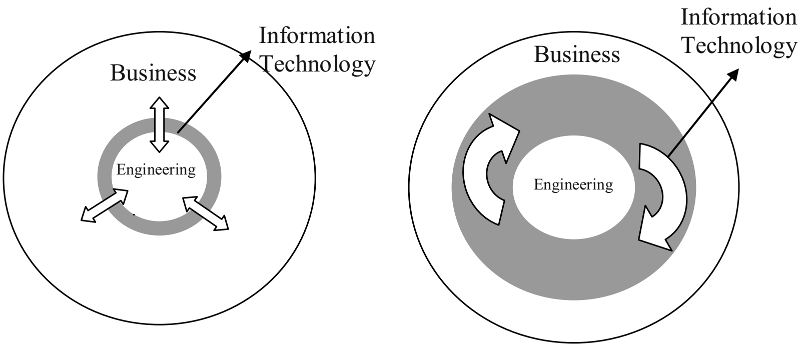


Figure 3 Integrated Engineering Asset Management (IEAM) Diagram.
Source: Developed by the authors



(a) (b)

Figure 4 Information Management layer evolution. (a) IT incipient level; (b) IT mature level; Source: Developed by the authors

managing information and communication between the EM and BM areas via "point-to-point" interfaces between individual systems intra or inter EM and BM domains (Figure 4a). The evolution of Information Technology and the increased role of Internet lead to a more mature and robust IM infrastructure which is currently able to support not only static, but also dynamic integration between systems, on a larger scale and from a variety of disparate sources (Figure 4b).

In order to perform an analysis of standards related to the integration of asset management systems an investigation needs to be made not only into the standards and evolution of trends inside the two main domains, EM and BM, but also into the developments inside the IM area to understand the directions and opportunities created by the latest progress in the IM realm.

4 Interoperability Levels on the IEAM Diagram

In the IEAM diagram the core of the IEAM diagram shows an overlapping area between EM, BM and IM. This is the area of most importance in the discussion of *integration* of asset management systems (Figure 5). This area would represent the achievement of complete interoperability among systems from the EM and BM domains, based on the most mature and robust IM models and architectures. The level of maturity of the IT is an important factor in the functionality of an Information System, as it defines the characteristics of the system as a whole and it dictates the level of interoperability with other systems. Therefore, the standards that belong to the core of the IEAM diagram are standards that support this high level of integration.

For example, the B2MML standard (see Appendix) is situated in the EM-BM-IM area, because it covers both the EM and BM areas and is based on XML format for data exchange; hence it has the potential of integrating systems over the

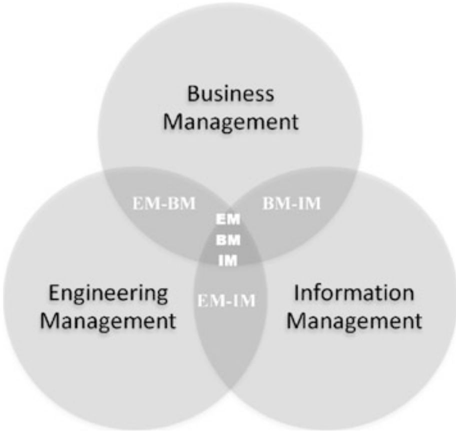


Figure 5 Integrated Engineering Asset Management (IEAM) Standard Types; Source: Developed by the authors

Internet. The corresponding standard ISA-SP95 (with its international version ISO/IEC 62264) is not at the same level of interoperability, as it does not provide a proper data exchange structure (hence the need to create an XML version for it). BatchML on the other hand, even though it is an XML version of another ISA standard (ISA-88), it is not situated in the EM-BM-IM area because it lacks the BM component.

This research investigates the standards that are currently available to support the interoperability of asset management information systems. Depending on the number of overlapping layers on the IEAM diagram, three main categories of areas of standards are shown in Figure 5.

The first category is a "single layer" type of domain, *i.e.* the Engineering Management (EM), Business Management (BM) or the Information Management (IM) realms (Figure 5); in these areas we will place standards concerned only with a particular domain. These standards impact on the communication inside the domain, they define procedures and specifications for internal activities. An example could be the UML specification which deals with issues specific to the IM domain. Even though UML can be at the foundation of other standards used in other domains, the UML in itself is part of the IM domain, as it deals with issues specific to the IM area. Another example is CORBA – Common Object Request Broker Architecture, which proprietary data formats used in various applications require a form of translator or wrappers around applications to facilitate communication at the enterprise level [18]. CORBA could be also considered a framework for implementing distributed systems. On the IEAM diagram CORBA is situated in the IM area as it does not refer specifically to any of the EM or BM domains.

The second type of area is a "double layer" domain, *i.e.* the EM-BM, BM-IM or the EM-IM. Standards in this area interconnect activities from two domains. Examples could be the ISA-95 for the BM-EM area, FpML for the BM-IM area or OSA-CBM for the EM-IM area.

The third and most complex area is the "three layer" domain, covering activities from all three domains: EM-BM-IM. An example of such a standard is the

MDA (Model Driven Architecture). Even though MDA could be considered an IM standard in the first instance, due to its universality and the fact that it can be applied across platforms and domains, it belongs to the EM-BM-IM, due to its potential of interoperability. MDA is based on OMG's established standards: UML, OMA, and MOF technology such as CWM, the Common Warehouse Metamodel [19]. Platform independent models can be realised through MDA on any platform, proprietary or open (Web Services,.NET, CORBA, *etc.*). This flexibility makes MDA an excellent candidate to support interoperability between the three areas of the IEAM diagram, as it is generic enough to cover all three IEAM domains, and it is specific enough to cater for each individual domain needs.

Even though these architectures do not cover BM and EM areas explicitly, their universality include these domains, as well as any other, so we could conclude that these architectures are the first step towards building fully integrated systems in the future. The information architecture dictates the level of interoperability and its design is the first step towards interoperability. Only after the information architecture is in place, further analysis of various parts of the asset management lifecycle and their level of interoperability can be made. On the IEAM diagram, the more layers a standard covers the more useful to the goal of integration it is, and following this criterion we will assign existing standards to specific areas on the diagram.

5 Distribution of Standards on the IEAM Diagram

A better view of the distribution of activity in the standardization space can be gleaned by populating the IEAM diagram with the corresponding standards for each of its domains. This distribution is presented in Figure 6. Brief information on each standard discussed is listed in the Appendix.

5.1 The EM-IM Area

This area is by far the most populated area with standards at this stage. Standardisation efforts of ISA (The Instrumentation, Systems and Automation Society), the ISO (International Organisation for Standardisation), MIMOSA (Machinery Information Management Open Systems Alliance), IAI (International Alliance for Interoperability), OMG (Object Management Group), OPC (Open Connectivity Foundation), IEC (International Electrotechnical Commission) and WBF (World Batch Forum) all have standards included in this area. These standards use various IM technologies in order to increase interoperability between various systems dealing with various aspects of the lifecycle of an asset, especially the Operation and Maintenance block.

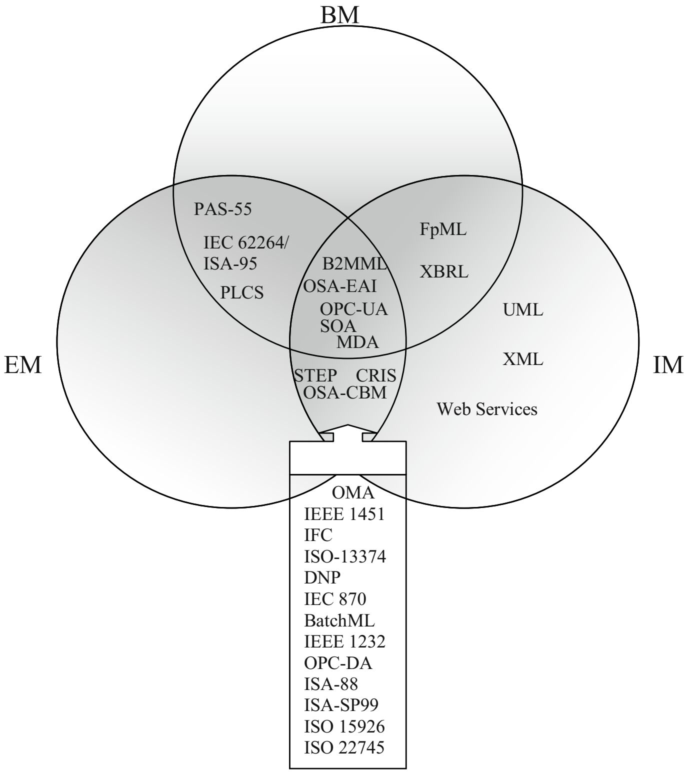


Figure 6 Standards distribution on the IEAM diagram. Source: Developed by the authors

Examples of standards in this area include the WBF's *BatchML*, based on the ISA-88 standard that defines models and terminology for batch processing industry. BatchML is an important standard in this area, due to its XML format that allows easier data exchange across platforms.

STEP-*Standard for the Exchange of Product model data* (ISO 10303) is another important standard in this area, covering data exchange throughout the lifecycle of the assets. Efforts are underway to make STEP information universally available using XML and UML standards. ISO/DIS 10303-28 focuses on XML representations of EXPRESS schemas and data, and ISO/TS 10303-25 specifies a mapping from the EXPRESS data specification language into the Unified Modeling Language (UML), for the purpose of generating files conforming to the OMG XML Metadata Interchange (XMI) standard. This will allow STEP to provide support for more flexible Web Services applications and STEP databases to become an important resource in identifying compatible products and processes on the Web [20].

IEC 60870 (IEC 870) – *Telecontrol equipment and systems* is one of the communication protocol standards used by SCADA (Supervisory Control And Data Acquisition) systems, especially in Europe and Middle East. North America and

Australia use instead the DNP3 (Distributed Network Protocol), which is based on the IEC 60870-5 but not identical [21]. DNP3 and IEC 60870-5 are two of the most widely recognised open standards by the SCADA vendors. MIMOSA's OSA-CBM (Open System Architecture for Condition Based Maintenance) is also included in the EM-IM area. Baldwin [22] argues that one of the main benefits of open protocol standards such as those developed by MIMOSA, is access to various information systems holding different information types (*e.g.*: work history, reliability data, vibration analysis, infrared thermography, oil analysis, control device monitors, *etc.*), via a unified view. The OSA-CBM is a standard architecture/ framework for monitoring and diagnostic of assets. It integrates all Condition-Based Maintenance processes, from data acquisition to decision making [23]. It can be argued that MIMOSA OSA-EAI covers partially areas of BM as well, as it supports various business aspects such as risk management and lifecycle costing, but considering its main role is supporting Operations and Maintenance applications integration, it is considered better situated at this stage in the EM-IM area. MIMOSA CRIS (Common Relational Information Schema) is an standard model for data fields. It represents a static view of the data produced by a CBM (Condition Based Maintenance) system and it allows communication of diagnostic, health and prognosis, models maintenance and production work requests. MIMOSA has adapted CRIS to XML [24]. MIMOSA CRIS (Common Relational Information Schema) covers aspects from the EM domain (targeting technical areas of asset management) and it provides an information framework for storing data (defining data fields for these areas), therefore it belongs to the EM-IM area as well.

5.2 The EM-BM Area

The integration between the EM and BM areas is much less represented by international standards. ISA created the ISA-95, a standard for the integration of enterprise and control systems, and IEC brought it to an international level, via IEC 62264. The PLCS-Product Life Cycle Support is an ISO 10303 Application Protocol 239 supported by OASIS (Organisation for the Advancement of Structured Information Standards) that develops and publishes the PLCS Data Exchange Sets (DEX). PLCS is an attempt to cover both EM and BM areas in a single integrated information model. PLCS standard is built on a modular architecture in order to construct a single integrated information model.

Another standard falling into this category, PAS-55 is a public specification intended to support the Asset Management activities related to physical infrastructure assets. It is based on the *Plan-Do-Check-Act* (*PDCA*) *methodology* and employs a "*continual improvement*" life cycle for managing physical assets. PAS 55-1 [25] considers that the life cycle steps are to be implemented either through separate Information Systems or through an integrated AM information system (AMIS). Guidelines are provided in PAS 55-2 [26]. While the PAS 55 specification has a great value as a guideline for implementing an asset management strategy, it has little to do with defining concepts or terminologies that could support an Asset Management ontology, therefore it does not cover very well the Information Management (IM) area.

5.3 The BM-IM Area

Standards in this area would cover information integration from a business perspective. Examples of standards that cover the BM-IM area are the FpML standard from the FpML.org organisation, a business information exchange standard for electronic dealing and processing of financial derivatives instruments and XBRL (eXtensible Business Reporting Language) a business standard which communicates information by describing documents using financial terms and concepts defined in commonly agreed taxonomies, covering well the IM area. Standards in this category are usually written in XML.

5.4 The BM-EM-IM Area

In order for a standard to be categorised in the area BM-EM-IM it needs to cover all three areas: BM, EM and IM. The EM-BM-IM area is the potential location for standard information models of a more formal structure, such as ontologies, which are expected to play an important role in the exchange of information over the Internet [27].

One current international standard that falls into the BM-IM-IM category is the B2MML (Business to Manufacturing Markup Language) from WBF. Based on ISA-95 which already focused on the integration between the EM and BM domains, B2MML takes a further step towards the full integration of the three domains, by designing an XML interface to it, so it could be situated in the IEAM core area. Other useful standards for complete integration of the BM and EM domains are the universal architectures developed in the IM arena recently. The MDA (Model Driven Architecture) developed by OMG (Object Management Group) is based on other useful technologies developed by OMG (UML, MOF and OMA – see Appendix for details). MDA aims to separate the business and application logic from technical details of how the system operates in order to increase interoperability between systems.

OPC UA (OPC Unified Architecture) is an attempt from the Open Connectivity Foundation to unify the data exchange by exposing information models via services. OPC UA is closely related to the SOA (Service Oriented Architecture), which attempts to define business and application needs using the idea of services.

MIMOSA OSA-EAI (Open Systems Architecture for Enterprise Application Integration) may also be included in the BM-EM-IM area.

One important issue that has to be investigated in relation to these information model standards is their adoption and diffusion in practice [28, 29] as unless they are adopted and diffused on a large scale, such as the industry level, they cannot provide the full benefits they are designed to offer.

6 General Findings

Several observations occurred from this meta-analysis of standards research:

1. High activity towards the creation of standards in areas of overlapping domains (EM-IM, EM-BM and BM-IM) has been noticed, with most covered domain being the EM-IM. These standards support interoperability between EM and BM systems.
2. Some of the existing standards have been translated or are currently in the process of being translated into XML format in order to make them more flexible and allow better interoperability between systems. An example of this trend is the US ISA-95 standard, adopted internationally as IEC 62262 and "translated" into XML by WBF as B2MML; the US ISA-88 was adopted internationally as IEC 61512 and turned into XML format as BatchML by WBF. A strong tendency towards the *creation of standards in XML format* has been noticed in all overlapping areas, to allow data exchange via the Internet using the Web applications.
3. Recent efforts in the IM domain have been concentrated towards creating *universal architectures* to support integration from disparate domains (*e.g.* the Model Driven Architecture (MDA) or the OPC-UA), in order to provide full support for interoperability between systems and for new types of Asset Management architectures based on these highly flexible structures.

7 Conclusions and Limitations

This paper reported the initial stages of ongoing research in identifying, classifying and evaluating the efficacy of standards in the area of Engineering Asset Management. It provided initial thinking towards the development of a generic view of the integration of Engineering Asset Management through a three domain integration diagram, the IEAM. A review of current standards was undertaken in an attempt to classify them according to the domains of the IEAM.

It is suggested that international efforts are currently concentrated in the "double layer" areas of overlapping domains, with the core of the diagram containing already some flexible universal IM architectures that could be built upon to achieve full interoperability of the IEAM domains. A tendency towards the adoption of Web Services and the Service Oriented Architectures initiatives has been noticed, which promises enhanced interoperability and integration of EAM information systems.

8 Future Work

The purpose of this paper was to provide a general overview on standards that would promote and facilitate the integration of Asset Management information. The goal was to investigate various types of standards relevant to the interoperability of Asset Management systems within organisations (internal interoperability) and between organisations (inter-organisationsal interoperability). A future objective of this study is to investigate the adoption and implementation of such standards in practice.

Additional future objectives may include the investigation of interoperability between systems from different lifecycle stages of the Asset Management (such as the interconnection between CMS and the ERP or GIS from within the same institution), as different systems store different data in different ways, hence using different metadata and metadata schemas, which can raise many issues for information standardisation.

Recent developments of Internet technologies and the rise of the 'cloud' promise to 'open up' to the world (or private networks) the information currently stored in heterogeneous asset management information systems through the use of web technologies such as XML syntax for representing web-accessible metadata and the RDF and/or XSLT for expressing semantic equivalences. SOA and Web Services allow a level of integration and interoperability between systems that was not possible in the past and how these new technologies can be exploited to create the required interoperability level between Asset Management systems is another avenue of research for the future.

Future work will concentrate also on re-designing Asset Management information architectures according to the new views of integration and interoperability in order to provide the loosely coupled environment in which semantic interoperability can be achieved.

Appendix – International Standards and Main Standardisation

Name	Standardisation body	Type	URL
B2MML-Business to Manufacturing Markup Language	International Society of Automation	Development language	http://www.isa.org
BatchML – Batch Markup Language	ISA-88 (IEC 61512)	Development language	http://www.isa-88.com/
BSI PAS 55 – Publicly Available Specification	BSI British Standards IAM –The Institute of Asset Management	Specification	http://www.bsigroup.co.uk/en/ http://www.theiam.org/
CORBA – Common Object Request Broker Architecture	Object Management Group	Architecture	http://www.omg.org/
FpML (Financial products Markup Language)	International Swaps and Derivatives Association	Development language	http://www.fpml.org/
IAI – International Alliance for Interoperability	Building SMART International	Standardisation body	http://www.iai-tech.org/
IEC 60870 (IEC 870) – Telecontrol equipment and systems	International Electrotechnical Commission	Systems specification	http://www.iec.ch/
IEC 61512	International Electrotechnical Commission	Reference model	http://www.iec.ch/
IEC 62264 – Enterprise Control System Integration	International Electrotechnical Commission	Data/Application integration	http://www.iec.ch/
IEC – The International Electrotechnical Commission	International Electrotechnical Commission	Standardisation body	http://www.iec.ch/
ISA – The Instrumentation, Systems, and Automation Society	International Society of Automation	Standardisation body	http://www.isa.org/
ISA-88 (IEC 61512)	International Society of Automation	Standard for describing equipment, and procedures	http://www.isa.org/
ISA-95 (IEC 62264) standard for the integration of enterprise and control systems	International Society of Automation	Data/Application integration	http://www.isa.org/

Name	Standardisation body	Type	URL
ISA-SP99 – Manufacturing and Control Systems Security	International Society of Automation	Systems specification	http://www.isa.org/
ISO 10303 – STEP	International Organization for Standardization	Data and schematic representation	http://www.iso.org/
ISO 10303 – STEP-Standard for the Exchange of Product model data (STEP File)	International Organization for Standardization TC 184	Data and schematic representation	http://www.iso.org/
ISO 10303-11 EXPRESS	International Organization for Standardization	Data and schematic representation	http://www.iso.org/
ISO 10303-22 SDAI Standard data access interface	International Organization for Standardization	Data and schematic representation	http://www.iso.org/
ISO 10303-28 XML representation for EXPRESS-driven data (STEP XML)	International Organization for Standardization	Data and schematic representation	http://www.iso.org/
ISO 10303, Application Protocol (AP) 239 Product Lifecycle Support (PLCS)	ISO – International Organization for Standardization	Data and schematic representation	http://www.oasis-open.org/
ISO-13374 – Condition Monitory and Diagnostics of Machines	International Organization for Standardization	Data and schematic representation	http://www.iso.org/
ISO 15926 – Industrial automation systems and integration – Integration of life-cycle data for process plants including oil and gas production facilities	ISO – International Organization for Standardization	Data integration	http://www.iso.org/
ISO 22745 – Industrial automation systems and integration – Open technical dictionaries and their application to master data	ISO – International Organization for Standardization	Data integration	http://www.iso.org/
MDA-Model Driven Architecture	Object Management Group	Architecture	
MOF-Meta Object Facility	Object Management Group	Models export	http://www.omg.org/

Name	Standardisation body	Type	URL
MIMOSA OSA-CBM v3.1L- Open System Architecture for Condition-Based Maintenance	MIMOSA – Machinery Information Management Open Systems Alliance	Data exchange	http://www.mimosa.org/
MIMOSA OSA-EAI v. 3.0g- Open Systems Architecture for Enterprise Application Integration	MIMOSA – Machinery Information Management Open Systems Alliance	Data exchange	http://www.mimosa.org/
MIMOSA CRIS- Common Relational Information Schema	MIMOSA – Machinery Information Management Open Systems Alliance	Data and schematic representation	http://www.mimosa.org/
OASIS-Organization for the Advance-ment of Structured Information Standards	Organization for the Advancement of Structured Information Standards	Open standards	http://www.oasis-open.org/
OMA – Object Management Architecture	Object Management Group	Software architecture	http://www.omg.org/
OPC (Open Connectivity) Foundation	OPC Foundation	Industry automation; data inter-operability, access, exchange	http://www.opcfoundation.org/
OPC Data Access (OPC DA)	OPC Foundation	Data access	http://www.opcfoundation.org/
OPC Unified Architecture	OPC Foundation	Data access	http://www.opcfoundation.org/
UML-Unified Modeling Language	Object Management Group	Modelling language	http://www.omg.org/
W3C – World Wide Web Consortium	World Wide Web Consortium	Web standards	http://www.w3.org/
XBRL – eXtensible Business Reporting Language	XBRL International	Data exchange	http://www.xbrl.org/Home/
XML- Extensible Markup Language	World Wide Web Consortium	Development language	http://www.w3.org/

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Part V
Scope (Sustainability and Safety)

Sustainability-Based Asset Management in the Water Sector

David R. Marlow

Abstract Asset management should be a key vehicle for delivering sustainability goals of a business. However, for this to be the case, the link between sustainability outcomes and asset management inputs/outputs needs to be translated into terms that are meaningful to asset managers. In practice, however, asset managers often cannot see how their decisions link into sustainability objectives. Operationalising sustainability within asset management thus represents a significant challenge, even within the water sector where business activities are explicitly linked to 'triple bottom line' outcomes. To help meet this challenge, research has been undertaken into the role sustainability principles should play in asset management. As part of this research, a series of interviews have been undertaken with water sector professionals in Australia. The interviews aimed to collate opinion on the role sustainability concepts currently play in asset management, the role sustainability should play in the future, what the key barriers are, and where there is a need for research to help bridge the gaps. This paper outlines the conceptual relationship between asset management and sustainability principles, presents a synthesis of the results from these interviews, and indicates subsequent research efforts undertaken to help embed sustainability principles within the asset management business function.

Keywords Asset management, Sustainability, Water sector, Triple bottom line

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1 Introduction

In economically developed countries, the majority of urban water and wastewater services are currently delivered through distributed systems of above and below ground assets. The provision of these services is an integral part of a healthy society. However, the urban water sector today faces a complex range of challenges, including declining availability of water from the terrestrial environment, an unstable global economy, increasing energy prices, and increasingly complex regulatory and social circumstances. Meeting these challenges is vital if water utilities are to maintain the confidence of the communities they serve. Adapting business thinking to cope with emerging realities requires a new operating paradigm to be embraced by the water sector – that of sustainability [1].

Given the asset-intensive nature of the sector, asset management should be a key vehicle for delivering sustainability goals of a water utility [2]. From an asset management perspective, however, sustainability goals can simply be an expression of the intent to provide broadly affordable levels of service into the future [3, 4]. Notwithstanding the importance of achieving sustainable service provision, sustainability is increasingly being interpreted in line with the concept of 'sustainable development' [5]. With this later context in mind, achieving sustainable outcomes through effective asset management is a relatively new challenge facing water utilities. To help meet this challenge, asset managers need to see how their decisions link into the high-level sustainability objective of their water utility, which in turn requires that the link between sustainability outcomes and asset management inputs/outputs be explicitly mapped out.

To help address this challenge, research has been undertaken into the role sustainability principles should play in asset management, focusing specifically on the urban water sector, and designed to help asset managers 'operationalise' sustainability objectives, and provide tools and approaches for decision support. As part of this research, structured interviews were undertaken with a range of industry professionals who provided insight into current industry practices and opinions on where there remain research gaps.

This paper outlines the conceptual relationship between asset management and sustainability principles, then presents summary results from these interviews. An overview of two projects undertaken in response to research priorities identified in the interviews is then given, to show how insights gained in the interviews were used to inform research direction.

2 The Meaning of 'Sustainability'

As intimated earlier, the definition of the word 'sustainability' arises from the verb "to sustain". At a basic level, the use of any related terms like 'sustainable', 'sustainably' or 'sustainability' merely implies an attempt or intention to continue to do something indefinitely. In an asset management context, such terms could therefore be simply an expression of the intention to continue to deliver services into the future [6]. However, the concept of sustainability being discussed herein is more in line with the concept of 'sustainable development', a widely accepted definition of which is given in the Brundtland Report [5] as:

> *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

Very weak to very strong versions of sustainable development have been defined, which differ in the degree of allowable substitution between environmental, social and economic capital stocks [6]. However, all the definitions recognise that appropriate consideration should be given to the constraints imposed by the environment and social circumstances. As shown in the definition given above, sustainable development also requires consideration of inter (and, by implication, intra) generational equity. Given the long life of many water assets, this is implicit a concern for asset management as well.

2.1 Sustainability in the Water Sector

The water sector is arguably in a unique position to take the lead on broader sustainability issues [1], not least because water utilities supply services that underpin all other social and economic activity in a specific (spatially constrained) area. These aspects mean that there is an implicit requirement for utilities to maintain a social license to operate from the communities they serve. Water utilities are also engaged with simultaneously delivering financial, social and environmental outputs, the so called triple bottom line (TBL) of business [7, 8], which must be maintained into the future. The complex linkages between the water authority, community and the environment are illustrated schematically in Figure 1.

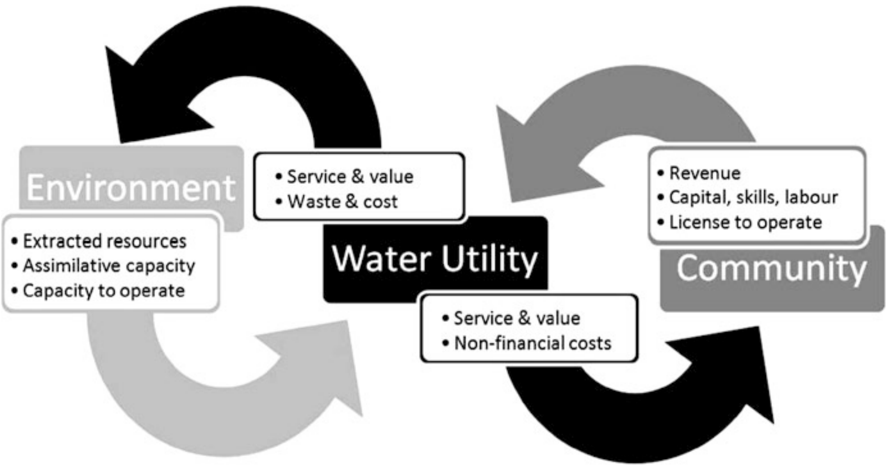

Figure 1 The linkage between a utility, the community and environment

Even given these linkages, discussions of sustainability within the water sector still often focus on ecological sustainability alone [9]. A more holistic definition was proposed by ASCE/UNESCO [10], who defined a sustainable water system as: "*… one that is designed and managed to contribute fully to objectives of society, now and in the future, while maintaining ecological, environmental and hydrological integrity*." The ASCE/UNESCO definition provides a reasonable basis from which to assess the sustainability of a water utility, especially from the perspective of its management of water resources. However, it is still somewhat vague from an operational perspective. With this in mind, Marlow & Humphries [1] discussed requirements for a useful operational definition, noting it should:

1. Provide a basis for improving communication and facilitate assessment of whether 'sustainability' has been achieved.
2. Not exclude the opportunity of becoming 'more sustainable' or preclude the possibility that a once-sustainable water utility could be shown to have slipped into unsustainable operations; *i.e.* a dynamic, rather than static, measure should be embedded into the definition.
3. Be couched in positive aspirational terms and not just in terms of 'no further deterioration', especially since there is compelling evidence that human pressure on the planet is truly unsustainable [11].
4. Address the needs of the now, not just the needs of the future, so as to engender a positive drive towards action.

In light of these requirements, the following operational definition was proposed: "*For a water utility, sustainability is practically achieved when all its activities, both internal to the business and across its supply chain, achieve net added value when assessed across each of the triple bottom line outcomes* (*financial, social and environmental*) *over the medium to long timescales, considering all costs and benefits, including externalities*." Although this definition does not explicitly address the asset base, both natural and manufactured assets managed by water utilities have a direct influence on TBL outcomes, which implies that effective asset management is a component of delivering sustainability.

3 Asset Management

Whilst it is becoming increasingly adopted in asset intensive sectors, 'asset management' in itself remains an ill-defined term and numerous definitions are in use [12]. While it can be usefully viewed as a business process [13], the following definition, modified from that given in the International Infrastructure Management Manual [14] encapsulate the main features of this emerging discipline:

> *"The combination of management, financial, economic, engineering and other practices applied to physical assets with the objective of providing the required levels of service to customers and the environment at acceptable levels of risk and in the most efficient manner."*

In practice, the focus of asset management effort can vary significantly depending on where in the ‘asset management’ journey an individual organisation is. For example, a succession of dominant philosophies has underpinned the strategic asset management approaches applied to existing assets in the water sectors of countries such as the UK, Australia, and increasingly the USA [15], namely:

- ***Condition-based asset management***; focused on maintaining ‘what assets are’ (the condition the assets are in).
- ***Performance-based asset management***; focused on ‘what assets do’ in a local sense; that is, the question is posed, is the asset doing the job that it was intended to? (This is a question that can often be related to the asset’s condition, but may not be.) If not, maintenance and/or capital investment are required.
- ***Service-based*** **(*service level driven*)** ***asset management***; where performance is no longer viewed in terms of local considerations (the design intent of individual assets), but instead is considered in more inclusive terms and at a higher level. The question is posed; are the assets contributing appropriately to the delivery of service?
- ***Risk-based asset management***; seeks to achieve optimum life cycle management of assets through consideration of risk to service provision. Issues taken into account include business risk factors such as those associated with safety and the environment, customer expectations, reliability, efficiency and effectiveness, finance, reputation and regulatory relationships.

This progression should not be conceptualised as discrete steps, as each successive development has built upon previous approaches by retaining the best practices developed to that point, but using them differently, and with a different emphasis. Through this process, ‘best practice’ strategic asset management frameworks have evolved over time so as to shift the focus away from a purely asset-centric view, to one that considers explicitly the underlying purpose of owning and maintaining the asset portfolio; the provision of service at an acceptable level of risk. In a similar vein, and assuming a growing commitment to sustainability (in line with the concept of sustainable development, as defined above), the next logical development is to focus on sustainability principles, and to fully develop ***sustainability-based asset management*** frameworks that deliver desirable outcomes that are fully aligned with the concept of sustainable development across the asset life cycle [2]. At present, however, asset management frameworks such as PAS 55 [16] and the International Infrastructure Management Manual [14] do not explicitly consider sustainability from this perspective.

4 Asset Management Within the Australian Water Sector

To understand where the Australian water sector is with respect the development of its strategic asset management philosophies, and thereby identify the need for further research and development, a series of structured interviews were undertaken with water sector professionals from various water utilities and other stakeholder organisations. These interviews aimed to collate opinion on the role sustainability concepts currently play in asset management, the role sustainability should play in the future, what the key barriers are and where there is a need for further research to help bridge the gaps.

4.1 Interview Design

As noted by Cohene & Easterbrook [17], interviews have the potential to elicit a large amount of information and can be undertaken in a structured, semi-structured, or unstructured format. In structured interviews, interviewers ask a set of predefined questions. In contrast, semi-structured interviews can be delivered in an exploratory and dynamic manner. In unstructured interviews, there is no pre-defined agenda, and interviewers may explore a range of issues with stakeholders. Given the aims of this research were to elicit viewpoints on relatively specific issues, a semi-structured format was considered to be the most appropriate. A questionnaire was therefore developed for use in the interviews and the following interview protocol adopted:

1. All interviews were undertaken face-to-face.
2. Interviews were recorded (with permission of the interviewee); this allowed detailed notes to be made outside of the interview.
3. A set of 13 standardised questions was used to provide structure to the interviews. The questions were split into three groups:
   - understanding of the terms ‘asset management’ and ‘sustainability’, and the link between the two (5 questions, see Table 2);
   - what is working and what isn’t working with respect sustainability and asset management in the water sector (6 questions, see Table 3);
   - What are the remaining research challenges (2 questions, two examples of research projects arising from these questions are given at the end of this paper).
4. In accordance with the wishes of the interviewee, the discussions were either:
   - structured; *i.e.* the questions were addressed sequentially (most interviews were of this type, see Table 1); or
   - semi-structured; *i.e.* the interviewee made general comments relating to the research context, with specific reference to questions as desired/necessary.
5. Additional questions were asked by the interviewer throughout the interview to seek clarity on points made and/or to seek views on issues raised.

4.2 Details of Participation

Five water utilities located in three states (Victoria, New South Wales and Western Australia) took part in the interviews; the roles of the interview participants are summarised in Table 1. Auxiliary interviews were also undertaken with other stakeholders involved in the water sector, including industry associations (1 interview), consultants (1 interview) and regulators (2 interviews). These auxiliary interviews provided additional perspectives on issues under discussion. As shown in Table 1, 25 interviews were undertaken.

It should be noted that no attempt was made to be representative of the Australian water sector overall. In fact, utilities were approached who were considered (by the researcher) to be actively engaged in a sustainability journey, as well as undertaking relatively advanced approaches to asset management. Furthermore, since individuals volunteered to participate in the interviews, it can be anticipated that they represent a self-selecting sample of people actively engaged with (or at least having an active interest in) the sustainability challenge. As such, the interviews provided a rich source of information and insights, rather than being a means of gaining an independent and representative view from the sector. This approach was justified because the overall aim was to determine the research needs for developing sustainability-based asset management.

Table 1 Role of interviewees

		Type of Interview	
Role of interviewee	Number of interviews	Structured	Semistructured
Senior managers (CEO, general managers)	4	3	1
Mid-level manager (asset management)	7	7	–
Mid-level manager (sustainability)	5	5	–
Other asset management role	2	2	–
Other sustainability role	3	3	–
Other stakeholders	4	1	3

4.3 Results

Detailed presentation of the results of the interviews is beyond the scope of this paper. Tables 2 and 3 summarise common responses for the first two parts of the questionnaire. As can be seen from Table 2, a sophisticated definition of asset management (in line with the definition given previously) was generally stated. In particular, asset management was not considered to be associated with ageing assets, but was instead concerned with a life cycle focus (*i.e.* planning, design, construction, operation, maintenance, rehabilitation and disposal were all considered aspects of asset management). The definition of sustainability expressed was generally in line with the concepts of 'sustainable development' discussed above, along with strong business themes and a triple bottom line focus. The opinions expressed also indicated that participating water utilities have a high level of commitment to sustainability, and are investing in various initiatives to raise awareness of associated issues and to embed new modes of thinking into decision-making.

One reoccurring theme expressed was that there are strong links between asset management and sustainability in the water sector, and thus a strong expectation that asset management will play a significant role in achieving sustainability-related outcomes. Besides the direct impact of more efficient use of funds and resources through effective asset management, this seemed to be related to the opinion that physical water service assets, and the ability of these assets to meet society's needs in the future, form part of the legacy we leave future generations.

As shown in Table 3, despite the high level of commitment to sustainability expressed, the general feeling was that sustainability is not yet embedded in the day-to-day practices of the water utilities. While much effort has been expended to develop policies and raise awareness, there was a general opinion that sustainability is still a 'bolt on' consideration in many business processes and/or decisions (*i.e.* not fully integrated into practice), and that legacy drivers like financial efficiency and regulated outcomes are often still overriding considerations.

Information obtained indicated that a range of tools and approaches are currently been used in the quest for more sustainable solutions (as listed in Table 3), but overall there seemed a desire for more quantitative approaches that removed subjectivity where possible. In terms of asset management practices, the participating water utilities all appeared to be expending most effort to integrate sustainability principles into the early stages of the asset management cycle (especially strategic planning approaches). This focus can be explained from a number of perspectives; including the quite reasonable expectation that 'sustainability envelope' for a system is set at this stage (*i.e.* systems can be operated in a less sustainable manner than set at the planning stage, but it is difficult to operate them in a more sustainable way).

Overall, the later stages of the asset management cycle (operations, maintenance, renewals, and disposal) did not appear to have been re-examined in the light of sustainability principles. In fact, some interviewees expressed the opinion that the concept of sustainability does not need to cascade further down than high-level strategy plans. The inference being that addressing sustainability concepts at the strategic planning phase embeds sustainability into the resultant schemes, and thus allows the detailed planning phase to focus just on asset management considerations (*e.g.* reliability and robustness of assets). In contrast, others expressed the opinion that there is a need to re-examine sustainability aspects of these assets to determine if there are opportunities to make incremental changes that will provide large benefits across existing asset portfolios. For example, at one utility it was suggested that water distribution networks could be reconfigured from a sustainability perspective (to optimise pumping), as current zoning is still reflective of legacy issues such as location of offices for district office managers who had responsibility for parts of the network before corporatisation of utility.

Table 2 Questions relating to the understanding of asset management and sustainability

Question posed	Common themes in answers
What does the term 'asset management' mean to you?	Answers were generally couched in terms of whole of life concepts, with a focus on service and risk.
In practical terms, is 'asset management' within your organisation primarily concerned with aging assets?	In general, no … ageing assets are only part of the story, as asset management has a wider whole of life focus.
What does the term 'sustainability' mean to you?	Sustainability was generally considered in terms that align with the concept of 'sustainable development', with strong business themes and a triple bottom line focus being expressed as well.
Does your organisation have a formal commitment to sustainability as a core business concept? If so, how is this expressed?	There was significant high-level commitment to sustainability as a core business concept, expressed in terms of corporate goals and objectives, as well as planning frameworks.
From the perspective of the water sector, where do you think the key links between asset management and sustainability are or should be?	Sustainability and asset management were seen to be considerably interlinked, with elements of sustainability occurring in each part of the asset life cycle, but especially at the strategic planning level.

Perhaps as would be expected, the interviewees considered that the water sector has a history of delivering good social and environmental outcomes aligned with the needs of society. This achievement was considered to reflect the appropriateness of asset management and other policies and practices to date. The upcoming challenge is that the solutions applied to yesterday's problems may not meet emerging challenges such as climate change, changing demographics, and a carbon constrained future. The need for pragmatic sustainability-based tools (and/or ways to use these tools), and the need to fully embed sustainability principles into all business and asset management processes (rather than treating them as a bolt-on consideration) were also seen as significant challenges to be addressed.

Lack of information, appropriate tools and broader systems knowledge were seen as some of the key barriers to achieving a more sustainable sector, as were the willingness to pay for sustainability, especially where the outputs of investment are less tangible to customers and other stakeholders. In a broader context, institutional and personal inertia with respect to the need for change were also considered to present barriers to achieving sustainability outcomes, as were regulation and wider governance issues within the sector. Some interviewees also noted that urban planning can drive changes in the water industry and better links with developers and urban planners must therefore be developed. Furthermore, it was noted by some that the link between water, wastewater, solid waste and energy must also be explicitly considered if we are to make the water sector more sustainable.

A number of interviewees expressed strong opinions that regulation is a barrier to the innovation needed to meet sustainability goals, although there was a general acceptance that where there is a regulatory need, it is relatively easier to obtain funding for capital investment in solutions to meet that need. The direct corollary of this, however, is that solutions that are considered/shown to be more sustainable are more difficult to get approved where there is no regulatory requirement, or where there is conflict between wider sustainability outcomes and an existing regulation.

As noted in Table 3, a common theme expressed was that regulation is focused too narrowly to allow sustainability to be achieved in some schemes. An example quoted a number of times was the requirement for zero discharge of effluent to some creeks, which severely limited the options that could be considered, and ultimately drove the selection of less sustainable solutions. Another example given was the regulatory drive to spend money on upgrading sewage treatment plants, when a different use of the money (*e.g.* investment in stormwater discharges) would deliver a better return on investment when judged in terms of wider output measures and outcomes like environmental quality. The opinion was expressed that a nutrient trading scheme could allow this latter issue to be addressed, but that environmental regulators culturally have a problem with this kind of trade off.

Table 3 Questions relating to the understanding of asset management and sustainability

Question posed	Common themes in answers
In your opinion, are the requirements of sustainability-related written policies and procedures embedded in day-to-day practices across your organisation and supply chain? Are they effective?	In general, high-level commitment was not considered to be embedded in day-to-day practices, so policies and procedures are not as effective as they could be. There was generally less opinion expressed on the sustainability credentials of the supply chain.
How is the sustainability of asset management measured and reported in your organisation, and do the approaches used drive sustainability effectively?	High-level triple bottom line measures were generally discussed, along with post implementation studies of capital schemes. Non-financial asset management KPIs like spills, bursts and blockages were seen by some as relating to sustainability.
What techniques does your organisation apply to the quest for more sustainable solutions to the asset life cycle?	Strategic planning frameworks, advanced risk analysis, advanced cost-benefit analysis, multi-criteria decision making tools, life cycle assessment and whole of life costing were mentioned.
From your view of asset management within the water sector, what have we already got right from a sustainability perspective and what are the remaining challenges?	What the sector has got right: a history of delivering good social and environmental outcomes aligned with the needs of society. The challenge is that the world is changing rapidly and the solutions for yesterday's problems may not be suitable to meet emerging challenges such as climate change, changing demographics, and a carbon constrained future.
From your view of asset management within the water sector, what do you consider are the most significant barriers to advancing sustainability?	Information, appropriate tools and knowledge were seen as some of the key barriers, as were the willingness to pay for sustainability, especially where the outcomes are less tangible to customers.
Does current regulation of the sector promote or hinder the attainment of sustainability goals?	Overall, regulation is seen to aid delivery of outcomes where the regulation is focused on these outcomes. However, most held that regulation is focused too narrowly to allow sustainability to be achieved in some schemes, and that regulation can stifle innovation.

5 Embedding Sustainability Principles Within Asset Management

As outlined above, the overall intention of the interviews was to gain insights into the development of 'sustainability-based asset management' in the water sector of Australia, and thereby allow research needs to be identified and undertaken. While detailed presentation is again beyond the scope of this paper, it is considered worthwhile to present a summary of two projects that arose directly from the insights gained, since this highlights that the interviews provided tangible outputs and action.

5.1 Aligning Sustainability Through Risk Concepts; the Inclusion of Externalities

Given the importance of risk management frameworks to asset management, one interviewee noted that a means of integrating sustainability into 'business as usual' processes would be to ensure risk and sustainability concepts and analysis are fully aligned. As noted by Marlow [2], sustainability principles can be incorporated into risk assessments through a more comprehensive treatment of failure consequences. Categories of consequence to consider include health and safety impacts, environmental impacts, social impacts, public relation impacts, direct costs and direct third party losses. After review of the knowledge gaps, a research project was undertaken to target one aspect of this analysis; the treatment of externalities.

A variety of definitions of externalities can be found in the literature [18, 19, 20], but there is common linkages between them all, namely that externalities:

1. have direct impacts on the physical characteristics or attributes of the environment and people, which in turn generate indirect impacts on ecosystem functions and human wellbeing [15];
2. occur when those impacted are not involved in a transaction (they are imposed on a third party);
3. can be positive (*i.e.* provide a benefit to others) or negative (*i.e.* create a cost to others);
4. are measured as a change in welfare or social wellbeing; sometimes termed social cost and social benefit [21];
5. have specific boundary conditions that relate to people, environment, governance, time, space, measurement unit and event (*e.g.* not every pollution spill has the same impacts), therefore estimation of externalities is specific.

Historical experience has shown that ignoring externalities like pollution and greenhouse gas emissions can skew decisions towards short-term solutions that result in unsustainable practices and industry outcomes. Legislative requirements can and do compel asset managers to address such issues, but approaches are still needed to assess tradeoffs between allowable impacts associated with different interventions; this is the aim of integrating externalities into decision support approaches for asset management.

By taking into account all of the impacts associated with a management option that are valued by society, irrespective of whether they are captured by the market, or whether or not there is a reasonable expectation of compensation, available interventions would be judged from the perspective of total cost imposed on society. This may change the type of service provision strategy (*e.g.* decentralised solutions), the management strategy adopted (*e.g.* level of maintenance provided), the type of intervention selected (*e.g.* trenchless technology versus trenched replacement) or the type of incentive to stimulate a response (*e.g.* price rebates on low water use).

Clearly for this to be the case, the relative magnitude of the externalities involved need to be significant enough to influence the decision making, and asset managers need guidance on how to assess this. With this in mind, a framework for consideration of externalities in asset management decision making was developed, as reported in Marlow *et al.* [22]. Notably, this research effort also aligned with the operational definition of sustainability presented earlier in this paper (which indicates a water utility must deliver net added-value when assessed across all costs and benefits, *including externalities*).

5.2 Assessing Sustainability Culture Within a Water Utility

In one interview with a sustainability professional, it was noted there is a need for pragmatic indicators of sustainability progress that give signals akin to those used in the monitoring of health. Consider, for example, the fact that high level human health outcomes are quite complex, but easily measurable indicators like weight, cholesterol and pulse rate at rest can be used as a proxy to give meaningful information. Other interviewees considered that cultural aspects within water utilities, and between the water utility and its stakeholders, need to be addressed. For example, it was noted that achieving better sustainability outcomes requires appropriate signals to be sent that modify individual's actions and thought processes, and encourages engagement with the 'sustainability journey'.

Again, after review of the knowledge gaps, a research project was designed to target these issues. The basis of the research approach drew from the literature on action-research, which seeks to understand and modify the way in which organisations learn, considering the mental models of personnel involved in decision making processes. It was hypothesised that the ability to make decisions that align with broader sustainability principles is likely to depend on a wide range of influences, enablers and constraints, including an individual's interpretation of their role and duties. Furthermore, while with hindsight it is often evident if a specific decision was good or bad from a sustainability perspective, it is not always obvious why this is the case, or what or who influenced the decision making. Of particular interest from the perspective of sustainability adoption is that individuals can be driven to make decisions that they consider are suboptimal in the face of conflicting demands. Alternatively, legacy measures of performance can mean that individuals and teams are incentivised to act in a way that is not fully aligned with sustainability principles, and this may not be obvious until analysed.

With such challenges in mind, a methodology was sought for analysing decision making and business initiatives (with an initial focus on asset management) to determine why specific decisions had resulted in successful or sub-optimal outcomes from the perspective of sustainability policy. Overall, the intention is to help water utilities be able to determine what is driving individual and group action, where the points of leverage are and thus how to encourage engagement with the 'sustainability journey'. This process utilises qualitative research techniques to understand the motivations, constraints and enablers that influence decision making and action.

While the research was still in progress at the time of writing, the approach taken involved the following steps:

1. identify a range of decisions that have had a significant business impact (positive or negative) in a workshop environment;
2. characterise what ideally should be driving the specific decision, and what balance should have been struck between financial, technical and social/environmental considerations (this reflects the belief that an appropriate balance depends on the particular nature of the decision in hand);
3. quantify the impact of the decision on business outputs from a TBL perspective; this will help identify the level of detail the assessment required (proportionality of analysis being an important consideration);
4. map out the agents (*i.e.* individuals and groups involved in the decision making), constraints and enablers that influenced the decision making using a range of techniques;
5. identify critical agents, constraints and enablers using a systematic process;
6. identify key 'learnings' and recommend action;
7. subsequently measure engagement with 'sustainability culture' using a rigorously designed survey based approach (this will act as a KPI if assessed over time).

6 Conclusions

This paper has described research initiatives undertaken to clarify the role of sustainability concepts in asset management. In particular, interviews with water sector professionals in Australia are described. These interviews facilitated engagement with the sector, allowed a broader understanding of the research space to be developed, and provided tangible outputs in the form of identified research needs. Two examples of research projects undertaken in response to insights gained are also given for completeness.

The interviews indicated that the participating water utilities have made a strong commitment to sustainability, and this is being expressed in a range of initiatives intended to deliver benefits across the triple bottom line. The interviews also indicated that, within the participating water utilities, a significant focus is currently being given to the integration of sustainability principles into strategic planning. It can be anticipated that the impact of this effort on overall sustainability outcomes will depend on how much growth is occurring (*e.g.* the relative investment in new assets compared to the modern equivalent value of existing assets), as well as the inherent sustainability of that growth. This later aspect must be considered within the wider context of urban development, transport policy, environmental factors associated with the water cycle, and social aspects, including those related to equitability of water service provision.

Addressing assets in the middle of their life cycle still remains a challenge, and less emphasis is currently being given to this aspect of sustainability. In fact, there was at least some indication that funding of maintenance functions may be at risk due to the pressure to invest in the sustainability of new developments and/or the development of alternative water supplies. While this issue requires further research, it is worth noting that any concept of sustainability-based asset management necessarily requires both sustainability and asset management to be considered simultaneously. A corner stone of asset management is getting maintenance right to ensure assets achieve an economic life, not least because an asset that continues to provide service does not require additional resources or funds to be diverted from other endeavours. Any move to reduce maintenance budgets without solid justification must therefore be considered as potentially counter productive, both in terms of asset management and wider sustainability outcomes.

A key issue in any consideration of sustainability remains the need to ensure that corporate and political rhetoric is translated into on-ground solutions and initiatives. In particular, there is a need to develop appropriate regulatory and governance frameworks that enable innovation and take a holistic view of sustainability. At the other end of the spectrum, and given the need for individual engagement in the challenge, there is also a requirement for organisations to create an enabling environment, where individuals have the space to influence decisions on how best to contribute to sustainability goals. A clear and consistent expression of corporate and political intent with respect sustainability objectives would help in this regard.

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Asset Management of Portuguese Educational Facilities

Ana C.V. Vieira and António J. Marques Cardoso

Abstract Despite the importance of building and infrastructure maintenance and its role in cost control, savings in materials and lifetime enlarging of equipment and facilities, maintenance in service organizations is often still regarded as a disturbing factor only. Since the resources dedicated to the maintenance and operation of school building infrastructure come mainly from the state budget, during tight financial times the maintenance and operation budgets are frequently among the first cuts. Public school infrastructures often resent themselves from this philosophy, presenting in some cases precocious degradation, generally as the result of the priority on allocating funds to items that directly affect education. It is important to focus on areas such as maintenance, building systems, safety improvements and technology, leading managers to improve maintenance performance of these organizations, if possible anticipating in time problems and opportunities. In this scenario, maintenance audits provide a framework for organizations to systematically review, analyse and recommend improvements in performance.

This paper refers to a study that has been under development concerning asset management of Portuguese Educational Facilities, namely infrastructure and fixed equipment. This study comprises different approaches for Educational Facilities with different levels of education and this paper refers to some of the specificities

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that governed the audit performed in a University as well as to the methodology followed for Portuguese Secondary schools.

This paper also presents some results of that study, specifically the ones concerning Secondary Schools. It identifies some areas needing improvements, as well as the suggestions made to improve maintenance management, regarding management decision making, human resources, information systems and strategies employed in maintenance management, among others.

Keywords Strategic asset management, Maintenance audit, Maintenance management, Educational facilities, Maintenance strategies in asset management

1 Introduction

According to the Portuguese law for the Educational System, published in 1986, the dimensions of educational buildings must provide the possibility to receive a reasonable number of students, in order to guaranty the necessary conditions for a good pedagogical practice and to promote a true scholar community. Simultaneously, the management of spaces, installations and equipment, human and material resources, as well as financial and administrative management, should contribute to the education and scholarly success of each student. In order to accomplish that, fundamental areas such as Fixed Equipment, Building Structure, Safety, Technology and Maintenance must be considered in a well-balanced way [1–4].

Economical factors often tend to regulate options, however, it must be undertaken that public expenditure control measures do not stand only in financial factors. Most of them should be management decisions leading to relevant financial effect, even if they don't present instantaneous results [1, 5]. Without an effective coordination regarding planning and administration, and without the necessary investments in school preservation, keeping them in good state of conservation, their progressive degradation will inevitably lead to assets precocious degradation and the need for their substitution [1, 6]. Bad conditions of equipment may interfere directly not only in the organization economics, but also by reducing the overall availability of buildings while simultaneously interfere with occupants' safety. This is why both installations and equipment associated with the operation of school organizations must be maintained in good conditions. However, Educational Institutions do not always have the necessary funds or the economical stimulus needed for the implementation of new projects. In addition to this disadvantage, the available personnel usually do not have the necessary background for the development and application of such projects, and frequently that makes unfeasible the undertaking of new programs [3].

The resources dedicated to the maintenance and operation of school building infrastructures come mainly from the state budget, and the maintenance and operation budgets are frequently sparse, reason why maintenance management and a clear definition of its structure and organization is so important when aiming the maximum outcome of the expended sum. Moreover, for the particular case of school buildings, a great number of maintenance actions may be organized in a systematic way, with foreknowable costs and controlled funds and it is considered adequate to adopt preventive maintenance strategies, condition based or planned and scheduled in time [6].

2 Educational Facilities Maintenance Policy

In the matter of building's maintenance, the legislation published in Portugal is vague and sometimes even not existent, which contributes for the precocious deterioration of some buildings. As an example, Portuguese Laws 38382/51, 555/59 and 177/2001 only state that "(...) *at least one time every eight years constructions should be object of preservation actions* (...)". It is also important to refer that building's maintenance activities in Portugal only represent 4 % of the global construction activity, while in the European Union the mean value for this percentage is of 35 %, and that the maintenance sector is also below the standards of other countries like the United States of America, Canada or Japan [7–10].

Educational buildings maintenance policy reflects the scenario described for general building's maintenance, but they are also the result of the evolution of Portuguese Educational system along the last four decades, since the objectives defined for the educational system development have direct implications in school assets preservation [6].

The thought of generalising the access to all levels of education appears at the beginning of the 1970's, yet, the growing number of students has not been followed by the necessary investments in installations and equipment nor in teaching staff competency until the end of the following decade. The publication of a new law for the educational system in 1986 [2], and the almost simultaneous integration of Portugal in the European Union, helped to change the scenario. The first introduced a new perspective of decentralisation in the educational system and the second one gave the economical support needed to invest in educational building renovation, new constructions and equipment [3, 11–13].

Paradoxically, and as a result of pressures in order to enlarge the educational offer, the significant growth of new constructions tends to coexist with spare or non-existent budgets available to maintain schools in good state of conservation, resulting in functional expenses restraint and public schools infrastructure precocious degradation, sometimes until the need for mandatory replacement [3, 6, 14].

The growing amount of funds dedicated to education until the end of the last century conducted to a significant development and improvement of human and material resources. As a result, Portugal presents a public expenditure in education that overtakes the average of the countries members of the Organization for Economic Cooperation and Development (OECD). However, the national effectiveness does not come to the pattern of OECD and Portugal must reduce significantly its public expenditure [3, 11].

Education is one of the most resource absorbing sectors and thus it is becoming more and more important to improve its efficiency [11, 15]. Despite the complexity of the educational sector, it is obvious the need to review management and administration models, applying the principles of the law for the educational system published in 1986, in particular the principle of institutional autonomy [3, 11, 13].

Despite the described scenario, the importance of building's maintenance is not yet being considered as a key element of Portuguese school board's mission statements [16, 17]. For example, the Portuguese law for the Educational System only states that "(...) *construction and maintenance of school buildings and its equipment must stand on an effective regional policy, with a clear definition of competencies for every intervenient, who, in this matter, should have the necessary resources* (...)" [2].

Furthermore, the several studies that have been carried out in Portugal, concerning Primary, Preparatory and Secondary schools, were almost all of them dedicated to areas such as pedagogic, politics and administration. The evolution of the Primary, Preparatory and Secondary schools politics and administration have been substantially distinct from the evolution registered for the superior level of education. This distinct evolution reached the highest point with the creation of the Ministry of Science and Superior Education in October of 2002, separating the superior level of education from the first three levels of education that remained under the supervision of the Portuguese Board of Education [13].

Among the numerous publications of the Portuguese Board of Education, a few consider the operational area of educational organizations and only two were found that focused on the importance of maintenance in educational buildings [6, 16, 17]. These publications were presented as informative documents, suggesting that "(...) *each school board should develop its own operation, maintenance and security manual* (...)" considering, for example, each building constructive characteristics as well as the installed equipment and collecting data [16, 17].

In countries such as the United States of America, the United Kingdom, Canada and Australia several reports related to state buildings' maintenance have been published [1, 18–22]. These reports enhance the relationship between budgeting plans and maintenance activities for both equipment and buildings.

The British Standard Guide to Building Maintenance Management is an example of a standardization document whose structure allows its application both in more complex organizations and in domestic properties. This document emphasises the importance of health and safety in buildings maintenance, both by the perspective of the building user and the maintenance management work executants [23].

The development and implementation of suitable maintenance plans, for the full range of building systems, equipment and components, is systematically referred. It is also pointed out that such maintenance plans must be the result of a real and participative commitment of each organisation [14, 19–21].

Both operation and implementation of the abovementioned requirements involves funding. One of the mentioned approaches to budgeting for preventive maintenance needs considers 5 % of the operating budget to be adequate. Another one sets the budget based on 5 % of the buildings present value [19].

The development of databases with information about frequent problems and maintenance global costs as well as long-term maintenance plans and inspections, are some of the several methodologies used to improve buildings maintenance [14, 18]. Among the considered requirements are [1, 18, 19, 24]:

- regular inspections for assessing equipment and structures current state;
- regular inspections for assessing equipment and structures evolutionary state;
- long time planning for maintenance operations;
- preventive Maintenance Plans;
- periodic Audits of the organizational structure of maintenance management personnel;
- computerized Maintenance Management Programs or similar;
- data bases with the most common problems;
- records of all maintenance activities;
- data bases with all maintenance costs;
- energy management.

3 The Methodology Applied to Study the Portuguese Educational Facilities Asset Management

The Portuguese Educational System is a complex structure and, therefore, any suggestions to improve maintenance management, regarding management decision making, human resources, information systems and strategies employed in maintenance management, among others, must be based on the objective identification of those areas needing improvements, as the first step of an overall maintenance improvement process.

In the Portuguese Educational System the specificity of the several levels of education refers not only to pedagogical practices but also to spaces, installations and equipment policies management, human and material resources management, as well as financial and administrative management. Consequently, the methodology for studying the Portuguese situation should reflect this reality. In this context, the undertaken study concerning the asset management of Portuguese Educational Facilities considers in each phase a different level of education: Primary, Preparatory, Secondary and Superior. It was decided to evaluate separately the situation for each level of education, not only in terms of maintenance management, but also regarding building characteristics, building systems, safety improvements and technology. Since it was not available any survey of the Portuguese Educational Facilities, referring to those areas in particular, several questionnaires have been developed, with the aim of collecting information for later analysis.

In the framework of the Portuguese Preparatory School level of Education the developed questionnaire was designated by $PANAMA^2{}_3C$, while regarding the

Portuguese Secondary School level of Education the questionnaire developed was designated by CARMA^{EE}. The target for both questionnaires was all the Portuguese Schools with each considered level, and they were developed with the aim of collecting information regarding administrations maintenance management policies, building characteristics and safety, both inside and in surrounding areas of the schools.

The particular characteristics of the remaining levels of education compelled to an individualized analysis. For example, it must be considered the participation of local political institutions in the maintenance of schools within the Primary level of education and, with respect to the Superior level of education, the different realities of the universities and polytechnic institutes. The autonomy of Portuguese Universities was first stated in the constitution of 1976 and the Educational System Foundation Law of 1986 gave it a new perspective that led to the publication, in September of 1988, of the Universities Autonomy Law. Later, in 1990, it was also published a law that regulates the autonomy of Polytechnic Institutes and in September of 1997 it was approved the "Funding Bases for the Institutions with the Superior Level of Education" law, reviewed in 2003, that introduced the need of pluriannual budgets (for at least five years) aiming at the curricular development, quality enhancement, system rationalisation and equipment and infrastructure reinforcement and maintenance. The complex reality of the superior level of education suggested the development of a first study applied to a single University: the University of Coimbra, established in 1290.

As a result of the University of Coimbra historical evolution, this institution owns a large variety of buildings, including the old royal buildings where the university was first installed. The University of Coimbra (UC) is also the owner of buildings constructed during the Marquis of Pombal Reform, in 1772, including several former University Colleges, and the twentieth century new buildings. In the framework of the University of Coimbra two groups of questionnaires were developed, designated by the MENFIS and CAMPUS questionnaires.

The MENFIS study had the goal of evaluating the UC not only in terms of maintenance management, but also regarding building characteristics, building systems, safety improvements and technology. It was developed during 2005 and dedicated to the entire University and its Organic Units. Five different questionnaires were developed, one dedicated to all the 22 Organic Units of the institution, and the other three dedicated to the University stadium, the Social Action Services and to the University Division for Buildings, equipment and infrastructure Management, the later one mainly oriented to all the UC assets not assigned to a particular Organic Unit or service/office. The fifth questionnaire was designed to be answered by students, professors, workers and users in general.

The MENFIS study aimed at characterizing the situation of the buildings of the University of Coimbra concerning their age and state of conservation, with special attention to the policies and strategies being adopted for the necessary maintenance. Each Organic Unit governing bodies was asked to provide information regarding their maintenance management policies, building characteristics and safety, both inside and in surrounding areas of the institution [25].

The MENFIS study was the breaking point to test methods and procedures to apply to other institutions within the Superior level of education and also led to the development of the CAMPUS study in 2006, entirely dedicated to the stadium, sporting centre and athletic grounds of UC.

4 A Case Study: Portuguese Secondary Schools

The information about the Portuguese Secondary Schools maintenance management was collected in 2004, with the help of the CARMA^{EE} questionnaire, developed in the framework of the Portuguese Schools with Secondary level of Education.

The first versions of the questionnaire were the outcome of a previous study regarding surveys theory and the Portuguese educational system structure. The proposed questionnaire was a semi-structured questionnaire with simple, specific and closed questions but also with multiple choice ones and some semi-closed questions, due to the diversity of situations expected.

During pretesting phases, those first versions of the questionnaire were submitted to several school board administrators, randomly selected, with the aim of identifying respondent understanding of the survey questions. In the undertaken pilot study, administrations were asked to answer to the entire questionnaire, verbalizing all their doubts and suggestions, allowing the evaluation of the test instrument.

Several aspects were considered, in order to avoid non-responses. None of the questions should raise any doubts regarding their interpretation: none should disturb or upset the respondent, nor should be rejected. In such cases, the verbal information helped to redraw the question [26–28]. Reactions to the pilot questionnaire also presented an important feedback regarding the general acceptance of this study and to the structure of the list of questions: was it to long, to difficult or uninteresting?

As the result of the first stage of pretesting, several changes where introduced to the initial version of the questionnaire and another pretesting was undertaken, in order to validate the CARMA^{EE} questionnaire presented in Figure 1, in its final version, ensuring that [26]:

- every word and question was fully understood;
- the way by which questions are presented ensure that they are not ambiguous;
- every closed question, being multi-choice or not, consider all the possible answers;
- the order by which questions are presented, guarantee that it allowed an easier understanding and response.

The understanding of various boards and individual members concerning maintenance and especially asset management may differ, reason why it was introduced a scale description (whose full understanding was also tested during the pretesting) whenever the initial scale used in the pilot study raised some doubts or non compliant responses. Figure 2 presents an example of a scale and its description.

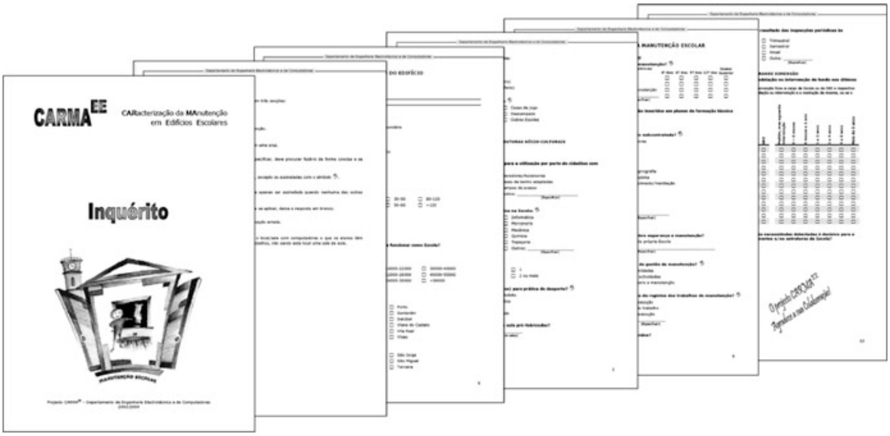


Figure 1 Some pages from the final version of the posted CARMA^{EE} questionnaire

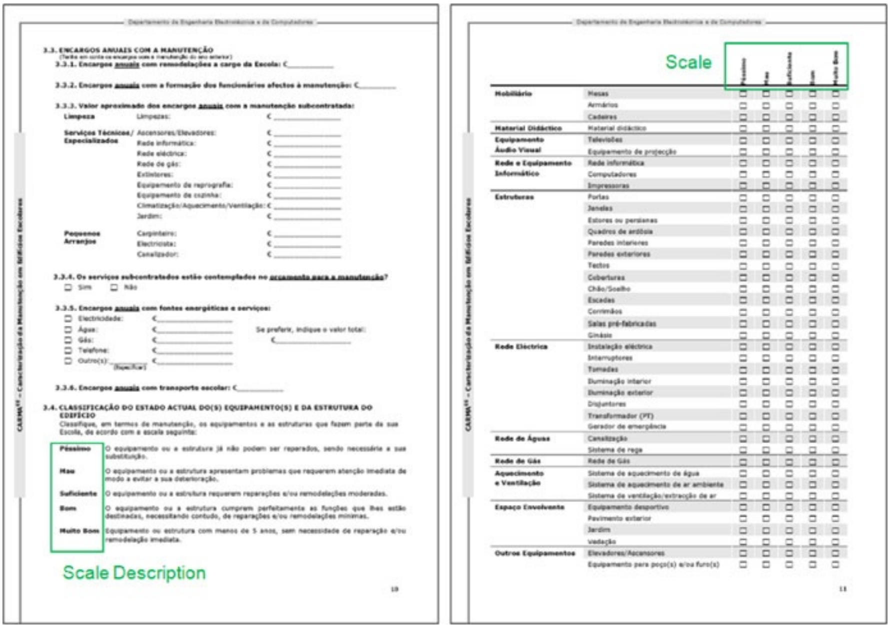


Figure 2 Scale utilization and respective description – an example

The final version of the above mentioned CARMA^{EE} questionnaire was posted to all the 869 Portuguese Schools with Secondary Education, whose administrations were asked to provide information regarding their maintenance management policies, building characteristics and safety, both inside and in surrounding areas of the school.

The data collection procedures for all questionnaires administered included field activities like:

- e-mailing school administration and other school contact motivating them to encourage the school administrations to participate in the study;
- authorization request to governmental institutions, namely the Board of Education;
- governmental, teacher unions and other organizations related to the secondary educational system were asked for collaboration releasing notes and information about the CARMA^{EE} questionnaire;
- mailing an advance postcard to the schools;
- mailing and e-mailing the CARMA^{EE} questionnaire to all the 869 Portuguese Schools with Secondary Education;
- e-mailing Schools, Governmental bodies, teacher unions and other individuals and organizations related to the secondary educational system, updating them on the progress of the study, as a way of motivating those administrations who had not yet responded;
- updating information on a web-site dedicated to the study collection data procedure.

A total of 279 Secondary Schools administrations answered, 10,65 % on-line and 21,64 % by post. It is important to note that, for this kind of studies, it is considered to be acceptable a percentage of participation from 5 % to 40 % and that the number of received answers exceeds 32 % of the 869 Portuguese Schools with Secondary Education.

Every one of the received questionnaires was revised accordingly to a number of checks that rigorously examined as many aspects of the data as possible, namely those regarding [26]:

- general data quality;
- non-responses;
- non-compliances;
- consistency within items or respondents;
- responses variance.

Key variables and cross tabulations of key variables were examined for distributions and relationships that were expected based upon prior research, as check of face validity. The specific data checks included edits or frequency counts. It was verified that each item in the questionnaire had the number of responses it should have if skip instructions were followed correctly. Whenever edit specifications quality checks resulted in some corrections, they were treated as a form of imputation. Variables with out-of-range values or inconsistent values were identified, and, if not justified, those were not considered.

The codification of responses provided to semi-closed questions was also an important step for the data analysis process.

The analysis of the gathered information allowed the identification of the areas of opportunity in terms of maintenance management enhancement. The results

Table 1 Main structure of the CARMA^{EE} questionnaire

Data categories	Subjects
School Characterization	School identification and building characterization Geographical location Functional characteristics and socio-cultural structures Transportations and parking facilities Human resources General information
Security	People safety and assets security Fire protection Gas infrastructure and equipment Safety, health and hygiene Electrical infrastructure
Maintenance Management	Human resources Documentation Annual budgeting and operations and maintenance costs Building infrastructure and equipment conditions Maintenance strategies Large retrofitting interventions

presented here are based on the analysis of the answers to the set of questions associated to Maintenance Management and its related subjects, as asset condition appraisals and maintenance planning.

The CARMA^{EE} questionnaire was focused on the data categories presented in Table 1 [3].

4.1 General Overview and Budgeting

Portugal is divided in Continental Portugal and two autonomous regions with specific administrative and fiscal framework: Açores and Madeira. The designation Continental Portugal is used to differentiate the mainland territory of Portugal from the insular territory, which is composed by Açores and Madeira Portuguese archipelagos, located in the Atlantic Ocean. Continental Portugal is divided in 18 districts, considered not only for political and administrative subdivisions but also for public education or health care purposes.

Figure 3 represents mainland and insular Portugal territory, divided in its 18 districts and two autonomous regions.

As illustrated in Figure 4, among the 20 Portuguese districts and autonomous regions (Açores and Madeira), the highest rate of participations occurred in Açores archipelago with 51,52 % responses received. On the other hand the lowest rate of participation (20,00 %) refers to Évora district.

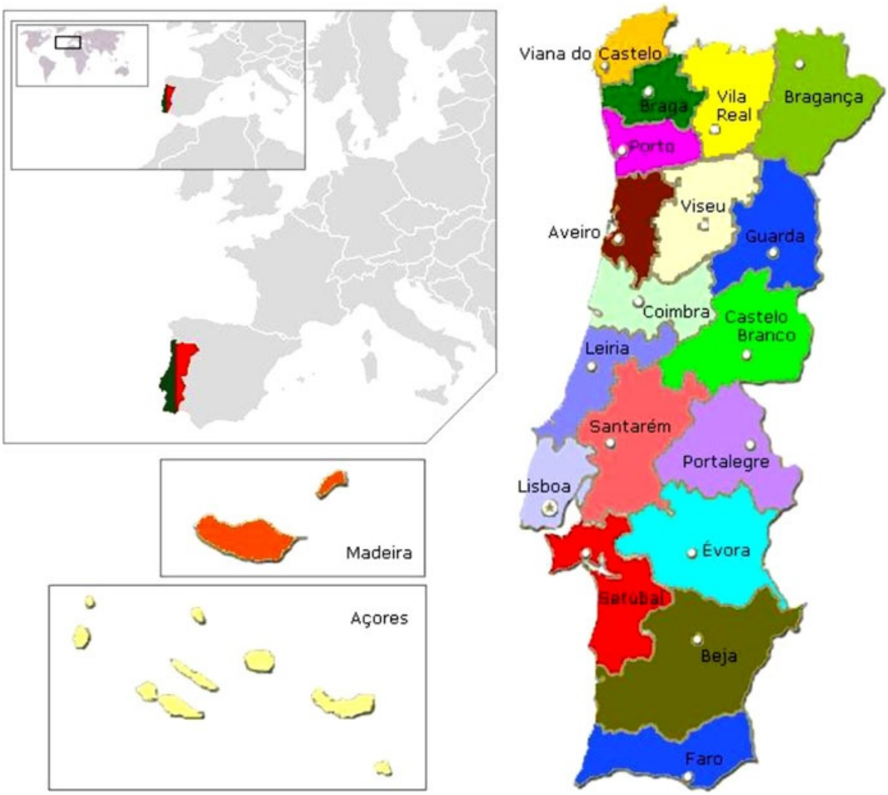


Figure 3 Portugal in the world, mainland districts and autonomous regions of Açores and Madeira

Considering the 279 participant Portuguese secondary schools, 47,25 % are less than 20 years old and only 12,92 % of those school buildings are more than 50 years old. As illustrated in Figure 5, all the Viana do Castelo district participant schools occupy buildings are less than 25 years old and, on the other hand, all the school buildings in Bragança are more than 20 years old.

Figure 6a illustrates that 39,78 % of the school buildings are more than 25 years old and 80 of the 279 participant institutions (28,67 %) occupy buildings that are less than 15 years old.

The maintenance and operation costs indicated by each school board reveal that those expenses are not only a function of the buildings age and size but also depend on the public or private administration of the schools. Effectively, in Figure 6b the average values for each age interval tend to follow the building age, except for the extremes (below 10 years and above 80 years). The lowest values, corresponding to school buildings that are more than 80 years and less than 10 years old, can be explained by the relation with the buildings areas, as illustrated in Figure 6c. Most of the buildings that are more than 80 years old occupy areas less than 10 000 m^2.

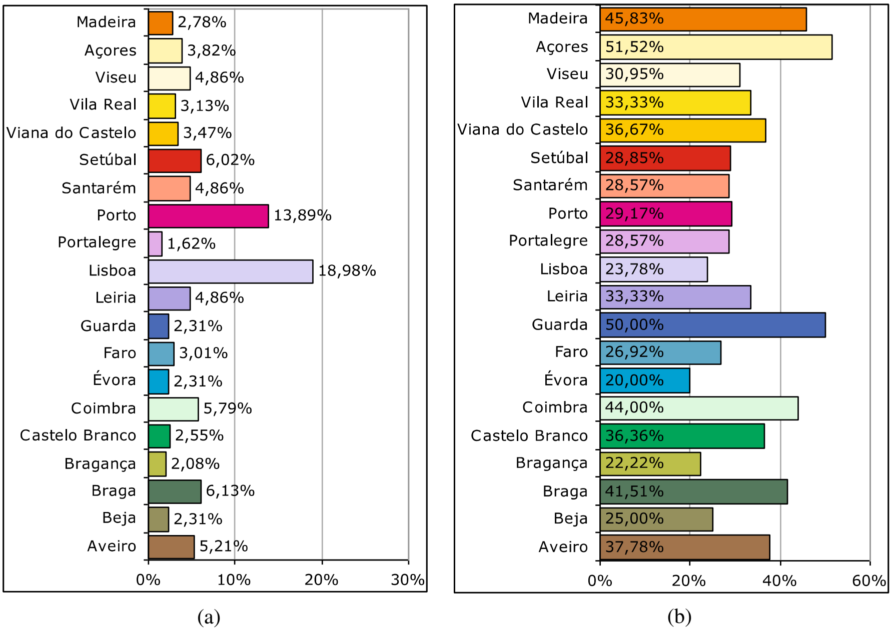


Figure 4 Portuguese school institutions with secondary level of education: (a) distribution of the 869 schools by the 20 districts and autonomous regions under analysis; (b) percentage of participation from the 20 districts and autonomous regions under analysis, considering the 279 answers

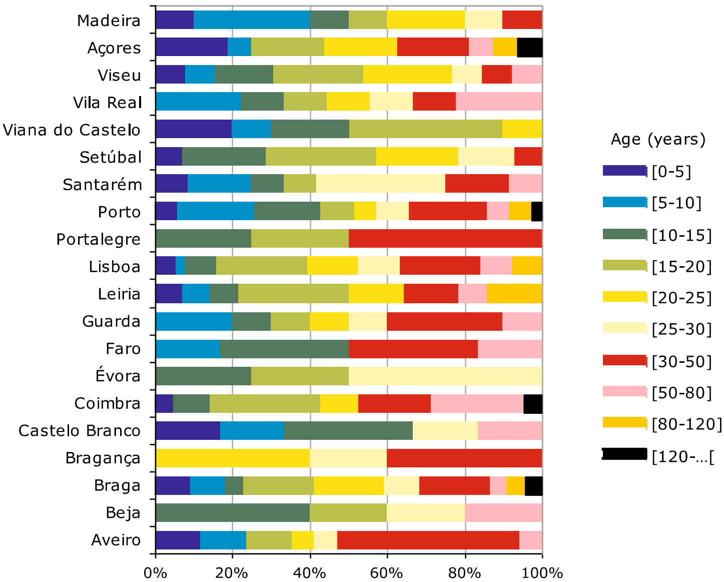


Figure 5 School buildings distribution by age, considering the districts and autonomous regions of Portugal

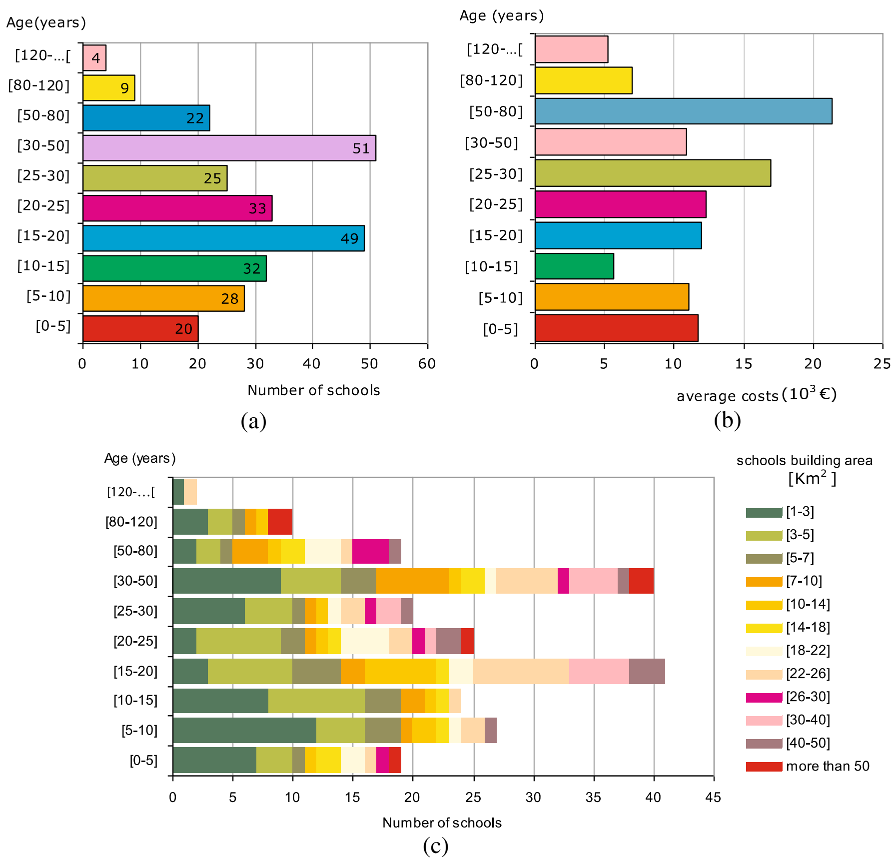
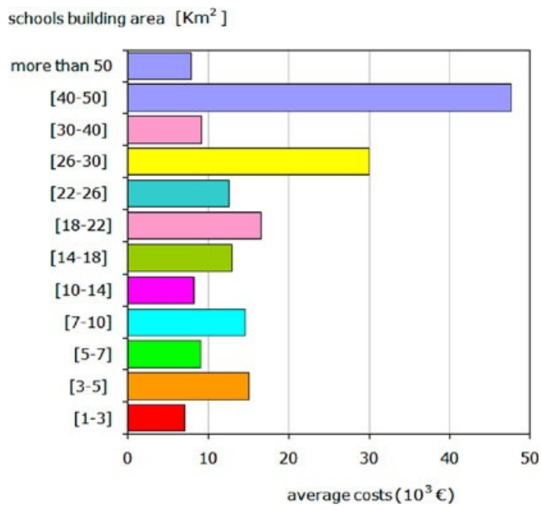


Figure 6 School buildings distribution by age: (a) number of schools for each given age interval; (b) school's average maintenance and operation costs in each age interval; (c) schools building area in each given age interval

From the 279 participating schools, only 181 refer the amount of money expended in outsourcings, for example in maintenance of elevators and acclimatization systems. Simultaneously, no more than 81 of these schools assumed to have an annual budget for operation and maintenance.

Figure 7 presents the distribution of average values for the total cost of outsourced maintenance services. With respect to the group of schools with area between 30 000 m^2 and 40 000 m^2, the values indicated for outsourced maintenance do not follow the expected evolution. However, this can be explained by the CARMA[EE] study conclusion that public schools expenditure in maintenance is by far less than the particular schools maintenance spending. In fact, all the respondent schools in this area interval are public schools. On the other hand, private schools institutions do have a strong impact on the value presented for the area interval between 40 000 m^2 and 50 000 m^2 and also interfere in the value presented for the age interval between 50 and 80 year old, presented in Figure 6b.

Figure 7 School buildings maintenance costs average values for each given area interval (m^2)



4.2 *Maintenance Strategies*

Figure 8a presents the number of schools referring to follow only one of the preventive or corrective maintenance strategies and those using both strategies simultaneously. As shown in Figure 8b a significant number of those 264 schools (90,15 %) refer the application of preventive strategies. Nevertheless, 40 of this 238 schools (16,81 %) were not able to identify any equipment or structure maintained in a preventive basis nor the periodicity of the preventive maintenance applied.

For some assets, it was also observed that school boards indicated a time period for preventive maintenance that is not in accordance with the standards. As an example, some schools mentioned a monthly based maintenance of the roofing

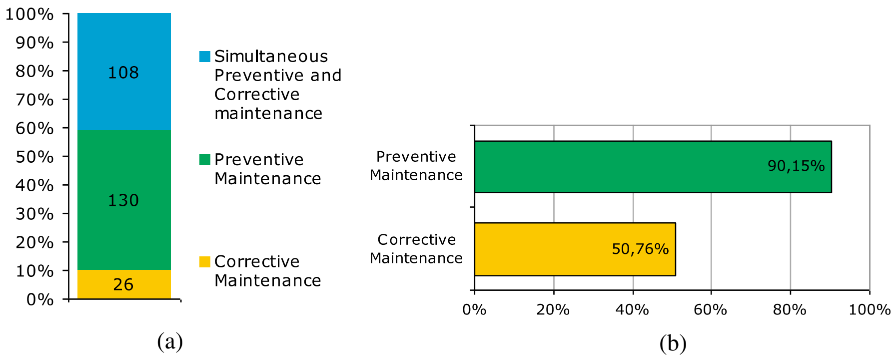


Figure 8 Maintenance strategies: (a) total number of schools referring to follow a maintenance strategy; (b) percentage of the 264 schools using preventive and corrective maintenance strategies

while others indicated a time period of less than one year (69,56 %), despite the 15 years time interval suggested in the literature for the same structure [6].

A similar situation was observed with respect to walls. Respectively, 73,33 % and 61,9 % of the schools indicated time periods of less than one year between preventive maintenance interventions in interior and exterior walls, when the literature usually indicates periods of 5 years between small interventions in interior walls and 10 years between interventions in exterior walls [6, 7, 18].

4.3 Documentation

According to the maintenance policy for Portuguese schools, expressed in Section 2, each school should implement its own operation, maintenance and security manual. Several other documents referred in Section 2 reinforce the idea that this manual must be developed in order to address the individual and different needs of each school and their systems.

Besides their own manual, documents like manufacturer's literature, legislation or test results may be used by school boards to support their activities. Table 2 shows that 74,55 % of the participating schools use support documentation, mainly manufacturer's manuals and legislation (58,65 % and 76,92 %, respectively).

From the 208 school boards that have answered to this question, only two of them identified the "*Schools Operation, Maintenance and Safety Handbook*", publish by the Portuguese Board of Education, as one of their supporting documents.

The percentage of schools developing their own operation, maintenance and security manuals is very low (22,22 %), as shown in Table 2, and every one of the participant schools from the districts of Beja, Bragança, Évora, Portalegre and Santarém and from the autonomous region of Madeira do not have a school own manual.

Effective preventive maintenance programs depend on the feedback from maintenance personnel and the reporting system used, namely with respect to costs associated with preventive maintenance efforts [19]. With respect to maintenance management documents, Table 3 shows that 46,59 % of the participant schools

Table 2 Support documentation for safety and maintenance activities

Use of supporting documentation	Frequency	Percentage of the 279 participating schools	Percentage of the 208 schools using documentation
Yes	208	74,55 %	
School own manual	62	22,22 %	29,81 %
Manufacturer manual	122	43,73 %	58,65 %
Legislation	160	57,35 %	76,92 %
Others	11	3,94 %	5,29 %
No	51	18,28 %	
Do not answered	20	7,17 %	

Table 3 Documents for maintenance management developed by the school board

Annual documents	Frequency	Percentage of the 279 participating schools	Percentage of the 208 schools using documentation
Yes	130	46,59 %	
Maintenance Plan	77	27,59 %	59,23 %
Reports	72	25,80 %	55,38 %
Budget for maintenance	81	29,03 %	62,31 %
No	138	49,46 %	
Do not answered	11	3,94 %	

developed annual documentation, such as budgets (29,03 %) and reports for maintenance activities (25,8 %). For those schools, 29 (10,39 %) guarantee to develop simultaneously Maintenance Plan, Reports and Budget for maintenance, but 23,08 % of them refer to follow a corrective maintenance strategy. At the same time, only 59 school boards assured the simultaneous development of documents for recording execution dates, description and costs for every maintenance activity.

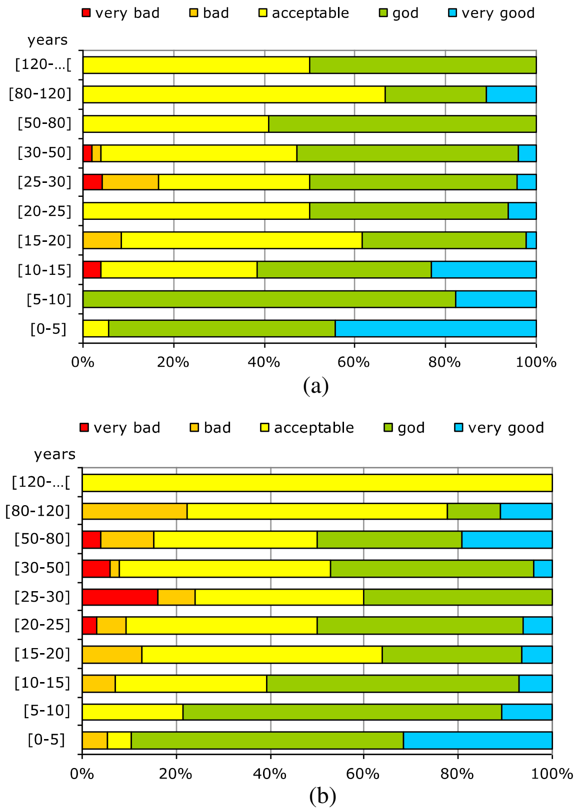


Figure 9 Building infrastructure and equipment conditions: (a) interior lighting systems; (b) interior walls

4.4 Building Infrastructure and Equipment Conditions

Figure 9 presents two examples of the analysis made for school building's assets general situation.

In the particular case of the interior lighting systems, Figure 9a shows that, in general, these assets are considered by school boards administration to be in god conditions. Only three schools have very bad problems with interior lighting but two of them have already asked for an intervention.

The results presented in Figure 9b show that almost 20 % of those schools with ages between 25 and 30 years old have serious problems with their interior walls. It is important to note that none of these schools considers itself to be using preventive strategies.

5 Conclusions

In order to manage the available resources in an effective way, it is extremely important that educational organizations may have actualized, detailed and accurate information about the buildings, their systems and equipment, and the way they are managed. In this scenario, maintenance audits provide a framework for organizations to systematically review, analyse and recommend improvements in maintenance management performance.

This paper presents the results of a case study regarding the Portuguese secondary school buildings and it emphasises the necessity to develop periodic asset inspections, not only to verify their condition, but also as a support to establish retrofitting maintenance programs.

The study supported by CARMA^{EE} questionnaire lead to the main conclusion that it is very important to review management and administration models, since it is necessary to improve the global effectiveness of the Portuguese educational system, namely by using resources in a most effective way.

Not only school board administrations but also the authorities responsible for educational system management must be aware of the importance of school building's assets maintenance management and so training must be considered. Areas such as maintenance management and organization provides the indispensable technical support for their activities of planning and scheduling maintenance activities, as well as a support for inspection activities, reporting and analysis of the collected data. Additionally, team management, leadership and motivation are a valuable support for school managers to better deal with maintenance personnel.

Unquestionably, school buildings have special management needs but they also present unique development challenges in terms of new studies and applications. Simultaneously, school organizations may have a privileged influence both in individuals and institutions.

When effectively applied, maintenance management and organization allows school buildings to be preserved in good operation conditions and simultaneously guaranties occupant's health, well-being and safety. Therefore, maintenance management and organization will contribute to ensure Portuguese educational system effective operation, reason why it is important to develop not only manuals but also standardization for buildings maintenance in general and for school buildings maintenance in particular.

It is important for managers to improve maintenance performance of school organizations, focusing on areas such as maintenance, building systems, safety improvements and technology, if possible anticipating in time problems and opportunities. To accomplish all of those goals these organizations must be determined to manage their available resources effectively and to seek improvements for increased efficiency, while they must implement a regularly scheduled detailed maintenance plan for all building systems.

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On the Development of an Integrated Framework Based on 'PERS' and 'EFQM' for Environmental Sustainability Management in Seaports: A Case from Egypt

Alsnosy Balbaa and Jayantha P. Liyanage

Abstract Various industrial sectors are interested in adopting Total Quality Management (TQM) today as they meet new challenges. At the same time, protection of the environment is also an issue constantly demanded from assets. In this emerging context, managing environmental sustainability through operational excellence in seaports is an important issue to be addressed. The managerial excellence here depends on many factors, for instance, personnel, organization, processes, *etc.*

Notably, Egyptian seaports have not often been seen applying or using any formal comprehensive environmental or quality management system to date. Therefore, a project was initiated in one of the major commercial seaports in Egypt, with the intention of developing a suitable methodology to enhance environmental sustainability through a comprehensive quality management process. In this novel method, the well-known *European Foundation for Quality Management* (EFQM, which represents TQM), and what is called *Port Environmental Review System* (PERS) – an Environmental Management System (EMS) – were integrated together to develop an integrated methodology for managing environmental sustainability. This covered a number of aspects which are important to resolve current challenges and problems in Egyptian seaports in environmental management terms.

This paper discusses the integration of EFQM and PERS as the basis for the development of a comprehensive method, termed an *Integrated Method for Environmental Sustainability Management* (*IMESM*), for a commercial seaport. It demonstrates an attempt to make a strategic combination of quality and environ-

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mental review processes to develop a management framework. This method was developed in close cooperation with a seaport in Egypt to ensure that it is sensible as well as practically relevant to the industrial sector.

Keywords Seaports asset management, Sustainable environment

1 Introduction

Seaports are affected by the rapid developments and competition between each other in introducing their services in the light of growing stakeholder demands and customer awareness. Seemingly, seaport leaders have shown a major interest in adopting Total Quality Management, in order to meet the new challenges [1]. Increasing pressures from various port stakeholders and the international legislation make many ports willing to demonstrate a positive environmental response. Thus, many ports throughout the world are developing environmental management systems to fulfill their environmental responsibilities and to respond to the external and internal pressures. In fact, nowadays, the protection of the environment can be considered as the guarantee of a port's commitment towards sustainable operations.

During 2004 Egyptian seaports received 13565 ship calls [2], a fact which has serious impacts on the marine environment. Negative impacts include: oil spills, collision accidents, sewage drainage, garbage residuals, ballast pollution, air emissions from ship funnels, *etc.* In fact, the annual volume of cargo handled by Egyptian ports is continually increasing [2]. Such a situation can directly affect the marine environment as a result of inefficient operations while handling, incorrect land transport handling and cargo storage, the possibility of residual cargo falling into the sea while loading or discharging, air emissions from certain kinds of cargo, garbage effect, *etc.* Notably, most terminal cargo and garbage residuals go into the sea. In 2004, Port-A received 2772 ships (20.4 % of the total ships calling at all Egyptian ports), with a monthly average of 231 ship calls [2]. *The numbers of ships calling at Port-A are increasing annually.* Waiting time in the port varies from 0.8 day for container ships to 5.6 days for bulk carriers presenting possible risks for oil spills, garbage effects, *etc.* In 2004 Port-A handled 22.3 million tonnes of cargo (27.2 % of the total cargo handled by all Egyptian seaports). (*The total cargo received by Port-A is increasing year after year.*) Moreover, Balbaa & Liyanage [3] stated that the Total petroleum hydrocarbon concentration in the surface water inside the port basin is also increasing. A high concentration (4.14 μg/g) was observed, during the pre-study phase, which seemingly is a result of improper operation and management of bulk and general cargo handling, and also of improper operation of cargo equipment.

In addition, Port-A specifically has some plans to make necessary extensions towards an integrated inter-modal transportation point, turning it into a hub-port. This will subsequently turn it into an international trade centre. Port-A expects to launch two new projects soon: a new container terminal and a gas plant. The current level of expansion and ongoing activities imply that the port's competitiveness will become increasingly dependent on the coordination and management of various stakeholders and emerging demands. These developments, if not acted upon proactively will have a considerable potential to introduce more risks to the environment, for instance an increasing level of pollution (*e.g.* oil spills) and congestion in the port area with more vehicles and lorries.

Ideally a port's operation should be sustainable from all aspects particularly including the environmental viewpoint. Despite the fact that a number of seaports use some form of environmental review system, they are not seen as adequately quality-enriched or capable of providing a comprehensive managerial framework. Since Egyptian seaports are not often seen using comprehensive environmental or quality management systems to date [4], rather than reviews, many ports require more focus on the quality of operations and services while having a key focus on the protection of the environment. In the case of Port-A, it was found that such a consideration can provide a far better approach to managing the port in an environmentally friendly and a quality assured manner, than the situation today. This can give the port a better position in terms of assurances of more environmentally sustainable operations particularly in a commercially expanding environment [5]. The challenges of Port-A (and also many other ports in Egypt) were seen, including:

- lack of environmentally sustainable mind-sets and quality-oriented cultures;
- current managerial challenges relating to environment and quality and growing potential for further aggravation of the situation due to increasing sea traffic;
- the visible needs for further expansion and modernization for commercial benefits;
- the potential impact of environmentally friendly operations on customer satisfaction and competitiveness;
- the need for a comprehensive framework that helps support the managerial tasks.

This challenging setting raised a principal need to take initiatives to develop an appropriate method to help support managerial processes. As the challenges were centralized around quality and environment, an integrated approach was needed following trends and developments within competitive industrial environments and at the same time retaining well-established tools intact within the port's focus. From that perspective, as Balbaa & Liyanage [6] state, the application of TQM was seen as very complimentary to formal EMSs to deal with the current environmental management problems in Port-A. They also found that a smart integration of the two concepts has major potential benefits for Egyptian ports in general. The paybacks can be expected in many terms, for instance raising environmental and quality awareness, better mobilization of the port's resources and personnel, and also motivating the port authority towards a better practice for environmental sustainability as well as total quality. In this context, this paper addresses the development of the novel framework called *Integrated Method for Environmental Sustainability Management* (IMESM) blending EFQM and PERS for an application in seaports in Egypt. This has been a challenging and an interesting task since it aimed at bringing two concepts together and developing a new framework for seaports.

2 Study Methodology

The complexity of the various pressures coming from different stakeholders regarding environmental issues in seaports has created a need for novel approaches to assist seaport authorities and managers to maintain environmental sustainability in their seaports. At the same time, as mentioned above, there was a timely need to look for quality oriented approaches to help the managerial processes of ports. Accordingly, this study aimed at developing an *Integrated Method for Environmental Sustainability Management* (*IMESM*), to help support the study of Port-A to realize environmental sustainability requirements through a comprehensive quality oriented process, blended with environmental review systems. This was identified as a novel and innovative approach necessary to challenge the Egyptian ports to adopt a better managerial practice.

As a part of the project, a qualitative analysis was conducted with the close cooperation of the port in order to exhibit the necessary set of elements to be incorporated into the proposed IMESM. The study included a three-fold approach: a) analysis of EFQM and PERS elements, b) revision of the port's environmental quality management literature, and c) conducting unstructured interviews in the port of study. Part a) was conducted to investigate, review and identify both EFQM & PERS criteria and sub-criteria that can be considered in the IMESM. In part b), the port's environmental quality management literature was reviewed in order to identify how the application of both EFQM and PERS can contribute to the operation and management. It was also intended to learn from other industrial applications about the potential of quality in the improvement of the management process. Part c), on the other hand, was carried out by interviewing environmental management personnel who have been in such a capacity for more than 15 years in Port-A. During the unstructured interviews, explanations were given about the elements of both PERS and EFQM criteria. The framework also incorporated the views and opinions of people with professional expertise in different environmental management disciplines as well as TQM. These interviews and other forms of interactive data collection processes were important to assure that the final outcomes would be sensible as well as practically relevant to the port's managerial set-up.

3 Port Environmental Review System (PERS) and Features of Self Diagnosis Method (SDM)

3.1 Port Environmental Review System (PERS)

Naniopoulos (2006) finds that "Self-regulation in the sector's policy refers to many forms of Environmental Management Systems (EMS) that many ports throughout Europe and the World are developing and implementing, as a mecha-

Table 1 PERS Features (see [13])

Section	Section Title	Section Function
First Section	Port profile	Gives some general information on legal status, geographical characteristics and commercial activities.
Second section	Environmental policy and statement	Covers the intentions of the port regarding the environmental performance and its framework for action.
Third section	Register of environmental aspects and legal requirements and performance indicators	Shows the documented evidence of environmental aspects, impacts and relevant legislation.
Fourth section	Documented responsibilities and resources relate to environmental aspects	Covers the identification of key personnel and structure of the organization.
Fifth section	Conformity review on legal requirements and policy	Shows the review of legislative compliance and formulation of action plans.
Sixth section	Environmental report	Shows requirements for preparation of annual report.
Seventh section	Selected examples of best practice	Shows some successful management options or solutions to environmental challenges.

nism to assist in fulfilling their environmental responsibilities and duties" [7]. Moreover, the European Sea Ports Organization (ESPO) published the new code of practice in September 2003 [8], with a main objective of how to improve the environmental performance in seaports through publishing specific recommendation related to the environmental practices.

The Port Environmental Review System (PERS) is one of the tools that were developed for port environmental management; it has been prepared within the framework of the ECOPORTS project [9] and [3]. *The benefits of adopting a management approach are widely reported and well accepted by many leading industrial companies and organizations* [10]. PERS was developed to supply the basis for developing an environmental management system by identifying significant environmental aspects, policy and performance criteria, as well as the implementation of the European Sea Ports Organization's Environmental Code of Practice.

The scheme provides the basis for independent validation and certification. On the other hand, PERS allows seaports to show evidence of their good practice just as ISO and EMAS do. Table 1 highlights the features of PERS.

3.2 Features of Self Diagnosis Method (SDM)

The Self Diagnosis Method was developed under the ECOPORTS project within the framework of the ECO-information European research project (1997–1999) by 25 ports and two research teams [11] [12]. The Self Diagnosis Method was considered a Strategic Analysis Questionnaire for the Environmental Port Managers to support them in regularly reviewing the environmental management performance in their ports. It is based on a checklist, which concentrates on the situation of the port's environmental management. It is considered as a comparison tool for comparing the environmental situation in present year with that of the previous years, and as a tool for periodical evaluation of environmental improvement in the port.

SDM is considered as a valuable and active tool for assessing the environmental management, especially in European seaports. The SDM tool has been issued in more than one version. The first one was issued and applied for testing in more than 60 European seaports, and the feedback of the application in the ports was collected and analyzed. There were some remarks about that version which can be summarized as follows: *language and terms did not appear to be well define;, the previous document proved to be too long and complex; there was no explanation of why ports should undertake the SDM* (*benefits of its application*)*;* and *the SDM should be a practical first step towards meeting ISO 14001 and /or EMAS, etc.* [7]. Those remarks were later considered and subsequently some modifications were implemented to the SDM tool and introduced again to the ports of Amsterdam, Barcelona, Dover, Genoa, Gothenburg, and Rotterdam. The implementation process was expected to cover about 150 European seaports. Notably, the geographical context of the port is essential for developing the environmental solutions. The Self Diagnosis Method is an independent tool but it has been designed with the other tools produced within the framework of the ECOPORTS project. The Self Diagnosis Method is a prerequisite to the Port Environmental Review System (PERS) and both are mutually consistent. As revealed, detailed SDM results are very essential for the ports which would like to adopt PERS. It is simple to do an effective comparison of port environmental performance against a European benchmark, through ESPO, and identify the environmental priorities of the ports through the Gap analysis.

The Self Diagnosis Method contains two main sections; the first section is about the port profile and divided into five sub-sections, while the second section consists of eight sub-sections, as shown in Table 2.

Table 2 SDM Port Profile Sub-sections (adopted from [13])

Sub-Sec.	Title	Description/Content
1	Legal statutes of the port	Shows the legal position of the port whether it is governmental, private or a mixture of both, also the section establishes who carries out the port activities.
2	Port location and port area	Describes the physical features of the port, showing the use of surrounding land, and the coastal and marine characteristics.
3	Port business	Brief description about tonnage of cargo handling, passengers or and containers per year.
4	Main commercial activities & cargo handling	A check list for both activities and cargo.
5	Main cargoes	A check list of cargoes.

Table 3 SDM environmental management and procedures (see [13])

Section/ sub	Section/Sub-section Title	Description/Content
1	*Environmental – policy*	
	The environmental policy document	Examines the existence of an environmental policy and its main issues.
	Environmental policy scope	Analyzes the different aspects covered by the environmental policy.
	Environmental regulations, port activities & aspects	Discusses the environmental regulations and inventory of environmental aspects. This is examined to make sure that the port is aware of all the aspects deriving from its activities.
	Objectives and targets	Defines the objects and targets of the port.
	Resources and budget	Defines the financial resources for the environmental purposes such as: Training, Monitoring, *etc.*
2	*Management organization & personnel*	
	Responsibilities of environmental representative	Declares the responsibility of the environmental manager.
	Environmental responsibilities of key personnel	Establishes which employees are responsible for the key functions.
	Individual environmental responsibilities	Asks about the documenting of the responsibilities.
3	*Environmental training*	Asks about the employees' awareness and whether or not this training fits with the employees' jobs.
4	*Communication*	
	Internal communication	Declares how the environmental information is communicated between the internal personnel.
	External communication	Declares how the environmental information is communicated between the port and external interested parties.
5	*Operational management*	
	Environmental management programs and action plans	Describes the features of management programs and action plans.
	Standard operating procedures and working instructions	Declares how non-compliance of standards – internal and external – is dealt with.
	Environmental management manual	Describes the contents of the environmental manual.
	Environmental documentation management	Declares the locations for maintaining the environmental documents and who is in charge of maintaining the documents.
6	*Emergency planning*	Declares the contents of emergency and incident plans.
7	*Monitoring and records*	
	Environmental monitoring	The issues related to environmental monitoring programs.
	Monitoring of management program	How the monitoring of the environmental management plan is carried out.
8	*Review and audit*	
	Environmental audit	About carrying out environmental audits and their scope.
	Review	On what procedures are used to review the port environmental management program.

The second section relates to the environmental management and procedures. It represents the core section of the SDM and it can be considered as a comprehensive checklist on environmental management aspects. Table 3 shows the eight subsections of the environmental management and procedures.

4 European Foundation for Quality Management (EFQM)

Moller [14] states that EFQM is a mechanism that helps the organizations to assess and evaluate themselves and how they could improve their services, but EFQM is not a mechanism that helps the organizations with what or how they should do.

The expectations and demands of all port stakeholders are very important to the seaport managers. Nabtize & Klazinage [15] state that EFQM is a good approach to be sure that performance meets the stakeholders' expectations and needs. They state that the EFQM approach is holistic and flexible and any type of organization can adopt it. Also, they state that the most important enablers are processes and leadership, and customer satisfaction for the result criteria. The EFQM framework is illustrated in Figure 1.

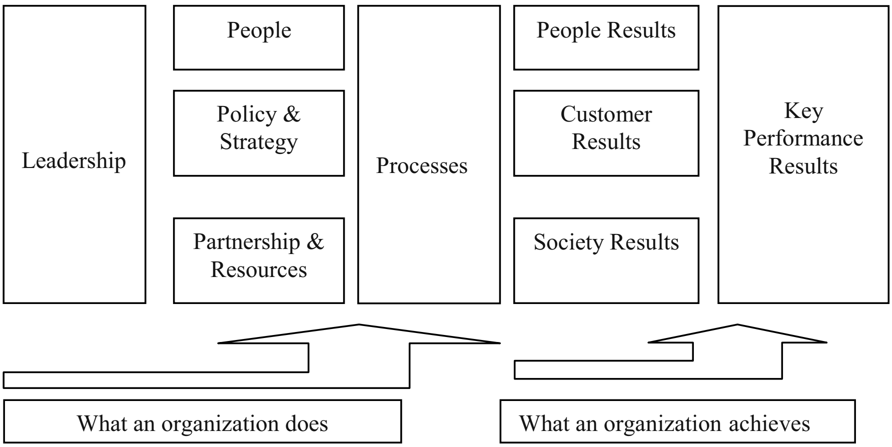

Figure 1 EFQM Framework

5 EFQM and PERS Comparison

EFQM is considered as a model not a standard, which facilitate its implementation and allows interpretation of all aspects of the business and forms of the organization. EFQM also allows comparison with other organizations, which provides the potential to learn from other competitors in specific areas by using common languages as well as PERS.

EFQM emphasizes a number of criteria in many areas which are not formally covered by PERS and vice versa. For instance, leadership is a criterion covered more properly in EFQM than in PERS. In fact, *the demonstration of leaders' commitment to excellence, continuous improvement, recognizing people's efforts and supporting people involved in improvement and releasing them from other commitments, etc.,* does have a critical effect on the port's environmental performance. Both EFQM and PERS are well established within the policy and strategy criteria, but PERS policy considers things related mainly to the environmental issues, for instance, the "*inventory of environmental regulations and their requirements for all port activities such as; dredging, shipping, waste management, traffic, cargo operation, port based industry, port infrastructure, administrative and planning activities, stakeholders, emergency situations, environmental incidents*" … It finally evaluates the level of significance of all the aspects identified. People management appears as a principal element in both. However, in PERS, it is stated from the point of view of *environmental management representatives, responsibilities of key personnel, as well as environmental training and monitoring*. On the other hand in EFQM, in addition to what is generally considered in PERS, many other sub-criteria are covered such as "*how people agree on targets and continuously review performance, how people are involved, empowered and recognized*", *etc.* It also comprises such important issues as "*encouragement of employees' superior performance and commitment and how the organization encourages and supports individuals and teams to participate in the improvement, how people and organizations can have an effective and positive dialogue, and finally how people are cared for*". Issues regarding resources seem to have been adequately covered in both EFQM and PERS, except that PERS does not consider technology management (*i.e.* "*how technologies are developed and protected as the basis of the organization's operations and services, how technology is harnessed in support of process, information systems and other systems' improvement, and how the skills and capabilities of the people are harmonized with in developing technologies, etc.*"). On the other hand, PERS considers other important elements, such as *the way that the port can allocate financial resources to environmental training for employees, impact minimizing, emergency response and prevention, environmental monitoring and audit and review, etc.* Process is considered as a key element for implementing any management system. As such, the process should include *how to deal with critical and emergency cases, how the system is reviewed and benchmarked*, *etc.* These issues seems to be clear in both EFQM and PERS. *Use of feedback from customers and users to stimulate process innovation and how processes are changed and their benefits evaluated*, are largely considered in EFQM while they are not adequately considered in PERS. Both tools take into account the customer satisfaction but EFQM is stronger in this area where the focus is on the *direct perception measures of the employees' feelings and or satisfaction and factors that relate to motivation and involvement*. Also, both claim to have direct impact on society. Accordingly, the principal expectation of the study is that meaningful integration of EMS or EFQM can have positive effects, enhancing the mutual strengths while compensating for each other's weaknesses, on the business results for the organization at large.

6 Proposed Integrated Method for Environmental Sustainability Management (IMESM)

Sustainable consideration in seaports is very essential and should be carefully adopted, as the seaports tend to be industrial production areas resulting in the generation of waste and other environmental problems that justify a need to focus on management for sustainability (see [16]). Apart from the current popular awareness, the excellence for sustainable performance could also be based on other critical aspects, such as the person ('people'), organization and society ("Organization's neighbours"), *etc.* [17]. On the other hand, special considerations are also to be given to specific values processes, which are important to the sustainable performance of seaports and deployed core values for business excellence. This can include, for instance as identified during the preliminary studies:

- Sustainable stakeholder balance, *i.e.* the long-term balance between the interests of all stakeholders, *i.e.* port users, port employees, ship-owners, partners, competitors, *etc.* from a basis of sustainable development and this is supported by policy and strategy and process.
- Learning excellence; this is needed for sustainability. This includes a climate of improvement and innovation created through good learning and is supported by people management.
- Personnelxcellence; this is represented in the setting of the mission, vision and values corresponding to sustainable development, and is supported by leadership.
- Process performance excellence; that is defined as managing the process effectively and efficiently with a result that maximizes the integrated stakeholder value in the long-term perspective while maintaining a balance between the interests of all stakeholders.
- Transparency; open information of compliance with performance standards for management and employees leads to fair and transparent competition.
- Stakeholdercracy; participation by everybody based on democratic values that must be encouraged; formal authority is temporary and subject to the scrutiny of stakeholders. The responsibilities and privileges of leadership are reflected to some extent.

The proposed *Integrated Method for Environmental Sustainability Management* (IMESM) had a focus on the above-mentioned issues, as well as to use TQM represented in EFQM and EMS represented in PERS as the bases. IMESM shows the elements of the integrated method and what the seaport needs to consider when implementing such a comprehensive system. The inclusion of PERS is to confirm that it can act as an effective and practical tool for the port environmental management and thus can contribute substantially to continuous improvements of the port environment. Furthermore, PERS gives the opportunity for the port authority to identify its environmental challenges and priorities. Through the environmental policy and strategy illustrated in IMESM, it is expected to identify the legal framework, 'international as well as local', related to the environmental issues and set up a mechanism for keeping updated with environmental developments. It is also expected to help support better compliance with legislation, identification of the appropriate action plans to respond to liabilities and responsibilities, identification of business risk, prevention of environmental accidents, *etc.* in addition to determining the environmental goals and the port stakeholders' needs. Resources comprises financial and human elements, in which both are considered very important, although there are approaches assuming that the human resources and knowledge management are the only key elements for successful development rather than technology and capital [18]. Moreover, Puffer and McCathanthy [19] state that the heart of successful TQM implementation is the leadership ability to create a vision and promote change. Thus leadership has been considered as a main element of the IMESM enabler criteria. People management, inclusive of "training, education, care for, motivation, *etc.*", has a very important role in dealing with the environmental impacts resulting from Port-A's activities aimed at achieving internal satisfaction and enhanced business results as well. In addition, processes have a key role in the determination and building-up of key and support port-processes in order to satisfy port stakeholder needs within the environmental strategic plan content. The defined 'core enablers' are expected to help guide the case study port towards environmental sustainability. As a result, the port is to aim at achieving its performance needs that can be defined in terms of stakeholder satisfaction, people satisfaction, improving public image, and increased port competition, subsequently, making it an environmentally friendly port. Figure 2 shows the elements of IMESM, and Table 4 gives some specific potential features that can be considered under the chosen criteria.

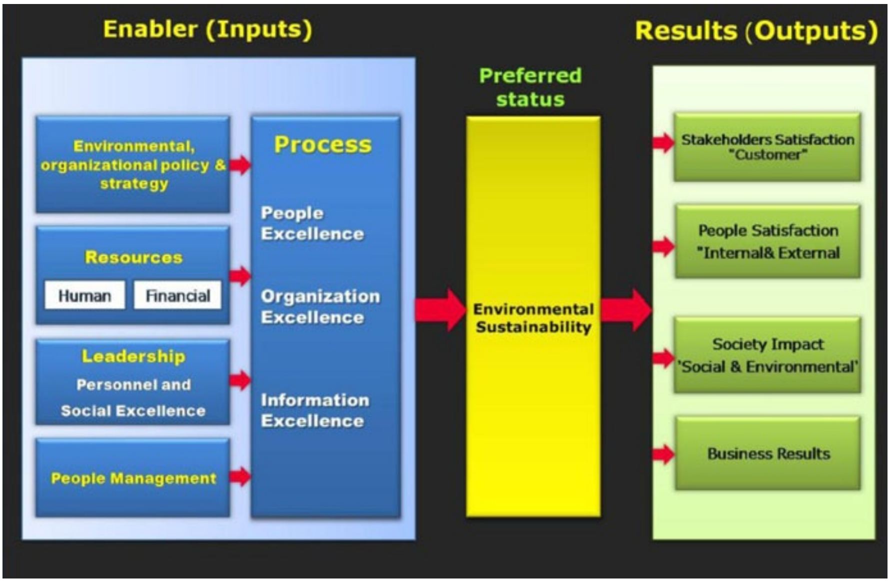

Figure 2 Proposed IMESM Criteria

Table 4 Criteria and features of the proposed *Integrated Method for Environmental Sustainability Management* (IMESM)

Criteria	Some Potential Features
Leadership	Setting the mission; vision to make learning excellence; looking at all internal and external stakeholder expectations from the social, economic and environmental view points; prioritizing the needs, and focus on change management and improvement techniques.
Policy	Policies should be set to comply with environmental protection, economical excellence, and social equity, and address internal and external port stakeholders and their needs.
Resources	Financial budgets, for instance related to physical assets and technology management, that are required to reach the goals; Human Resources, *etc.*
People management	Attaining personnel excellence through continuous learning and training; appraisal processes development to map and match the people's satisfaction.
Processes	How processes are controlled; how they are used for improvement, how they are measured against stakeholder needs and satisfaction; how they use information excellence, organization excellence, and people excellence to reach environmental sustainability.
Stakeholder satisfaction	Performance level of the port towards internal and external stakeholders; measurement of the quality of the port's activities towards customers and environmental conditions.
People satisfaction	Performance level of the port towards internal and external personnel involved with the port, and the level of their satisfaction with respect to environmental conditions and the port's activities.
Society impact	Strong positive co-operation with society at large, and a better public image.
Business results	Very positive benefits for the organization at all levels; those are critical to the business.

Each criterion given will have its own sub-criteria and group of items. These items will be appropriately chosen from PERS and EFQM self assessment criteria, and will be integrated under an IMESM framework as necessary. The actual content can in fact vary from case to case, but how it will be relevant and how it will apply to the port of study will further be investigated with the continuation of the project.

7 Conclusions and Further Work

Seaports in Egypt have a major need today to satisfy environmental demands as well as to adapt a good managerial approach based on total quality. Port-A, which was used as the reference site as well as the one for collecting basic data, justified the need for a novel and an innovative approach. This paper thus proposed a so-called *Integrated Methodology for Environmental Sustainability Management* (IMESM) based on the combination of EFQM and PERS. The IMESM framework integrated the environmental issues through PERS and the quality management issues through EFQM. The purpose was to provide the case study port with a structured and comprehensive approach for dealing with environmental responsibilities. It was also expected to raise environmental awareness and thus support the mobilization of port personnel and other resources for a timely important issue. Moreover, it is expected to provide the basis to enhance the current motivation level of the port authority towards the achievement of environmental sustainability. The implementation of such methods as IMESM also proves that sustainability flows from top to bottom, as well as from bottom to top. This IMESM framework thus intends to shift the focus purely on the economy element, and brings the "stakeholder needs and satisfaction" into the picture, making a positive contribution to the port to achieve a successful Triple Bottom Line (TBL) performance.

The study will be continued to identify (a) which items are relevant and applicable to a study port in Egypt, and (b) the level of compliance of the study port to the proposed IMESM-based criteria. It will give constructive feedback to the port authorities and the operational personnel about the current strengths and weaknesses in order to launch proper actions to improve its environmental sustainability performance.

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Dynamic Project Portfolio Selection in Infrastructure Sector

Tiina Koppinen and Tony Rosqvist

Abstract Infrastructure networks are vital to the national economy. Their Asset Management (AM) should result in long-term economic efficiency and optimal service levels. For AM to live up to the expectations of infrastructure sector, it has to meet four key challenges: 1) alignment of strategy and operations with stakeholder values and objectives; 2) balancing of reliability, service-level, safety, and financial considerations; 3) ensuring optimal packaging and timing of works, and adequate competition; and 4) promoting market development. Through educated decision-making, asset managers can actively develop their networks and use their limited budgets in a way that long-term goals and short-term budgets are met. In order to assist asset managers, a simplified Project Portfolio Selection Method (PPSM) is developed. The method applies the analytical hierarchy process (AHP) and real option ideology. PPSM aims at assisting infrastructure managers in optimising the life cycle profiles of their assets through selection of an optimal maintenance, repair and rehabilitation project portfolio. The developed method fills the void between strategic and operative decision-making methods facilitating management of multiple investments at the local network management level. Through the systematic, easy-to-apply project selection method, the asset manager can easily determine the optimal project portfolio and demonstrate the grounds to others.

Keywords Infrastructure asset management, Project portfolio selection, Asset project appraisal

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1 Background

Road, rail, and water supply and sewerage networks are vital to the national economy. Because the economical and technical life of the networks after green-field investment is great, numerous rebuilds, replacements and expansions take place during their life time, highlighting the importance of Asset Management (AM). Reduction in public financing together with increasing use of the networks, urge infrastructure managers to optimize their networks focusing on overall cost-effectiveness of their operations. In these circumstances, AM decision making should result in long-term economic efficiency and optimal service levels. For AM to live up to these expectations, it has to meet four key challenges: 1) alignment of strategies and operations with stakeholder values and objectives (Kaplan & Norton 2004); 2) balancing of reliability, service-level, safety, and financial considerations (Schneider *et al.* 2006); 3) ensuring optimal packaging and timing of works, and adequate competition; and 4) promoting market development (Koppinen & Lahdenperä 2004b). Also, often cited objectives include maximising the net benefit to the public, efficient use of resources, and early usage of the built facilities (Hsieh & Liu 1997). Through educated decision making, asset managers can actively develop their networks and use their limited budgets in a way that both long-term goals and short-term budgets are met. However, in reality, decision making in infrastructure development and operation under uncertainty is often far from optimal, reliable, and flexible (Zhao & Chung 2006). Approaches to municipal infrastructure management tend to be centred upon annual project execution. Simply executing existing backlog fails to consider projects in an appropriate context. This situation mandates an aggressive and structured approach to AM (Garvin *et al.* 2000).

2 Uncertainties in the Infrastructure Sector

Identification and anticipation of future changes and resulting uncertainties is an important part of AM. Uncertainty may be caused by factors both internal and external to an organisation. Uncertainties affecting the infrastructure industry in Finland (and in most developed countries) are listed below based *e.g.* Nippala & Petäjä (2004), Nippala & Vainio (2004), Orkoneva (2005), Piippo (2005), RHK (2004), Koppinen & Lahdenperä (2004a). The list of uncertainties is structured according to Komonen *et al.* (2005) in identifying and anticipating changes in the operating environment:

Market Oriented Changes

Products and assets

- Actual quality and service level of asset – Determination of an optimal quality and service level is difficult.
- Fluctuations in raw-material prices

- Interconnectivity of networks – Often utilities are located in the same canal within the transport corridor. Coordination of the networks' maintenance is complicated, as all networks are managed by different organisations.

  Competition

- Level of competition – Even though operation and maintenance of infrastructure have slowly been opened for private competition, locally lack of competent suppliers and adequate competition may be experienced.

  Success factors

- Delays in project delivery – In the construction sector delays are quite common.
- Efficiency and productivity requirements – In the future, infrastructure managers' ability to optimise their networks may be measured through an effectiveness measure.

  Financial market

- Level of public financing – One of the common themes around the world is lack of public financing and problems associated with annual budgets.

  Users

- Changes in user needs – Locally changing usage may put pressure on the network.

Technological Changes

Obsolescence

- Speed of wear and tear
- Adequacy and redundancy of capacity – Capacity of current networks may be exceeded in certain sections, while some sections may have redundant capacity.
- Demands for accuracy and reliability – Although reliability and predictability of services may be gained by integrating more techniques into the networks, at the same time, potential failures become more critical.

  Changes in product and production technologies

- Use of new materials and techniques.
- Increasing use of IT – New technology embedded in structures enables greater efficiency of operation, but requires learning. The technology also tends to have a shorter life-span than the structures.

Changes in Networks

Staff

- Loss of capable staff – Many infrastructure owners will soon face loss of capable staff since a significant proportion of the staff will retire during near future.

  Organisational networks

- Success in networking and cooperation – Public organisations benefit from networking and collaboration with other public and private organisations. However, it takes time to organise this collaboration efficiently.

Societal Changes

Legislation

- Fast changes in legislation

  Working culture and norms

- Level of litigation – There is a clear increasing trend in amount of litigation.

  Occupational safety

- Occupational safety level – Occupational and healthy risks are common in construction.

  Environmental norms

- Environmental requirements – Discharge, emissions and waste may be limited to an amount that results in current materials, systems, methods, equipment and machinery becoming obsolete. Also noise and vibration and other environmental restrictions will become more stringent. Use of recycled materials is expected to increase despite some uncertainty about their service, operating and technical life.

  Media and public opinion

- Acceptability of user fees – Even though user fees would be a good source of financing, people think that fees should be minimal in order to guarantee access to infrastructure for everyone. Fees are regulated and may not reflect true costs.

  Changes in Ownership

- Privatization/Incorporation/Concessions – Counties and states pursue to outsource delivery of services allowing them to concentrate on managing the infrastructure. These arrangements cause big cultural changes in the organisations involved.

3 Decision Making Methods

In general, local AM decision making needs to be in line with the organisational asset strategy, while still taking into account local objectives and constraints. Different decision making tools have been developed to assist managers in educated decision making. Here, AHP and a real option approach are selected as the basis for the simplified Project Portfolio Selection Method (PPSM) developed in this paper. The developed method aims at filling the void between strategic and operative decision making. The easy-to-apply method pursues to assist infrastructure managers in optimising the life cycle profiles of their assets.

4 Real Options

Traditional investment evaluation based on discounted cash flow analysis (such as NPV net present value, IRR internal rate of return, payback) ignores the upside potentials to an investment from managerial flexibility and innovations. A real option approach that borrows ideas from financial options offers a different perspective. It views investment strategy as being crafted as a series of options that are continually being exercised to achieve both short and long term returns on investment. Management's flexibility to adapt to changes in technology and market introduces a skewness in the distribution of investment payoffs with improved upside potentials (Yeo & Qiu, 2003). Options allow an organisation to respond to strategic and competitive opportunities rather than remaining locked into a fixed course of action.

According to Ollila (2000) real options may be divided into two groups: flexibility options and growth options. Based on this division and Hellsten (2001), real options available in infrastructure Maintenance, Repair and Rehabilitations (MR&R) projects are as follows:

Flexibility Options

- Option to Wait – The most common real option embedded in an investment opportunity is the flexibility of timing of the investment.
- Staging Option – Majority of investment opportunities are incremental and involve opportunities to delay, contract or increase the level of investment at some stage.
- Option to Abandon – Another consequence of an incremental investment policy is the option to abandon the project.
- Option to Change Raw-Material
- Option to Change Funding Source

Growth Options

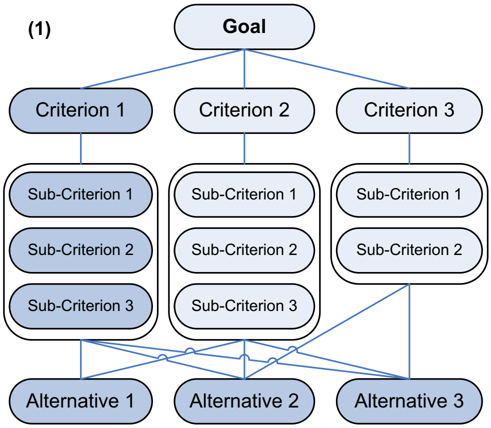
- Option to Change Service Level
- Option to Change Operation Mode – Enables more effective use of resources.
- Growth Options – Investment opportunities available to the decision-maker that were made possible by preceding investments.

Not all of above options are valuable in all circumstances. The value of each real option depends on the type and level of uncertainty experienced or expected. Additionally, even though real option based models overcome many deficiencies experienced with the traditional financial tools, they are often considered overly complicated. It has been suggested that few practitioners truly understand or use the real options approach (Alkaraan & Northcott 2006). This is why an easy-to-use and reliable tool is needed to assist infrastructure managers in selecting optimal projects in an uncertain environment.

5 AHP

This study adopts Analytical Hierarchy Process (AHP), a multiple-attribute decision making technique, as the primary method for selection of an optimal project portfolio. The AHP developed by Saaty (1980) provides a flexible and easily understood way of analysing complicated problems. AHP allows subjective as well as objective factors to be considered in the decision making process and it can handle factors that may be conflicting. Additionally, AHP forms a systematic framework for group interaction and group decision making which is often utilized in project evaluation.

(1)



(2a)	Criterion 1	Criterion 2	Criterion 3	Weight	**Relative weight**
Criterion 1	1	3	9	2.109*	0.703**
Criterion 2	1/3	1	2	0.620	0.207
Criterion 3	1/9	1/2	1	0.271	0.090
Sum	1.444	4.50	12	3.0	1

* Weight = !/1.444 + 3/4.500 + 9/12 = 0.705
** Relative weight = 2.109/3.0 = 0.703

(2b)	Sub-Crit.1	Sub-Crit.2	Sub-Crit.3	Weight	**Relative weight**
Sub-Crit.1	1	4	7	2.104	0.701
Sub-Crit.2	1/4	1	3	0.640	0.213
Sub-Crit.3	1/7	1/3	1	0.256	0.085
Sum	1.393	5.333	11	1	1

(3)	Sub-Crit.1	Sub-Crit.2	Sub-Crit.3	Criterion 1 Score
Weight	0.701	0.213	0.085	
Alt.1	4	3	9	4.208*
Alt.2	5	5	3	4.825
Alt.3	6	3	7	5.440

* Score = 0.701*4+0.213*3+0.085*9 = 4.208

(4)	Criterion 1	Criterion 2	Criterion 3	**Final Score**
Weight	0.703	0.207	0.090	
Alt.1	4.208	4.255	6.520	4.426
Alt.2	4.825	4.230	4.201	4.646
Alt.3	5.440	4.501	3.854	5.103

Figure 1 A decision hierarchy using AHP

Use of AHP in decision making is discussed by Dey (2005). The process starts with formulation of a decision problem in the form of a hierarchical structure ((1) in Figure 1). In a typical hierarchy, the top level reflects the overall objective of the decision problem. The elements affecting the decision are represented in intermediate levels. The lowest level comprises the decision options (sub-criteria). Once the hierarchy is constructed, the decision-maker begins a prioritisation procedure to determine the relative importance of the elements in each level of the hierarchy. The elements in each level are compared as pairs with respect to their importance in making the decision under consideration (2 a/b). After comparison matrices are created, relative weights are derived for the various elements. In order to derive the criterion-level (upper level) assessments for each alternative, intermediate level criteria are scored and the scores multiplied by respective relative weights and summed up (3). Composite scores are then determined by aggregating the weighted scores through the hierarchy to each alternative (4). The outcomes of this aggregation are the final scores of the alternatives which can be used to assess the superiority of different alternatives.

6 Investment Portfolio Evaluation

In order to manage infrastructure assets optimally, the asset manager must select optimal projects in the MR&R project portfolio. The asset manager has to rank the favourability of all investment alternatives and select the best ones according to the rank order and the budget limitations. According to Figure 2, investment port-

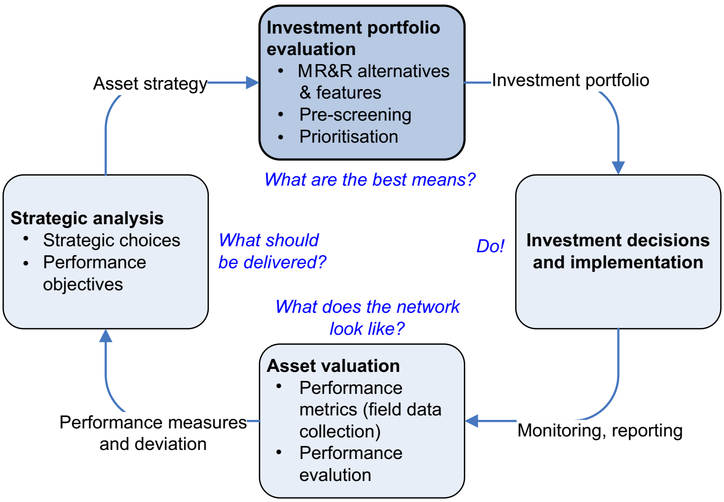


Figure 2 Linking between AM and strategic decision making

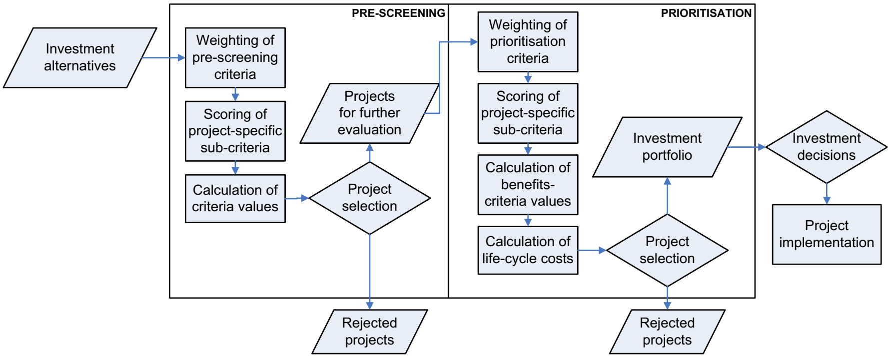


Figure 3 Project evaluation process

folio evaluation is a continuing process which provides list of investments and their timings for investment decision making and implementation. At the same time, to fulfil the pre-determined needs, the public agency has to base its decision on meeting of the objectives set in the asset strategy, while efficiently utilising available resources.

The optimal project portfolio depends on the operating environment. For an organisation operating in a stable operating environment, the success criteria of AM may relate to reliability of service quality and speed of response set against continuous improvements in cost efficiency. However, when uncertainty in the operating environment increases, speed and appropriateness of change become increasingly relevant elements of competitiveness (Kelly *et al.* 2002). The developed method pursues to incorporate this type of consideration as an inherent part of optimal MR&R project selection. The project evaluation process is divided into two consecutive functions: pre-screening and prioritisation (Figure 3).

7 Project Pre-screening

In pre-screening investment opportunities at the local network management level, both quantitative and qualitative information is utilised as criteria according to Figure 4 are: 1) Value creation (benefits); 2) Resource-availability (costs); and 3) Flexibility provided by the alternatives in case of future changes (real options). The level of Value creation is determined by whether the evaluated alternative: 1) fits into the organisation's strategy; 2) contributes to the organisation's strategic capabilities promoting continuous improvement; 3) provides important stakeholders with added value; 4) facilitates ensuring of safety, reliability and service-level of operations; and 5) promotes market and industry development. Resource-availability is determined based on whether: 1) public financing is available; 2) other sources of funding are available in case public financing is deficient;

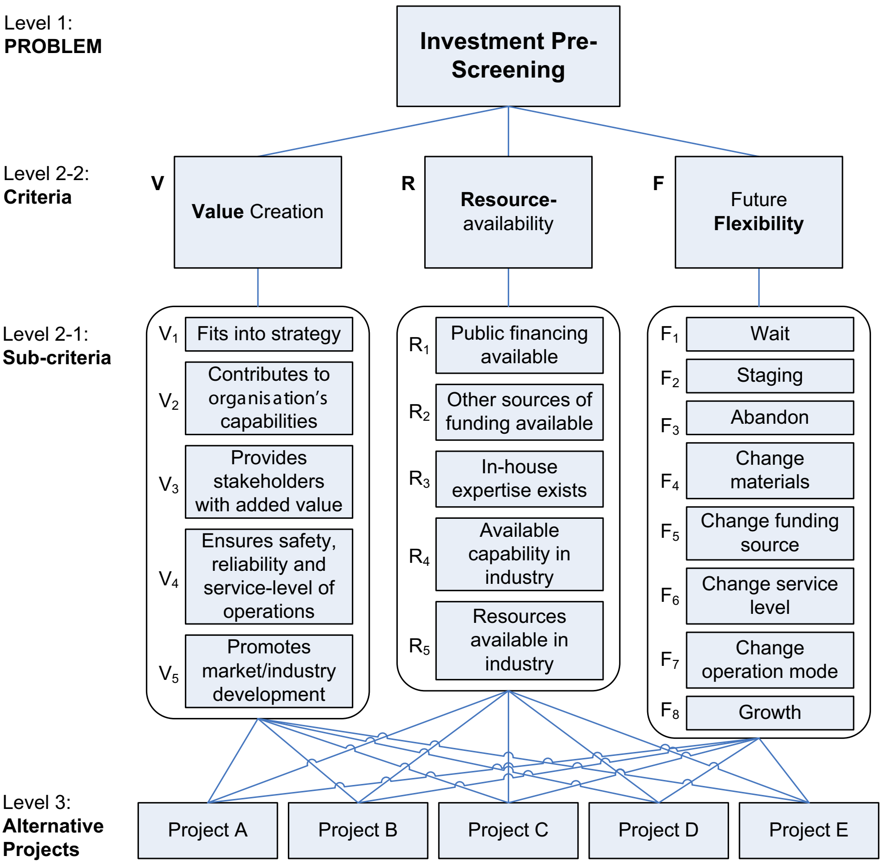


Figure 4 Investment pre-screening using AHP and taking into consideration real options

3) in-house expertise exist and is available; 4) industry has appropriate capabilities; and 5) market situation enables adequate supply and competition in the industry. Future flexibility is determined based on the availability and usability of real options inherent in the evaluated alternative.

The underlying principle is to establish relative weights (w_i) of the above criteria and sub-criteria using pair-wise comparison, as shown in Table 1. Since these comparison are performed using AHP-method described above, the recommended scale used for making the comparisons is presented in Table 2 (Saaty 1980). Generally, the more critical the criterion is in relation to the other criteria, the higher it should be weighted. For example, the weighting of the future flexibility depends on the level of uncertainty existing or expected in the operating environment; the more uncertain environment, the more valuable flexibility is, the higher its weight should be.

As infrastructure managers should reflect objectivity in assessing somewhat subjective factors, the sub-criteria scoring is determined based on Table 3. The

Table 1 Final importance of criteria and preferences of alternatives in pre-screening

Criteria	**Value Creation**					**Resource-availability**					**Future Flexibility**					**Total ***
Relative weights	w_V (weights through AHP)					w_R					w_F **					(sum=1)
Sub-crit.	V1	V2	V3	V4	V5	R1	R2	R3	R4	R5	F_i	F_i	F_i	F_i	F_i	
Weights	w_{V1}	w_{V2}	w_{V3}	w_{V4}	w_{V5}	w_{R1}	w_{R2}	w_{R3}	w_{R4}	w_{R5}	w_{Fi}	w_{Fi}	w_{Fi}	w_{Fi}	w_{Fi}	(sum=3)
Project A	a_{V1}	a_{V2}	a_{V3}	a_{V4}	a_{V5}	a_{R1}	a_{R2}	a_{R3}	a_{R4}	a_{R5}	a_{Fi}	a_{Fi}	a_{Fi}	a_{Fi}	a_{Fi}	A_{tot}
Project B																B_{tot}
Project C																C_{tot}
Project D																D_{tot}
Project E																E_{tot}

* $X_{tot} = w_V*(\Sigma w_{Vi}*x_{Vi})+w_R*(\Sigma w_{Ri}*x_{Ri})+ w_F*(\Sigma w_{Fi}*x_{Fi})$, i=1…5 (Flexibility: i=1…8, of which 5 most important options selected), x=a,b,c,d,e valued according to table xx; $1\leq X_{tot}\leq 10$

** The more uncertainties exist in the operating environment; the higher weight should be given to Future Flexibility.

Table 2 Intensity of importance

Scale	Definition	Scale	Definition
1	Equal importance	2, 4, 6, 8	Intermediate values between the two adjacent judgements
3	Moderate importance over another		
5	Essential or strong importance		
7	Very Strong importance		
9	Extreme importance		

asset manager may assess the level with which each alternative fulfils the sub-criterion according to the descriptions provided. This type of scoring system improves objectivity, as an effect of personal preferences may be reduced. For example, R3 – In-house expertise exists: Assume that expertise required by an alternative exists in-house (*e.g.* project management resources capable of handling large projects). However, at the moment these resources are located in another regional office, necessitating internal co-operation in order to utilize the expertise. If earlier experiences of cooperation between the two offices have been successful, the score would be 8. On the other hand, if the organisation has no history of co-operation between the different regional offices, initial inefficiency may be experienced. In this case, the score would be 7.

Available real options are taken into consideration in a similar fashion. Instead of complicated option-based valuation methods, flexibility provided by different real options may be valued based on the option costs involved with the options, since flexibility typically comes at a price and is only valuable as a hedge against the uncertainty (Du *et al.* 2006). Here, strategic real options (no more than the five most important ones associated with the alternative assessed) are determined based on uncertainties existing in the operating environment. These real options are scored based on the estimated level of option costs involved with the option when compared to an alternative without this option. For example: when there is a significant uncertainty about the level of competition in the industry, real options that provide value are: waiting, staging and changing of operation mode. If an alternative provides an option to implement the project in stages, and it may be expected that the competition level is significantly improved by phase two, the staging option is valuable. Now it is assessed how much more this alternative costs, when compared to an alternative without this option. If option cost (OC) is approximately 7% of project cost, the score would be 5, while an OC of 6% would result in a score of 6.

Finally, projects that provide x_{tot} values greater than a certain pre-determined threshold value may be selected as a promising set of projects. To visualise the above analysis, the results are drawn into a diagram shown in Figure 5. Here the x-axis depicts the score of resource requirements (costs), while the y-axis denotes the score of value generation (benefits). The size of the symbol depicts the score of flexibility. Projects in the upper most, right-side quadrant should be implementted, while projects in the lowest left-side quadrant should be declined. Other projects above the diagonal could be implemented, if resources are adequate. No further analysis is necessary. However, as resources are often deficient, these potential projects should be evaluated thoroughly in order to implement the best projects. This is done through project prioritisation. Projects underneath the diagonal should be omitted from the evaluation and declined unless the magnitude of uncertainty and flexibility provided by an alternative justify a further evaluation of that alternative. After the pre-screening analysis described above, the asset manager has indisputably determined the order of superiority (based on x_{tot}) of alternative projects.

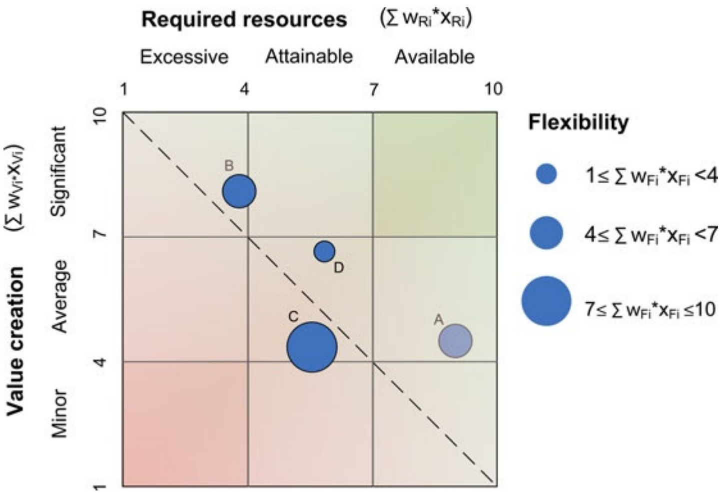


Figure 5 Selection of the potential alternatives

Table 3 Valuation of the pre-screening criteria (scale 1…10)

Criteria		Score				
		1–2	3–4	5–6	7–8	9–10
V1	Fits into strategy	negligible	fulfils fraction of strategy	fulfils basic principles of strategy	fulfils most of strategy	fulfils strategy
V2	Contributes to organisation's capabilities	negligible	improvement trivial	improves existing capabilities	broadens capabilities	builds new strategic capabilities
V3	Provides stakeholders with added value	negligible	some	average amounts	more than average	significantly
V4	Ensures safety, reliability and service-level of operations	negligible	improved to some extent	probability of failures <7%	probability of failures <5%	probability of failures <2%
V5	Promotes market/industry development	negligible	to some extent	industry cooperation increased	industry innovativeness improved	significantly
R1	Public financing available	none	minor part through annual budget	partial through annual budget	adequate/ total funding	abundantly
R2	Other sources of funding available	none	one source – partial funding	two sources – partial funding	adequate funding available	abundantly
R3	In-house expertise exists	negligible	requires long-term planning and training	requires some training	requires internal co-operation	expertise readily available
R4	Available capability in industry	negligible	requires long-term planning and training	requires some training	requires industry co-operation	capability readily available
R5	Resources available in industry	negligible	requires long-term planning and much funding	requires training or waiting for completion of current projects	requires good co-ordination/ management	resources readily available
Select max. 5 strategic real options (i=1…8) based on uncertainties in the operating environment (Table 2):						
F_i	n.n.	significant option costs (OC) involved	OC 10% of project cost	OC 7% of project cost	OC 4% of project cost	negligible OC involved
F_i	n.n.	significant OC involved	OC 10% of project cost	OC 7% of project cost	OC 4% of project cost	negligible OC involved
F_i	n.n.	significant OC involved	OC 10% of project cost	OC 7% of project cost	OC 4% of project cost	negligible OC involved
F_i	n.n.	significant OC involved	OC 10% of project cost	OC 7% of project cost	OC 4% of project cost	negligible OC involved
F_i	n.n.	significant OC involved	OC 10% of project cost	OC 7% of project cost	OC 4% of project cost	negligible OC involved

8 Project Prioritisation for Optimal Portfolio

In order to optimise the project portfolio, a more comprehensive assessment is performed on the pre-selected, potential alternatives in order to prioritise the optimal MR&R projects. The method used is similar to the pre-screening phase, but criteria used differ from the previous (see Figure 6). Now criteria used are divided into three groups as follows: 1) Improvement in maintainability of the asset; 2) Service improvements produced; and 3) Optimised life cycle cost (LCC) of the asset. The first two criteria determine the level of overall benefits of the projects, while the third criterion determines the true life cycle cost of the project (Table 4). The level of improvement in maintainability is determined by how the evaluated alternative impacts on 1) network or 2) system reliability and 3) maintainability of the network; and how it affects 4) the operation and 5) the remaining life of the network. Level of service improvement is determined based on: 1) increases in throughput; 2) network utilisation level; 3) system efficiency; 4) reliability of service; and 5) ability to meet user needs. Scoring of the benefits criteria are performed according to Table 5.

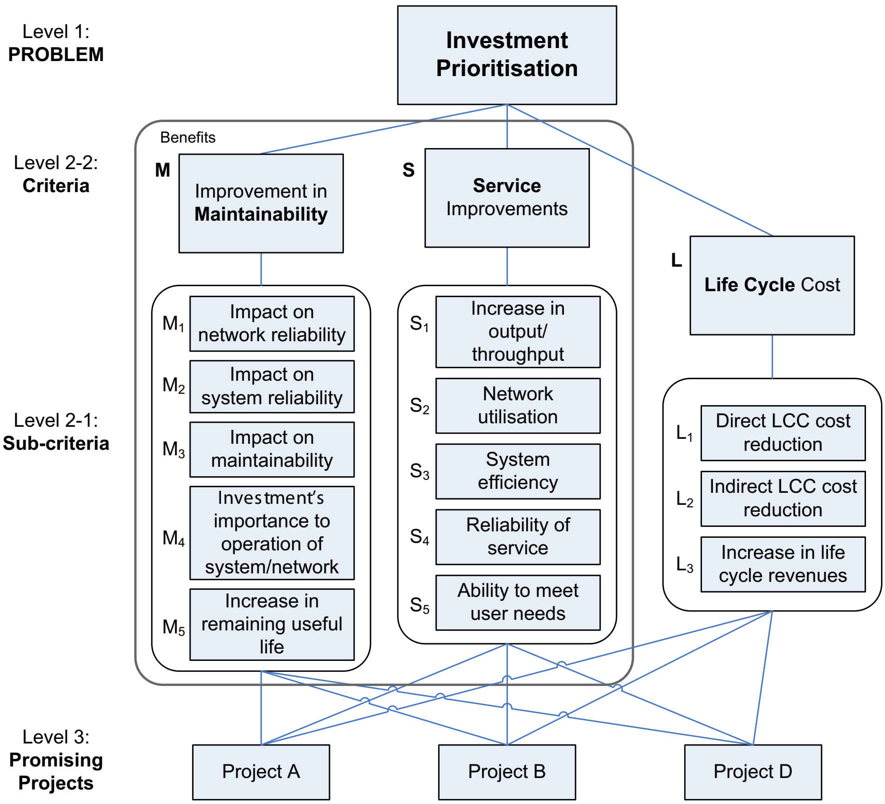


Figure 6 Investment prioritisation using AHP in order to optimise the network's life cycle profile

Table 4 Final importance of criteria and preferences of alternatives in project prioritisation

Criteria	**Improvement in Maintainability**					**Service Improvements**					**Total Benefits**	**Life Cycle Cost**		
Weights	w_M (weights through AHP)					w_S					(sum=1.0)			
Sub-criteria	M1	M2	M3	M4	M5	S1	S2	S3	S4	S5		L1	L2	L3
Weights	w_{M1}	w_{M2}	w_{M3}	w_{M4}	w_{M5}	w_{S1}	w_{S2}	w_{S3}	w_{S4}	w_{S5}	(sum=2.0)			
Project A	a_{M1}	a_{M2}	a_{M3}	a_{M4}	a_{M5}	a_{S1}	a_{S2}	a_{S3}	a_{S4}	a_{S5}	A_{tot}	LCC_A		
Project B											B_{tot}	LCC_B		
Project D											C_{tot}	LCC_C		

$X_{tot} = w_M*(\Sigma w_{Mi}*x_{Mi})+w_S*(\Sigma w_{Si}*x_{Si})$, i=1…5, x=a,b,c according to table xx; $1\leq X_{tot}\leq 10$

Table 5 Valuation of the prioritisation criteria (scale 1…10)

Criteria		**Score** 1–2	3–4	5–6	7–8	9–10
M1	Impact on network reliability	negligible	improved to some extent	probability of failures <5%	probability of failures <3%	probability of failures <1%
M2	Impact on system reliability	negligible	improved to some extent	probability of failures <5%	probability of failures <3%	probability of failures <1%
M3	Impact on maintainability	negligible	slightly facilitated	facilitated to some extent	maintainability better than average	significantly improved
M4	Investment's importance to operation of system/network	negligible	operation slightly facilitated	operation facilitated to some extent	operation more efficient than average	strategic/ significant
M5	Increase in remaining useful life	negligible	25%	50%	75%	100%
S1	Increase in output/ throughput	none	meets partially projected increases in future demand	meets projected average increases in future demand	meets projected increases in future demand	meets projected extreme increases in future demand
S2	Network utilisation	significant over capacity or severe problems during peak utilisation	mostly inefficient	some over capacity or average problems during peak utilisation	mostly efficient	optimal
S3	System efficiency	current level or worse	increased by 10%	increased by 15%	increased by 20%	increased by 25%
S4	Reliability of service	current level or worse	failures reduced by 10%	failures reduced by 35%	failures reduced by 50%	failures reduced by 65%
S5	Ability to meet user needs	negligible	meets minor user needs	meets primary user needs	meets most user needs	meets all user needs

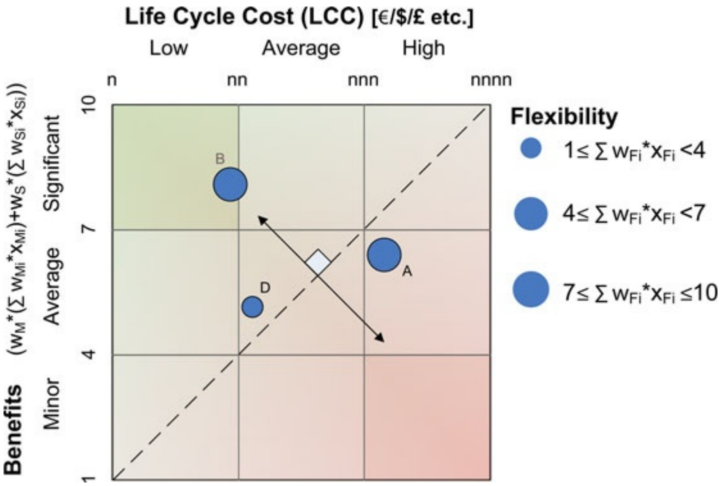


Figure 7 Selection of the project portfolio for implementation

The results of the prioritisation are drawn into a diagram shown in Figure 7. Here *x*-axis depicts the LCC of the project, while *y*-axis denotes the scored benefits of the project. (The LCC-axis may be divided into three segments based on general distribution of project LCCs.) The size of the symbol depicts the flexibility provided by the investment alternative (determined in project pre-screening). Again projects above the diagonal should be selected to the project portfolio, while projects underneath the diagonal should be declined. The diagonal can be moved perpendicularly depending on the availability of resources. The idea is to position the diagonal so that the level of available and attainable resources is equal to LCC of the project portfolio (= $\sum LCC_i$, i = A, B…). After the prioritisation analysis described above, the asset manager has determined the optimal MR&R project portfolio.

9 Conclusions

One of the biggest challenges for any public organisation today is, how to prioritise projects to maximise existing funding. The objective of the developed decision making method was to evaluate various alternatives and to recommend the most cost-effective maintenance, repair and rehabilitation projects to be implemented. For this purpose, the developed method provides answers to following questions:

- What should we do and not to do?
- What is possible and realistic?
- Do we have enough capable resources?
- What is needed (time, money, resources)?
- Is this truly sensible business-wise?
- What can we do if things change in the operating environment?

The developed Project Portfolio Selection Method is a generic, theoretical model for infrastructure sector as a whole. The developed method fills its intended purpose as an easy-to-apply link between strategic and operative decision making. Through this systematic project portfolio selection method, the infrastructure manager can determine and demonstrate the optimal project portfolio. Ensuring of adequate network condition and functionality through optimal MR&R project portfolio is also of benefit to the general allocation of resources in the economy.

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The Safety Indicator: Measuring Safety in Gas Distribution Networks

Ype C. Wijnia, René J.M. Hermkens and Jan Flonk

Abstract In the Netherlands, the safety of the gas distribution system is a hot issue. The public perception is that the safety of the system is decreasing, whilst the industry thinks that it is business as usual and that neither the number of incidents nor the consequences of incidents are larger than they used to be. Which of the claims is true? To this question there is no objective answer. First of all, no accessible database exists that contains records of all relevant incidents. Secondly, there is no agreed upon method to combine all those incidents into a simple, easy to understand indicator of safety. In this paper first the theoretical framework for such an indicator is explored. Combining this framework with actual incident data will result in a quantitative model. The paper ends with a review of the implementation of the safety indicator in the Netherlands and a short outlook for improvements.

Keywords Asset management safety, Risk assessment, Gas distribution network

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1 Introduction

The gas distribution industry in the Netherlands claims that the system is safe. To support this claim, they refer to countless numbers of NEN/EN/ISO standards, which are applied in the design and maintenance of the system. Phrased differently, they state that gas distribution is highly technical, that experts have thought about the details thoroughly, and that those experts should be trusted. As both the standards and the experts are from within the industry, the basic message is: “You can trust us, we are the experts, we know and we care”, a message that worked well for a long time.

In the current society, however, the trust asked for does not come naturally, as Shell, for example, experienced with the Brent Spar. In short, the Brent Spar was an oil storage rig in the North Sea that had to be decommissioned because its function had been replaced by pipelines. A Best Practicable Environmental Option study showed that the best way forward was a deep sea disposal. Greenpeace, however, did not agree with this study. They stated the volumes of toxic materials were much higher than Shell claimed and possessed the rig to prevent the disposal. The public assumed Greenpeace was more trustworthy than Shell and boycotted the Shell gas stations, an act which forced Shell to change course. In the aftermath, Greenpeace had to admit that they were wrong and Shell was right about the toxic content of the Brent Spar, but that did not help Shell anymore. The option of deep sea disposal was definitively out of question.

In the debate on the safety of the gas distribution system, some parallels can be drawn to this Brent Spar example. First of all, the liberalization of the Dutch energy markets in the period 1999–2004 resulted in lots of faulty invoices from the energy companies, destroying the image of a trustworthy industry. The 3 large energy companies ranked high in customer dissatisfaction (top3), according to consumer watchdog television programmes like Kassa and Radar. Secondly, because of this bad press, every gas related incident was connected to the liberalization, even if it had nothing to do with the gas distribution system. An example can be found in the explosion in The Hague (June 28, 2003), which according to the first reports was caused by gas leakage from a gas pipeline, where in fact it was caused by a leaking propane tank in the cellar. As a bonus, the public awareness of incidents was further enhanced by the rise of numerous reality TV shows and local human interest programs on the increasing number of nationwide television stations. The odds of an incident drawing attention of one of such shows were further enhanced by new technologies like the internet and cellular phones, speeding up the propagation of news. Furthermore, the Dutch safety board has published a few reports with some very alarming conclusions. As a result it seems as if the number of incidents is increasing.

In this light, it is not very surprising that the public did not take the industries claim of safety for granted and demanded additional measures. The awareness of incidents increased, and awareness drives the perception by the availability bias (Kahneman and Tversky, 1979). But is there any truth in the perception? Is the gas grid really becoming unsafe? Embarrassingly, to this question no objective answer existed. Beside the statistics on leakage and the standards, the industry did not have any facts supporting the claim of safety. On the other hand, there was no evidence for an increase in the number of incidents either, but the industry did have to prove its claim as perception was the public truth.

To issues revolving about the public perception, the best approach is not to claim expertise and declare safety, as the industry was used to (and Shell did initially with the Brent Spar), but to share knowledge and data (Shells reprise). This created an interesting challenge for the gas industry, as they did not have very much knowledge and data to share. First of all, they did not have an easy accessible database on all incidents and accidents related to the gas network. Secondly, they did not have any methods to translate such a list of incidents into an easy to understand measure of safety.

Fortunately, some experience on quality issues existed. Most gas distribution companies in the Netherlands also distribute electricity, and for the electricity grid, the major quality indicator is Customer Minutes Lost, which had been recorded for some 25 years in the so called "Nestor Enquete". If such an instrument could be developed for the safety of the gas grid, it might prove helpful in the public debate. However, discussions on safety issues are always difficult, as extensive research on this subject has shown (Slovic and Weber, 2002). Furthermore, even the existence of an objective metric for safety does not guarantee the right perception, as the reliability indicator for the electricity grid shows. The perception is that electricity is interrupted once every year for about 2 hours, where in fact it is only once every 4 years according to the 25 year statistics (Baarsma *et al.*, 2004).

Despite these potential barriers for acceptance, just knowing for sure was tempting enough for the industry. All authors were asked to take part in the development of the safety indicator. In this paper, the results of this development process will be presented. First the issues surrounding the concept of safety will be addressed, like actual figures versus disaster potential, adding different types of accidents, the value of a human life and so on. This is the value judgment section. The next step is building a conceptual model for the indicator which translates the measured inputs into a single metric. As will be demonstrated, a direct assessment of the safety consequences is not a reliable indicator for the safety of the gas distribution system. A deeper understanding of the underlying mechanism is needed. This is the conceptual part. This conceptual model will be applied to actual incident data, resulting in a quantitative estimation of the safety risk in the gas distribution system. The next part reviews the implementation of the safety indicator in the Netherlands. The paper ends with conclusions on the usefulness of the indicator.

2 Theoretical Framework

In this section the issues surrounding the debate on safety will be addressed. As will be demonstrated, much of the issues require some kind of value judgement on a certain aspect of the total safety abstraction. To structure the discussion, first focus will be on the different concepts of safety. Based on the characteristics of the safety risk and the uncertainty involved, a concept will be chosen for the indicator. Next, the issue of how to count safety incidents will be addressed. Safety incidents can have quite different consequences, like personal injuries or fatalities, but also property damage. Adding those consequences is not trivial. This non triviality holds within a consequence level (is every fatality equal), between different consequence levels (how much worse is a fatality than a serious injury) and between different values (how should a fatality be compared with financial losses, or customer minutes lost). The section ends with a valuation scheme for the different types of consequences.

2.1 The Concept of Safety

Safety can be used in a myriad of ways. Sometimes it refers to financials (this is a safe investment), sometimes to information (how safe is the internet), but in many cases it refers to personal injuries (road safety figures). Furthermore, safety can be about the actual figures (the annual fatalities on the road) or about the expected figures, the so called safety risk (*e.g.* nuclear power). Discussions on actual figures revolve around the definitions. For example, does the road safety figure only count the victims at the crash site, or are the ones in hospital afterwards included? Until how many days after the accident should those be counted? Those issues are solved relatively easy.

Discussions on safety risks are much more difficult. This is because different views exist about the essence of risk. In the first conceptual approach, risk is seen as an entity that can be objectively measured or calculated. In this view, risks are typically expressed as a product of consequence and likelihood. This objective risk is used by financial managers, safety engineers, decision analysts and so on.

The second approach challenges the assumption of objectivity, as it is not this objective risk that determines if a risk is acceptable. Some people smoke (high objective health risk) but worry in the same time about electromagnetic radiation from High Voltage Transmission Lines (health risk uncertain). Research has shown that this acceptance level is driven by so called psychometric factors which are shown below (Fischhoff *et al.*, 1987) and not only by the objective risk level. Risk is therefore very subjective.

Despite the usefulness of this subjective risk concept in risk communication, it does pose some problems for risk managers. For example, if the acceptance of a risk is determined solely by its disaster potential (like it was the case for nuclear power), no amount of risk measures can make it acceptable, as the disaster will always be thinkable. However, stopping all activities with a disaster potential might reduce the standard of living by a considerable amount, a sacrifice that few citizens are willing to make.

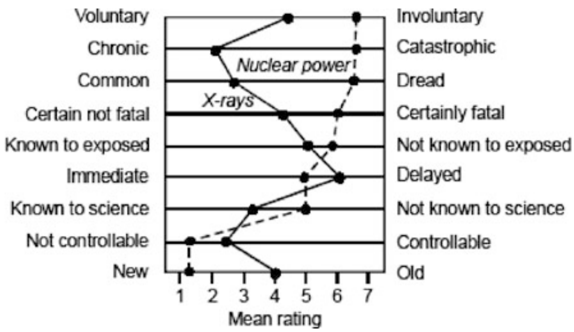

Figure 1 Psychometric factors for risk perception (source Slovic and Weber (2002) based on Fischhoff (1987))

The constructive approach tries to bridge the gap between the objective and the subjective concepts, by stating that a risk is a social construction that human beings have "invented" to deal with the dangers and uncertainties of life. The dangers and uncertainties are real, as is the response to the risk (Thomas Theorem), but the risk itself does not need to be real. This approach is advocated by the USA's National Research Council (1996). A risk can therefore be defined as *a potential problem that needs to be decided about*. This view is further supported by the value judgements needed to arrive at a risk figure (as mentioned in the introduction to this section).

Which of those concepts should be used for the safety indicator? For answering this question the classification scheme of Klinke and Renn (2002) could be used. They propose 4 different kinds of decision approaches for different risks, being rule based, risk based, discourse based and the precautionary principle. The drivers in this classification scheme are uncertainty, disaster potential and the social mobilization factor. As the uncertainty is pretty low (over 50 years of experience), the key issue is whether or not the gas distribution system has disaster potential. Natural gas can cause large explosions (*e.g.* Alpha Piper) but this is only possible at pressures well above the ones used in the gas distribution system (EGIG, 2008). Therefore, a risk based approach could be used, even though some value judgement is needed. To manage the potential for social mobilization it is best to make it a collaborative effort by the industry and the regulating bodies.

2.2 Comparing Incident Types

In order to be able to add different types of accidents into a single number, some kind of a valuation scheme is needed. This valuation scheme should answer three questions: Which are the affected values that will be taken into account? What levels of severity will be distinguished? What are the equivalent values for the different levels of severity?

Those questions are not unique for a safety indicator. On the contrary, most companies familiar with risk management use a valuation scheme in their risk

Table 1 Severity levels of personal injuries and damages

Severity level	Personal injury	Damage
6	Multiple fatalities	> 10 million euro
5	Fatality	1–10 million euro
4	Serious injury	100 k–1 M euro
3	Lost time incident	10 k–100 k euro
2	Near miss/first aid	1–10 k euro
1	Unsafe situation	< 1 k euro

matrices. What is needed would be a risk matrix without a probability axis, being a consequence scale (terminology based on ISO 31010 (2009)). In case of the safety indicator, the only question left to answer would be what affected values should be taken into account. The use of personal safety would be trivial, but was any other value needed? The obvious candidate would be property damage, a well known consequence of gas explosion. Property damage could be assessed objectively. Therefore its inclusion would not threaten the objectivity of the indicator. In Table 1 the severity of different consequences for those values is shown.

In this matrix the logarithmic character of the severity classes is very clear for the value "property damage". Quite surprisingly, this logarithmic character also holds for the personal injuries. Research shows (Heinrich, 1931; Whiting, 2001; Saldaña *et al.*, 2003; Perrow, 1984; Körvers, 2004; Nichols, 1973; Clark, 2004) that only a fraction of the near misses develops into a fatal accident. Numbers range from 300 near misses per fatality to 1000 per fatality. Even though summing injuries is quite different from adding damage (financial damage can be transferred, personal injuries cannot), if used with the mentioned scaling factors it makes sense statistically. It allows us to express any combination of safety incidents in the equivalent fatalities. The scaling factor between the values seems to be an industry standard (Shell Global Solutions, 2002). By expressing even the injuries in the monetary equivalent, all incidents can be expressed on a single scale, although this does in no way mean that a human life can be replaced by a certain amount of money. After all, no markets exist in which people sell their own lives.

3 Direct Assessment of the Safety Incidents

Now that safety has been defined, counting can start. For this the Kiwa/Gastec accident database will be used, which holds records of all network related accidents (Category I incidents) in the Netherlands dating back until 1993. In addition the reportable incidents (Category II incidents) of the Dutch safety board will be used, although they only kept records for 2004 and 2005. A Category I incident is an event in which someone got hurt or third parties property was severely damaged (> € 500,000) as a direct result of the event, whereas an Category II incident is an event in which this might have happened, or the property damages are below € 500,000. All Category II incidents require the activation of the emergency services, for example for evacuation. The total number of category I incidents was 39 over the period 1993–2003, which averages 3–4 accidents per year (van Akkeren and Wijnia, 2005). However, the variance is very large, as shown in Figure 2. The number of accidents varies between 2 and 5, but the equivalent value ranges from almost zero in 1996 to over 10 million in 2002. There is virtually no correlation between the number of incidents and the total value of the incidents, the calculated correlation is only 0,25. Besides, it is highly unlikely that the outcome is correlated to the quality of the grid. That does not vary this fast. It means a metric based on a direct assessment of the accidents does not produce a robust outcome if it is to be used for investment decisions.

This lack of robustness is a result of the low number of accidents, on average about 3 per year. As the indicator is meant to help in investment decisions, lack of robustness would be a fatal flaw. To overcome this problem, the data used to calculate the safety has to be extended. For this the incident process (Wijnia and Herder, 2004; Körvers, 2004; Morgan *et al.*, 2000) will be used to get a better understanding what those data should be.

The incident process states that value consequences do not appear out of nothing, but are a result of a chain of cause and effect. For example, excavation works (cause) can damage a service line (asset), resulting in leakage (direct consequence). The escaping gas might accumulate (appearance) in a closed space. If the gas explodes (technical effect), it might destroy property and injure people (value consequence). Barriers might exist between the different phases in the incident process. Not all excavation works damage pipelines, not all damaged pipelines

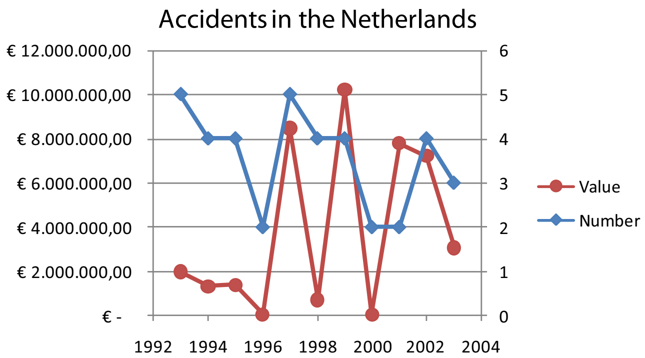

Figure 2 Gas related accidents in The Netherlands, number and equivalent value

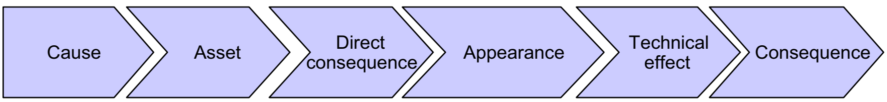

Figure 3 Incident process

leak and so on. This means that if the processes that led to the mentioned 39 accidents can be reconstructed, safety can be measured based on situations occurring earlier in the process, the so called near misses. As the number of those situations is much higher than that of real accidents, it is more likely to produce a statistically robust figure.

This incident process based approach also matches the concept of safety as a risk, as it addresses not only the real accidents, but also the potential accidents. Applying the incident process to the recorded accidents led to the conclusion that only a few combinations of causes and assets (the so called precursors) of the thousands possible ever led to a safety accident. The causes and assets are shown in the incident triangle (Figure 4).

A direct link exists between the incident process and the triangle. For each combination of asset and cause, four levels exist on which an incident can end, corresponding to the phases 3 to 6 of the incident process. The top level accidents (red, Category I) are those incidents that completed the incident process and had a significant value consequence. The second level accidents (orange, Category II) represents the incidents that showed technical effects, but did not create heavy value losses. The third level incidents (yellow) are the ones that did have a public appearance, but no immediate dangers. Finally, the bottom level (green) represents those incidents in which a cause had a direct effect on an asset. Situations in which the asset was not damaged by the cause are not considered to be incidents.

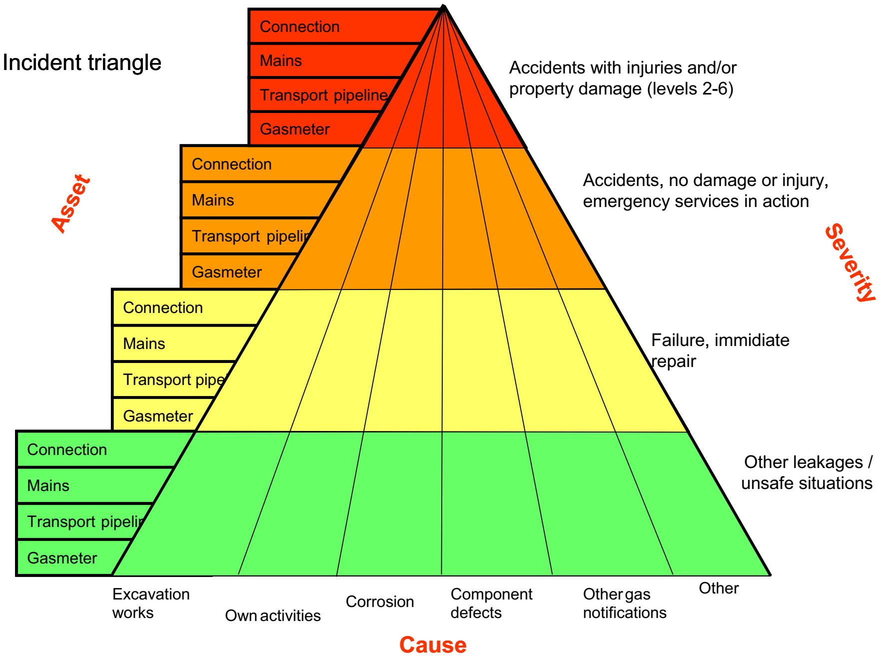

Figure 4 Incident triangle

In the incident process, a limited likelihood of propagation exists. Only a fraction of the assets will be exposed, only a fraction of causes acting on assets will create damage, only a fraction of the damage will reveal itself by escaping gas, only a fraction of the gas clouds will be within the explosion limits, and finally, not all dangerous situations will actually damage property or hurt people. Therefore, the number of incidents in the green level is much higher than the red level. This is in line with the iceberg model as described by Heinrich (1931). An indicator based on green level incidents should in theory be more reliable than an indicator that measures top level accidents. In practice, however, this does not hold, as the reliability of the indicator also depends on the quality of the incident registration, which is far better at the top level than at the bottom level. Fortunately, in the Netherlands there is Nestor-Gas, a database which holds records of incidents that required immediate action (yellow). This theoretically satisfies both the need for a robust number of incidents as the need for a reliable data source, and therefore will be used as the basis for the indicator.

With the framework presented above it is possible to calculate the total risk of a group of assets. However, absolute figures often do not mean much, as it does not tell about the size of the population from which the figures were derived. For example, road safety is always expressed as the number of fatalities per 1000 inhabitants, or per million miles. This makes it possible to compare different years within a country, or to compare different countries. Which metric is the correct one, however, depends on the question to be answered. The inhabitant based metric tells about the likelihood of an average person to die from a road accident. If the question is about the safety of road design, it is better to use the mileage based figure. For the safety indicator, both an inhabitant related metric and a network length related metric can be used. Because the issue is public safety, it seems logical to use the inhabitant based figure. So, to calculate the safety indicator for a group of assets, the total risk for that group will be divided by the number of connections in the asset group.

This concludes the theoretical framework of the safety indicator. The concept of the Safety Indicator has been defined and the methodology for adding accidents into a single number has been specified. In short, the safety indicator is a metric that is proportional to the likelihood of an individual to die from an accident in the gas distribution network. In the next section this will be quantified.

4 The Original Quantitative Model

In the previous section the concept of the safety indicator has been established, in this section the concept will be applied on the incident data. First the list of cause-asset combinations (the so called precursors) that led to an accident in the period 1993–2003 will be presented. Next, the calculation of the expected effect for a single precursor will be demonstrated. The section ends with the calculation of the expected average effects of all relevant incidents, that is, incidents that resulted in an accident in the period 1993–2003.

4.1 Relevant Precursors

In mapping the accidents on the incident process it was found that only a few combinations of assets and causes ever resulted in an accident. These combinations are presented in Table 2.

Note that the total number of accidents is higher than presented in the previous section. This is because the period of registration was longer. There were 11 years of only accidents (used in previous section), and 1,5 years of data on accidents and serious incidents. The serious incidents were extrapolated to a 12,5 year period to match the accident data.

Table 2 Accidents per precursor for the period 1993–2004

ID	Asset	Cause	Personal injury	Damage (= total number)
1	Service line	Excavation	4	47
2	Service line	Own activities	2	3
3	Service line	Soil settlement	1	1
4	Service line	Component defects	2	4
5	Service line	Corrosion	2	9
6	Service line	Other leakage	5	1
7	Mains LP[1]	Other	0	25
8	Mains LP[1]	Component defects	5	6
9	Mains LP[1]	Own activities	18	23
10	Mains LP[1]	Excavation	4	164
11	Mains LP[1]	Soil settlement	0	41
12	Mains LP[1]	Other	2	4
13	Mains LP[1]	Other leakage	1	12
14	Mains HP[1]	Component defects	0	1
15	Mains HP[1]	Corrosion	0	8
16	Mains HP[1]	Excavation	2	68
17	Mains HP[1]	Soil settlement	0	9
18	Gas Meter Installation	Component defects	4	2
19	Gas Meter Installation	Own activities	0	8
		Totals	52	436

[1] LP = Low pressure (30–100 mBar), HP = High Pressure (1–8 Bar)

4.2 Calculating the Average Incident Value

The method for calculating the average expected incident data will be demonstrated for the LP mains-excavation precursor. This is the combination with the highest number of reported incidents.

In the calculation the first step is to determine the number of reportable incidents per severity class. Then, this number of incidents per class is multiplied with

Table 3 Average incident value for excavation and LP mains precursor

	Severity levels						
	6	5	4	3	2	1	total
Number of incidents	0	0	2	44	94	28	164
Value per incident	1E+08	10000000	1000000	100000	10000	1000	
Value per level	0	0	2000000	4400000	940000	28000	7368000
Average value							44927

the value of an incident in that class and summed over the levels, to get the total value of this precursor. This total is divided by the number of reportable incidents to get the average value per reportable incident.

However, this is not the total number of incidents on this precursor, as most of the incidents do not qualify as reportable. They are near misses. Unfortunately, for the near misses, the available data spans an even shorter period. The near misses are recorded in Nestor Gas from Kiwa Gastec Technology, but that only started in 2003. The near misses incidents relating to the Mains LP – excavation precursor (some filtering within the database) were extrapolated to match a twelve and a half year period. For this, it was assumed that the quality of the grid and thus the number of incidents did not change significantly. This may sound as a bold assumption, but the involved experts all worked within the business for more than 12,5 years and felt it was a reasonable assumption. By dividing the number of reportable incidents by the number of near misses, the probability that the near miss turns into a reportable incident can be calculated. The results are shown in Table 4.

The last step was to multiply the average value of a reportable incident with the probability that a near miss turns into a reportable incident. This is the risk per near miss.

Table 4 Accident probability for incidents

			Near Misses		Reportable incidents	Probability
ID	Asset	Cause	2004	1993–2004	12½ year period	
10	Mains LP	Excavation	781	9763	164	0.0168

Table 5 Average risk per near miss

ID	Asset	Cause	Incident value	Incident probability	Near miss risk
10	Mains LP	Excavation	44927	0.0168	755

4.3 Results for All Combinations

Table 6 shows the results for all precursors.

Table 6 Risk figures for all precursors

ID	Asset	Cause	Incident value	Incident probability	Near miss risk
1	Service line	Excavation	172,660	0.00158	272
2	Service line	Own activities	1,066,667	0.00049	527
3	Service line	Soil settlement	1,010,000	0.00006	62
4	Service line	Component defects	3,052,500	0.00178	5,427
5	Service line	Corrosion	1,334,222	0.00104	1,394
6	Service line	Other leakage	60,000	0,00008	5
7	Mains LP	Other	71,200	0.00741	527
8	Mains LP	Component defects	2,538,333	0.00828	21,007
9	Mains LP	Own activities	701,435	0.01172	8,221
10	Mains LP	Excavation	44927	0.01680	755
11	Mains LP	Soil settlement	8,244	0.00576	48
12	Mains LP	Other	282,750	0.00041	116
13	Mains LP	Other leakage	102,333	0.00173	177
14	Mains HP	Component defects	1,000	0.01600	16
15	Mains HP	Corrosion	1,000	0.02286	23
16	Mains HP	Excavation works	51,721	0.15543	8,039
17	Mains HP	Soil settlement	100,000	0.01469	1,469
18	Gas Meter Installation	Component defects	2,050,500	0.00001	23
19	Gas Meter Installation	Own activities	100000	0.00137	137

Multiplying the number of incidents with the associated risk of the incidents and summing over all incident types gives the total safety risk. This is shown in Table 7.

Table 7 Total risk, connection risk and individual risk

ID	Asset	Cause	Near Miss Risk	# Near Misses	Total risk
1	Service line	Excavation	272	2,384	649,200
2	Service line	Own activities	527	486	256,000
3	Service line	Soil settlement	62	1,313	80,800
4	Service line	Component defects	5,427	180	976,800
5	Service line	Corrosion	1,394	689	960,640
6	Service line	Other leakage	5	1,010	4,800
7	Mains LP	Other	527	270	142,400
8	Mains LP	Component defects	21,007	58	1,218,400
9	Mains LP	Own activities	8,221	157	1,290,640

Table 7 (*Continued*)

ID	Asset	Cause	Near Miss Risk	# Near Misses	Total risk
10	Mains LP	Excavation	755	781	589,440
11	Mains LP	Soil settlement	48	569	27,040
12	Mains LP	Other	116	780	90,480
13	Mains LP	Other leakage	177	555	98,240
14	Mains HP	Component defects	16	5	80
15	Mains HP	Corrosion	23	28	640
16	Mains HP	Excavation	8,039	35	281,360
17	Mains HP	Soil settlement	1,469	49	72,000
18	Gas Meter Installation	Component defects	23	14,077	328,080
19	Gas Meter Installation	Own activities	137	467	64,000
	Total				7,131,040
	Per connection	**7,031,000**			**1,014**
	Per inhabitant	**16,000,000**			**0.445**

The risk per connection is about 1 euro per year, or 45 eurocents per inhabitant. In terms of equivalent fatality risk this is about once every 20 million years per inhabitant. Equivalent risk means that any financial damage is translated into a fatality risk. In the 12½ years only one fatality occurred, so the actual fatality risk was about once every 200 million years per inhabitant. Both figures are well below the once per million year limit for individual fatality risks.

5 Implementing the Safety Indicator

In the quantitative model significant differences occurred between types of incidents, that were recognized by the practitioners. The safety indicator thus had enough appeal for the network operators to adapt it. However, as the dataset was limited in size, the numbers could be wrong. The network operators thus agreed upon a trial period for the safety indicator in which it could be further tested and refined (Hermkens, 2005). They agreed to use 2006 as the trial period, after which the safety indicator would be updated. In this section, the major differences with the original model will be presented, based on "Statuut Veiligheidsindicator" (Hermkens and Pulles, 2007). "Statuut Veiligheidsindicator" describes the method by which the Safety Indicator score should be calculated, supplemented with the rules on how to add or alter parts.

5.1 The Value System

In the discussion on the safety indicator, the network operators mentioned that the social disruption (evacuations due to gas cloud) were not properly valued, as only

Table 8 Severity levels of personal injuries and damages revisited

Severity level	Personal injury	Property damage	Social disturbance	Norm value
6	Multiple fatalities	> 10 million euro	> 100000	1000000
5	Fatality	1–10 million euro	10000–100000	100000
4	Serious injury	100 k–1 M euro	1000–10000	10000
3	Lost time incident	10 k–100 k euro	100–1000	1000
2	Near miss/first aid	1–10 k euro	10–100	100
1	Unsafe situation	< 1 k euro	< 10	10

the financial consequences would be counted. The metric proposed to measure this was evacuation hours. For an incident, this is the number of people evacuated times the duration of the evacuation in hours. The metric is not perfect, as it does not capture all potential consequences (like closing down roads), but it seems to be a good proxy. Furthermore, network operators were not very comfortable in expressing everything in euros. Therefore, Consequences were translated into a dimensionless norm value. Table 8 shows the new severity levels.

However, even though the safety indicator uses a dimensionless number, in this paper the monetary equivalent will be used, to keep results comparable to the 2006 values. There is just a scaling factor between them, which is 60 euro's per norm point.

5.2 Normalization

In the original model, all risk was normalized to the number of inhabitants, based on the rationale that the safety indicator should express external risk. However, this was not very helpful in targeting investments, as it was not related to asset quality for all assets, specifically the gas mains. Network operators working in a low density area would score worse (= higher S.I. score) with the same grid quality, as they have more mains per inhabitant. That did not seem right, as a gas leakage in open field is virtually risk free, and gas leakage in cities requires evacuation. To correct this flow, mains related precursors would be normalized to the length of mains, whereas service line precursors, gas meter precursors and so on would still be normalized to the number of connections, as described in the formula below.

$$SI_b = \sum_{CRi} R_i \frac{M_{b,i}}{FA_b} + \sum_{MRi} R_i \frac{M_{b,i}}{FH_b} * \text{AML} \quad (1)$$

where:

SI_b: Safety indicator score for networp operator b

CRi: Connection related precursors

Ri: Risk per precursor *i*
$M_{b,i}$: annual number of incidents at network operator *b* for precursor *i*
FA_b: Number of connections at network operator *b*
MRi: Mains related precursors
FH_b: Length of mains at network operator *b*,
AML: Average length of mains per customer in the Netherlands

If all incidents in the Netherlands are reviewed, the number will be completely inhabitant based.

5.3 Precursors

The original model held only 19 relevant precursors that produced a real accident in the past period. Due to the expansion of the value system, the network operators felt more precursors were needed. This new list included two new causes (molestation and historical construction errors), a new asset (stations), and new combinations of existing assets and causes. Table 9 below shows the new precur-

Table 9 New precursors in the 2007 model and their annual risk

ID	Cause	Asset	Normalization	Annual CAT I risk [€]	Annual CAT II risk [€]	Total Annual Risk [€]
4*	Historical construction error*	Service line	Connections	6060	4200	10260
5*	Historical construction error*	Service line	Connections	0	4200	4200
6*	Molestation*	Service line	Connections	9000	12000	21000
11*	Corrosion/ ageing	Mains LP	Mains	0	209400	209400
13*	Historical construction error*	Mains LP	Mains	47580	33000	80580
14*	Molestation*	Mains LP	Mains	4380	2400	6780
23*	Historical construction error*	Mains HP	Mains	0	4800	4800
24*	Own activities	Mains HP	Mains	8760	13200	21960
27*	Molestation*	Gas meter	Connections	0	26400	26400
29*	Component defect	Station*	Connections	0	51000	51000
30*	Molestation*	Station*	Connections	0	102000	102000
	Total			**3,628,800**	**4,866,000**	**8,494,800**
	Total new precursors			**75,780**	**462,600**	**538,380**
	Total original precursors			**3,553,020**	**4,403,400**	**7,956,420**
	Totals in 2006			**3,847,636**	**3,283,404**	**7,131,040**

sors, their normalization, and the annual risk. At the bottom of the table, the annual risk in the new version and the new precursors is compared to the original model of 2006.

As can be seen, the new precursors did not contribute much to the category I risk, only about 2 %. This is no surprise, as if they would have caused an category I incident, they would have been in the original set. In the category II area the contribution is more substantial (about 14 %) which is enough to justify their inclusion. On the total risk the contribution is 8 %, as category I and II risk are comparable in size. The risk of the old precursors increased slightly (from 7.1 M to 8 M), though the risk in category I (the real accidents) slightly decreased. The increase is probably due to the new metric, which was added to address the issue of evacuation in category II incidents, the decrease is probably just the inherent variation in the annual incident value (see Figure 2).

5.4 Actual Implementation

After the revision of the method, the network operators started using the Safety Indicator for measuring their safety performance. However, during this implementation large differences occurred between network operators, that were hard to explain based on the perceived quality of the grid. Grids, constructed with the same materials, operated and inspected on the same code of practice, in a similar area, sometimes scored completely different in terms of the safety indicator. This was already mentioned in the first publications on the safety indicator (Hermkens, 2005; Wijnia and Hermkens, 2006). Potential explanations are differences in registration culture, or even just random variance. This sheds some doubts on the applicability of the safety indicator in the regulation of the distribution business in the Netherlands. If the safety score is essentially a random metric (despite efforts to make it more stable), it is not useful as a steering guide. And if it is differences in registration culture, the floor is open for manipulation. For this reason, the results per network operator have not been released to the public. In a report to the regulator KIWA (Pulles and van Eekelen, 2009) mentions that the safety indicator is only useful for regulation if the problems in incident registration are solved, and if the safety culture in organizations is mature enough. The network operators are currently working on a more consistent way of recording incidents, by standardization and stringent auditing. This might result in a certification scheme similar as that applied for registration of electrical outages (NESTOR E).

6 Conclusions

It is possible to link the accidents occurring in the grid to a limited number of precursors, that could be used to measure the safety of a system based on the number of occurrences of minor incidents. The benefit is that there are many more small incidents than large ones, and that and increase of small incidents would occur before the increase in accidents, thus providing the network operators time to respond. However, this is only possible if the registration of the minor incidents is reasonably reliable, as the benefit of having more data available might be offset by the diminishing quality of the data. This was considered in the original version of the indicator, and incidents were limited to incidents serious enough to make a phonecall about. In the test run of the indicator, some amendments were made, like a new value, other normalization and new precursors, but these additions did not alter the method much, nor the measured risk in the system.

However, despite the considerations on the data quality, in implementing the safety indicator this proved to be the showstopper. The safety indicator showed large differences between regional network operators with very comparable grids, which are probably due to differences in registration. For this reason, results on the individual network operators have not been published yet, and the Safety indicator is not adopted into regulation. For any progression of the safety indicator, the data quality issue has to be sorted. Future steps might be certification of the registration process, as happened in registration of electrical outages in the Netherlands.

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Part VI
Scope (Human Dimensions)

Behavioural Preferences for Engineering Asset Management

Joe E. Amadi-Echendu

Abstract The essence of managing engineered physical assets that form our built environment is to provide benefits to satisfy the continuum of constraints imposed by rapidly changing business strategy, economy, ergonomics, operational and technical integrity, and regulatory compliance. Innovative approaches to enhance and sustain the profile of values required from these assets demands a shift in thinking styles, cognitive and mental processing modes, and the attitudes of engineering professionals if they are to be effective in asset management occupations. This paper describes the results of a 2005 survey of 190 practicing engineers to ascertain what thinking styles should determine behavioural preferences for managers of engineered physical assets. The study confirms other results from cognitive theory and psychology, highlighting the top ten thinking styles as ranked by survey respondents. The paper provides a strategic view of engineering asset management (EAM) within the context of innovation, with particular focus on behavioural alignment towards the modern era of innovation, knowledge and learning economy.

Keywords Asset Management, Thinking Styles, Behavioural Preferences, Innovation

1 Introduction

The main elements of our built environment are engineered physical assets which include, for example, airports, seaports, buildings, manufacturing and process plants, power stations, road, railway, telecommunications and utility networks and

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systems, oil, gas and mining facilities. From an accounting and financial management point-of-view, these assets generally fall into four broad categories – (i) plant and equipment, (ii) buildings and infrastructure, (iii) furniture and fittings, and (iv) information technology. Overall management of engineered physical assets covers (i) acquisition, (ii) ownership, (iii) control, and (iv) utilisation. The essence of management is to ensure that the value profile defined by all stakeholders is enhanced in a sustainable manner throughout the asset's life. The value that an asset can provide may represent a combination of economic, social and environmental benefits depending on the preference and composition of the stakeholders. Acquisition, ownership, control and utilisation are high level management processes necessary to satisfy the continuum of constraints imposed by business strategy, economy, ergonomics, operational and technical integrity, and regulatory compliance (Amadi-Echendu, 2005).

From a systems viewpoint, the life of an engineered physical asset may be described in terms of the phases and stages (Amadi-Echendu, 2003) illustrated in Figure 1. The two broad stages of capital development and business operations may be subdivided into four phases and further resolved into dominant activity periods. Successful management of the asset depends on innovative and synergistic integration of a wide range of 'hard' and 'soft' skills through the life-cycle phases and stages. These skills include, for example, financial accounting, com-

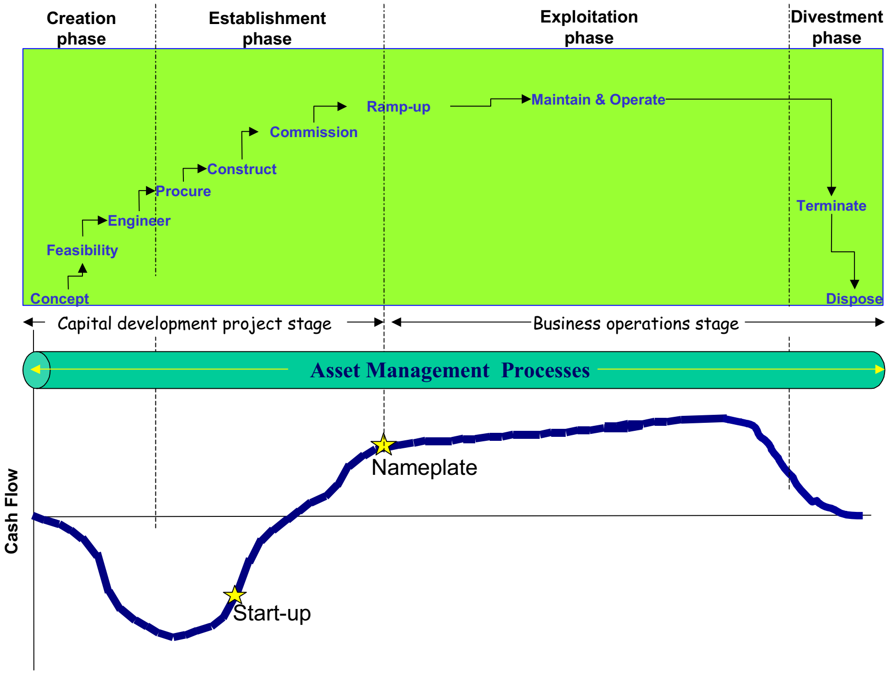

Figure 1 Life-cycle stages and phases of an engineered physical asset

munications, engineering and technology disciplines. These necessary skills are vested in humans, therefore, it can be assumed that primordial human behavioural preferences or attitudes really determine asset management effectiveness.

This paper examines the behavioural preferences of engineering professionals as physical asset managers within the context of innovation, knowledge and learning economy. In addition to managing the value profile defined by stakeholders at the various levels of the asset hierarchy, managers also have the responsibility to manage process innovation associated with, as well as technological innovation embedded in, engineered physical assets that form our built environment.

2 Thinking Styles and Behavioural Preferences

With the advent of the innovation, knowledge and learning economy era, knowledge has become the primary means of production. Knowledge creation, diffusion, and transformation are fundamental to innovative management practices. With regard to engineered physical assets, engineers and technical professionals are prime technical knowledge resources and they strongly influence the knowledge base, skills, as well as the motivation, roles and responsibilities for the management of these assets. Thus engineers and technical professionals form an important *ethnic* group of the innovation paradigm, such that their behavioural preferences or attitudes are not only implicit, but also vital in the processes involved in the management of engineered physical assets (Amadi-Echendu, 2007).

From the point-of-view of psychology, it is intuitive to assume that behavioural preferences are external manifestations of internal thinking styles of individuals or groups, and the corollary is that thinking styles precede or determine attitudes and behavioural preferences. Maccoby (1994) applied the context of cognitive development theory to discern four types of management thinking styles – *analyser*, *energiser*, *synthesiser*, and *humaniser*. He further argued that successful ‘information age organisations’ require managers with higher preference for synthesising and humanising thinking styles. Using a more rigorous approach, Herrmann’s Brain Dominance Instrument (HBDI) (Herrmann, 1996) articulates twenty thinking styles, classifying them into four quadrants of the Whole Brain Model. Herrmann’s approach as summarised in Figure 2 shows a proforma of ‘200,000 profiles of the mentality of 200 representative occupations’.

The question that arises from Figure 2 is – what should be the profile for the manager of engineered physical assets? What thinking styles should predominate so that appropriate behavioural preferences manifest into attitudes which, when combined with knowledge and skills, provide for innovative and effective management of physical assets? The paradox is tension between conventional thinking styles of engineering professionals and the requirement for innovative behavioural preferences that encompass a much wider range of cognitive and mental processing modes. The innovation, knowledge and learning economy era is characterised by continuous acquisition of new skills, with the corresponding rapid conversion

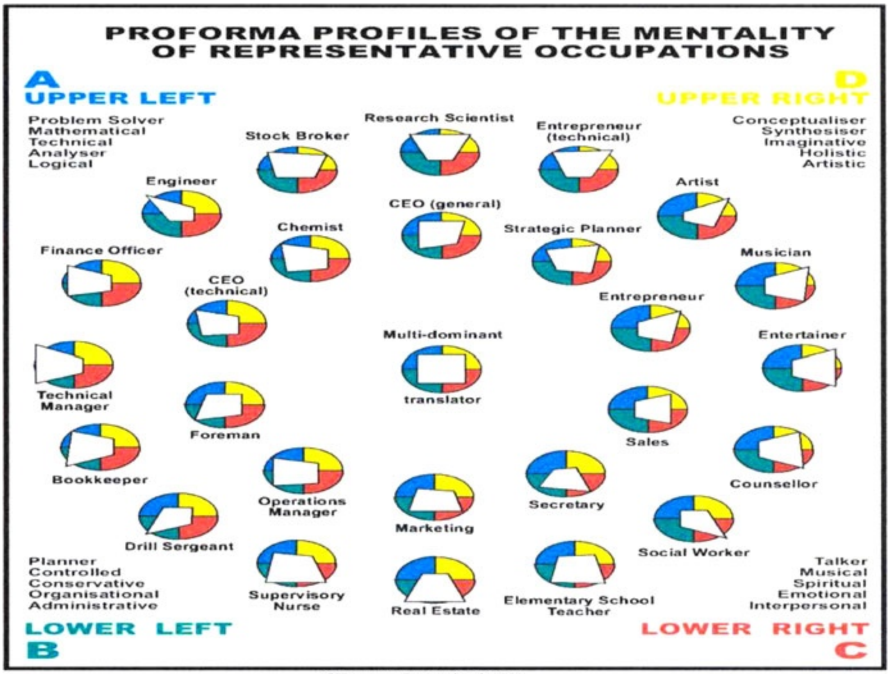

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Figure 2 HBDI thinking style profiles of representative occupations

and application of ideas and knowhow towards generating the value profile defined by multifarious stakeholders. A major challenge therefore is that, for the respective life-cycle phases/stages and organisational forms associated with the physical asset base, a manager of engineered physical assets has to continuously and rapidly acquire new knowledge, adapt to and/or adopt effective cognitive processing modes within the vagaries of the innovation paradigm.

3 Research

3.1 Survey

The presentation here is an attempt to identify the dominant thinking styles for EAM within the context of the innovation economy paradigm. Whilst on a speaking tour of Australia, the author requested that attendees complete a one-page questionnaire at the start of the meeting. The audience mostly consisted of practising engineers with primary responsibility for the maintenance of physical assets. Considering that the engineering professional of the innovation generation is a knowledge worker, respondents were asked to rank the twenty thinking styles described in the HBDI on a five-point scale, ranging from 'not important (score = 1)' to 'extremely important (score = 5)'. All respondents completed the questionnaire within five minutes. The results are presented here in a manner consistent with the four-quadrant HBDI delineation of Whole Brain Model and dominant thinking styles. For brevity, the focus is on the summarised opinions expressed in the feedback, bearing in mind that the data is non-probablistic, that is, the respondents do not form a statistically representative sample of the entire population of engineering professionals.

3.2 Results

A total of 190 respondents participated in the survey. Table 1 shows the number of respondents who indicated a ranking for each of the twenty thinking styles. Questionnaire feedback in which a ranking was not indicated for more than fifteen thinking styles was regarded as incomplete and not included in the data set.

The relative importance of thinking styles as indicated by the respondents is shown in Figure 3 in a manner consistent with the HBDI delineation according to the Whole Brain Model. This picture shows that a discernible number of respondents did not attach any importance to artistic (9.7 %), emotional (10.7 %), conservative (21.5 %), spiritual (33 %) and musical (46 %) thinking styles. This could be interpreted to mean that as much as 46 % of respondents suggest that musical thinking style should not influence the behavioural preference of the *Engineering Asset Manager* of the innovation dispensation.

Table 1 Number of respondents indicating a ranking for thinking styles

HBDI Whole Brain Model Delineation of Thinking Styles	HBDI Thinking Styles	Number of respondents indicating a ranking for each Thinking Style
Quadrant D, Upper Right, Cerebral	Imaginative	187
	Synthesiser	183
	Artistic	184
	Holistic	181
	Conceptualizer	183
Quadrant C, Lower Right, Limbic	Interpersonal	185
	Emotional	186
	Musical	185
	Spiritual	185
	Talker	186
Quadrant B, Lower Left, Limbic	Controlled	185
	Conservative	186
	Planner	187
	Organisational	186
	Administrative	186
Quadrant A, Upper Left, Cerebral	Logical	186
	Analyser	186
	Mathematical	186
	Technical	184
	Problem Solver	187

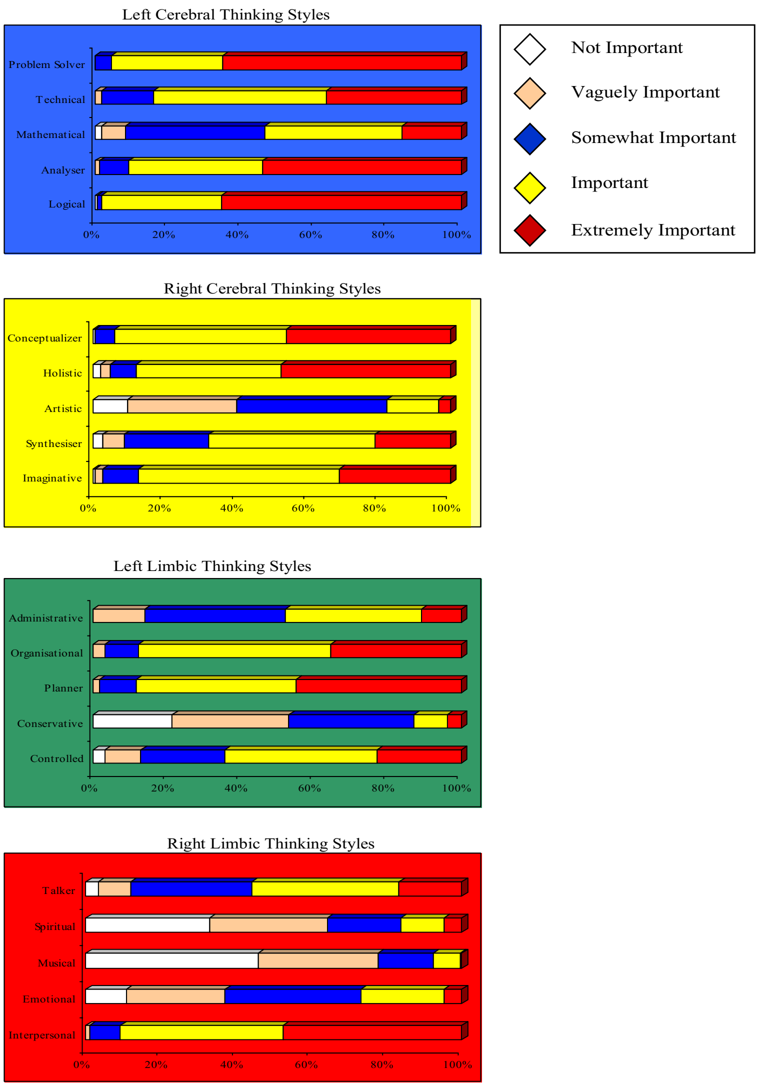


Figure 3 Respondent ranking of thinking styles

The top ten thinking styles ranked as *extremely important* by the respondents are shown in Figure 4 to include:

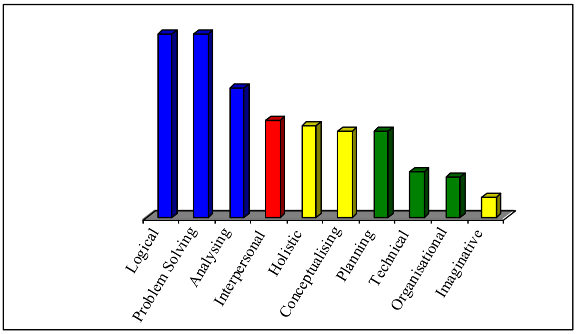
(i) **Logical** – Nearly 66 % of respondents indicate that the 'ability to reason deductively from what has gone before' is extremely important.

(ii) **Problem solving** – Again, 65 % of respondents indicate that the 'ability to find solutions to difficult problems by reasoning' is extremely important.

(iii) **Analysing** – 54 % of respondents indicate that the 'ability to break up ideas into parts and examining them to see how they fit together' is extremely important.

(iv) **Interpersonal** – Nearly 48 % of respondents indicate that the 'ability to easily develop and maintain meaningful and pleasant relationships with many different kinds of people' is extremely important.
(v) **Holistic** – About 47 % of respondents indicate that the 'ability to perceive and understand the 'big picture' without dwelling on individual elements' is extremely important.
(vi) **Conceptualisng** – 46 % of respondents indicate that the 'ability to conceive thoughts and ideas, to generalise abstract ideas from specific instances' is extremely important.
(vii) **Planning** – 45 % of respondents indicate that the 'ability to formulate methods to achieve a desired end in advance of taking actions to implement' is extremely important.
(viii) **Technical** – 37 % of respondents indicate that the 'ability to understand and apply engineering and scientific knowledge' is extremely important.
(ix) **Organisational** – 35 % of respondents indicate that the 'ability to arrange people, concepts, ideas, etc into coherent relationships with each other' is extremely important.
(x) **Imaginative** – 31 % of respondents indicate that the 'ability to form mental images of things not immediately available to the senses or never wholly perceived in reality, ability to confront and deal with a problem in a new way' is extremely important.

Respondent Feedback : Top Ten Extremely Important Thinking Styles



Thinking Style	% of Respondents indicating Extremely Important
Logical	65.5%
Problem Solving	65.2%
Analysing	54.3%
Interpersonal	47.5%
Holistic	47.2%
Conceptualising	46.0%
Planning	45.0%
Technical	37.0%
Organisational	35.4%
Imaginative	31.0%

Figure 4 Respondents ranking of top ten 'extremely important' thinking styles

4 Summary

Six of the top ten extremely important thinking styles belong to the left-brain quadrants, hence validating the HBDI proforma profile of engineering and related occupations. This is not surprising since all the respondents had an engineering background and technical orientation. What is more interesting is the fact that four of the top ten extremely important thinking styles belong to the right-brain quadrants, with three in the upper right mental processing mode. This result also supports the increased shift in emphasis towards behavioural preferences generally referred to as 'soft' skills. In comparing the respondent feedback with the HBDI proforma profiles of occupations shown earlier in Figure 2, the suggestion is that the profile for the *Engineering Asset Manager* should lie between that shown for technical chief executive office (CEO) and chemist. The ramification is that right-brained mental processing modes should be combined with scientific knowledge and technical skills to effectively manage the various life-cycle phases, stages and organisational activities associated with built environment assets.

The essence of managing physical assets that form our built environment is to provide benefits to satisfy the continuum of constraints imposed by rapidly changing financial, social and environmental compliance requirements. Innovative approaches to enhance and sustain the profile of values required from these assets demands a shift in the behavioural preferences or attitudes of engineering professionals in asset management occupations. This implies that engineering professionals in asset management occupations need to adapt to new thinking styles, and adopt effective cognitive and mental processing modes. Whilst assuming that thinking styles manifest in attitudes, this paper has described the results of a 2005 survey of 190 practicing engineers to ascertain what thinking styles should determine behavioural preferences of engineering-oriented managers of built environment assets of the innovation generation. The study confirms other results from cognitive theory and psychology, highlighting the top ten thinking styles as ranked by survey respondents. It is remarkable and worth emphasizing that interpersonal, holistic, imaginative and conceptual thinking all rank very highly in the attitude required of engineering professionals in asset management situations.

Although the sample size presents a limitation in terms of generalisation, however, the study has implications for education, research, training and leadership development of an appropriate cadre of innovative managers of engineered physical assets. Whilst the study points towards a strategic view of EAM within the context of human dimensions, however, the question still remains as to how to adapt and align traditional behavioural preferences towards the new mental processing modes and attitudes demanded by the era of innovation, knowledge and learning economy. The human dimensions ramifications even extend to issues of organisational development, that is, mindful of the need for synergistic integration of multidisciplinary knowledge domains and skills, for example, what forms of new organisational structures will be most appropriate for effective management of engineered physical assets of the future?

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The Development of Strategic Asset Management Leaders Through Postgraduate Education

David Thorpe

Abstract The modern engineering asset manager is required to develop, operate and maintain engineering assets economically and in a socially responsible and sustainable manner. Key issues confronting the asset manager of today include taking a strategic life cycle approach to asset management, meeting stakeholder requirements and minimising risks. To achieve this, it is necessary to understand asset life cycle issues including economic analysis and sustainability, be aware of social impacts, understand technological risks and work at the cutting edge of technology. While undergraduate engineering programs can meet this need to some extent, postgraduate education is often the best approach for learning the principles of strategic life cycle asset management. This paper discusses one such example of postgraduate engineering education, the Master of Engineering, offered by the Faculty of Engineering and Surveying at the University of Southern Queensland. Topics discussed include the rationale for this type of study program, how it addresses the needs of life cycle asset management including risk and innovation management, its approach to learning, and its role in developing strategic asset management leaders. The future role of programs of this type in developing leading asset management professionals is also discussed.

Keywords Asset management leadership, Education and training, Strategic asset management

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1 Introduction

The engineering asset manager of today faces many challenges, and requires not only engineering skills, but also those of strategic management, operational management, environmental management, economics, and a range of other professional disciplines.

One of the challenges in engineering asset management (EAM) is the requirement to manage, at both strategic and operational level, assets throughout their life cycle to the satisfaction of a range of stakeholders. These assets can range from infrastructure assets like major physical installations and distribution networks, to fixed and mobile plant and equipment such as manufacturing installations and transportation equipment, through to communication networks.

Further challenges include the need to achieve social and environmental goals as well as the more traditional technical and economic goals, the importance of managing risk, and the need to use the best available technologies in the asset management process.

The modern engineering asset manager therefore needs to be a highly skilled person that can plan, develop, operate, maintain and retire a range of engineering assets, economically and in a socially responsible and sustainable manner, to the satisfaction of a range of stakeholders.

While undergraduate engineering degree programs can develop some asset management skills, their content of necessity concentrates in technical engineering, and therefore they provide limited training in the wider skills required for effective modern EAM. Postgraduate programs aimed at providing sound engineering management training in asset management and related concepts like sustainable development, risk management and technological innovation can offer the additional academic development needed by today's integrated strategic asset managers.

It has been in this environment that the University of Southern Queensland has developed the Master of Engineering (MENC) (USQ, 2010). This program commenced as the Master of Technology Management, which was a 12 course program that, as well as taking graduate engineering and technology management education beyond that at undergraduate level, aimed to develop the skills needed to compete and be successful in the complex world of technology, engineering and entrepreneurship in which the advanced engineering and technological manager will work. This program was later replaced by the eight course Master of Engineering Management, which in 2009 developed into the Master of Engineering.

The Master of Technology program was developed out of the recognition that a large number of engineers and other practicing professionals aspire to managerial positions in a technology or engineering environment. It was also recognised that qualified managers of technology play a crucial role in technologically advanced as well as developing societies. Thus it was reasonable to expect that many of these professionals would want to achieve postgraduate qualification in a coursework-based management-focused program (USQ, 2002).

This paper discusses the way in which the Master of Engineering, and in particular its Engineering Management Major and to a lesser extent its Engineering Project Management Major, is aimed at playing a key role in developing strategic asset managers through an integrated program that teaches not only asset management but also explores related topics like technological management and its impact, sustainable development, management of technological risk, innovation management, project management, facilities management and other key technology management areas. Initially, the paper discusses the context and issues in strategic asset management. It then explores the options for strategic asset management education, discusses the Master of Engineering program and the approaches it uses for teaching, evaluates what it has achieved so far and explores the challenges of the future.

2 Context of Strategic Asset Management

In developing the strategic asset manager, it is firstly necessary to establish the context of the asset management process. This includes developing an understanding of the types of assets being managed and what the term 'asset management' means in the EAM environment. These definitions then form the basis for developing the concept of the asset life cycle and the goals that need to be met by the asset manager. This is followed by an evaluation of the challenges faced by asset managers in the delivery of their responsibilities.

While an asset may be defined in a financial sense to mean any item of economic value owned by an individual or corporation, a different definition is needed for an engineering asset, which for the purpose of developing the strategic asset manager may be defined as the installations, plant, equipment, knowledge, resources and related items that support the community, commerce and industry. Such a definition is of necessity wide, but is required in order that the engineering asset manager not only manages plant, equipment and related items but also resources, including physical resources, information technology and communication installations and software, and human resources.

Like 'asset', the term 'asset management' can be also defined in several ways. One definition of asset management used in highway engineering is 'a systematic process of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organised and flexible approach to making the decisions necessary to achieve the public's expectations' (Pakkala, 2002). While not all engineering assets will have the public as asset owner or user, this definition can form the basis of a more general description of many engineering assets by substituting the words 'expectations of asset owners and users' for the words 'public's expectations.'

The life cycle asset management process breaks into the four main streams of identification of the need for the asset; provision of the asset (including its ongoing maintenance and rehabilitation to suit continuing needs); operation of the asset; and disposal of the asset (Austroads, 2006). In performing these tasks, the asset manager is required to not only use sound engineering principles, but also sound business practice and an economic rationale. Modern asset managers also need to take account of social and environmental issues. The strategic asset management leader also needs to look to the future, and therefore as well as applying sound budgeting and engineering management practices is required to consider both short term and long term goals and objectives.

Engineering assets typically serve a number of communities of interest (or stakeholders), and are usually closely linked with the environment of which they are part (Thorpe, 1998). For example, physical infrastructure assets are founded on the natural environment and support the economic environment and social environment. They serve the communities of interest of the owner and/or manager, user and the community external to the asset. A road, for example, is constructed on a natural foundation and is part of the wider environment; supports the economic environment represented by the transportation industry; and serves the road owner, vehicle drivers and other users (such as cyclists and pedestrians), the local community external to the road (such as residents or owners of the properties passed by the road and the wider community whose products they transport). A similar discussion can be developed for other fixed (in location) assets like power stations, water supply and sewerage facilities, and distribution systems. This thinking can be extended to other assets, such as mobile plant and equipment, which although not fixed in location are at one time located in a particular environment and serve a number of stakeholders.

The stakeholders each have different requirements of the asset manager, who therefore has to meet a number of goals to meet these requirements, and has the task of optimising the combination of these goals in order that maximum effectiveness and efficiency can be obtained from the asset.

Thus, users expect the asset to have the ability to provide an adequate level of service at the required level of demand; and meet a required level functional serviceability (*i.e.*, condition). Owners and managers require the asset to deliver the optimum service life consistent with the requirements of stakeholders; deliver maximum benefit over the life cycle consistent with other requirements; and operate at minimum life cycle cost, again consistent with other requirements.

The local external community, which will have relatively close geographical proximity to the asset, will require the asset to satisfy external requirements of interest to that community (for example, environmental and political requirements) to a level acceptable to the community. Finally, the wider community, which often funds the asset (for example, taxpayers funding a community asset, financiers funding an industrial asset), will require the asset to deliver a whole of life performance (the integral of functional serviceability) acceptable to its stakeholders.

3 Trends and Challenges in Strategic Asset Management

While asset managers are required to meet (and optimise) the requirements of key stakeholders, they are also required to meet other requirements.

One of these – sustainability – follows from the need to meet social and environmental requirements of the wider community. It is part of the core of sound strategic asset management principles that ensure that assets not only meet the requirements of today's society but also the requirements of society into the future. This needs to be considered in practical terms. Johnston (2003) sees sustainability as an ideal state of long-term social, economic and ecological stability, a target towards which we strive, rather than one we expect to reach. Thus, the process of striving towards sustainability, while still pursuing production goals and overall economic growth would be commonly referred to as sustainable development.

Sustainability has been identified as a desirable quality in engineering leadership competencies (Seek, 2005). It has also been recognised as an important issue for research organisations, such as the Cooperative Research Centre for Construction Innovation, which developed a report on sustainable subdivisions (Miller and Ambrose, 2005) and placed considerable effort into the development of a life cycle assessment tools to evaluate eco-efficiency of buildings from CAD drawings (CRC for Construction Innovation, 2005). The social and environmental responsibilities of engineers have also been adopted by Engineers Australia, which in its Code of Ethics has stated that its members 'shall, where relevant, take reasonable steps to inform themselves, their clients and employers, of the social, environmental, economic and other possible consequences which may arise from their actions' (Engineers Australia, 2000).

A common outcome of the discussion on sustainability is that to achieve a sustainable future, any development and management project we undertake needs to carefully consider the needs of future generations, the ability of natural resources to continue to meet the needs of those generations, and what we can do to manage those natural resources to ensure that this occurs. This argument can be extended to include all aspects of human endeavour. Thus, when we consider a sustainable future, we should be considering (in addition to environmental sustainability) concepts like social sustainability, economic sustainability, technological sustainability and sustainability in other fields of human endeavour and nature. Examples include a sustainable and cohesive society, the maintenance of historical artefacts, the ability to economically support the world's population and management of technological knowledge. All of these are important to the sustainability oriented asset manager.

Clearly, the engineering asset manager has a significant role in ensuring that assets are planned, designed, developed, operated, maintained, rehabilitated, retired and disposed of in a socially and environmentally responsible manner. Thus, there is a responsibility to investigate and resolve social issues and conduct environmental impact assessments over the whole asset life cycle. An example of this is the use of modern asset management materials. Fibre composites, for example, are now becoming used as a strong lightweight construction material, and are also used in applications like bridge asset management to replace timber, which is in quite short supply. While they clearly deliver benefits from this aspect of sustainability, there is also potential concern with their disposal when the structure of which they are part has come to the end of its useful life. Will such materials be disposed of easily? Should consideration be given to making them biodegradable at the end of their useful life? What other issues will arise? Such considerations require careful thought by the strategic asset manager.

A second key issue for asset managers is risk management. Risk is defined by the Australian/New Zealand Standard for Risk Management as a 'systematic process to understand the nature of and to deduce the level of risk' and risk management as 'the culture, processes and structures that are directed towards realizing potential opportunities whilst managing adverse effects' (Standards Australia, Standards New Zealand, 2004a). Risk so defined can lead to both positive and negative outcomes.

The process of risk management as described in the standard consists of seven main components: communicate and consult, establish the context, identify risks, analyse risks, evaluate risks, treat risks, and monitor and review (Standards Australia, Standards New Zealand, 2004b). It is important to recognise the important role that the first component – communication and consultation – has in this process.

An example of the way that risk management has become more important in asset management is legal risk. One instance of this is the 2001 abolition by the High Court of Australia of the 'highway rule', which protected road authorities from action being brought against them due to failure to maintain a road, as part of the common law of Australia (Brodie vs Singleton Shire Council, 2001). This has lent impetus to the management of risk in civil engineering asset management and of the development of good asset and maintenance management systems.

In the case of infrastructure management, the risk management process is described in the 2002 version of the International Infrastructure Management Manual. This process is based on the consequences of failure of the asset (for example, repair cost, loss of income, loss of life, injury) in terms of a business risk exposure model based on consequences and likelihood. The model developed in this manual has a strategic focus – 'should do' work that has to be completed within the next five years, 'could do' work that could possibly be deferred for another five years, and 'defer' work that could be deferred for a further five years. It also develops risk reduction strategies, such as risk reduction through capital or maintenance expenditure, emergency response plans, acceptance of some risk and carrying the consequential loss, and insurance against the consequential loss (NAMS/IPWEA, 2002).

Other challenges for the strategic asset manager include the importance of seeking and adopting innovative practices in the asset management process, balancing short-term and long-term asset management requirements, quality management; systems management; project management; management of resources; and the challenges posed by globalisation. In summary, the asset manager is required to maximise life cycle economic return on the asset while optimising stakeholder goals, achieve social and environmental requirements, and to effectively plan and manage the asset management process to best achieve these results.

4 The Requirement for Post Graduate Engineering Asset Management Education

The above discussion has outlined a number of the challenges faced by the strategic asset manager, including the need to meet the requirements of various communities, address sustainability and other social and environmental issues, manage risk, be innovative, plan and manage the asset management process for the benefits of key stakeholders, and optimise the achievement over the life of the asset of a range of goals, some of which (such as the requirement to satisfy different stakeholders) can be conflicting.

A key requirement is that the asset requires to be managed to meet these goals over the whole of its life, from early planning until retirement. The author has demonstrated the complexity of this task over the life cycle of physical infrastructure (Thorpe, 1998). Other authors, such as Schuman and Brent (Schuman and Brent, 2005), have similarly demonstrated that it is similarly important to undertake asset life cycle management for assets in the process industry.

With respect to the complexity of the engineering asset manager's task, Amadi-Echendu *et al.* (2007) have demonstrated that a broader consensus interpretation of the requirements of EAM include spatial, time, measurement, statistical and organisation generalities. This may be interpreted to mean that EAM extends across all physical assets (including human resources) and time; that measurements include the economic and social dimension as well as the physical dimension; that risk should be taken into account; and that it occurs at all levels of the organisation. The authors contend that the implications of these generalities are that EAM requires skills input from a wide range of disciplines, that its decisions extend from operational and tactical aspects of asset management to strategic aspects and that its human dimension requires the use of both qualitative and quantitative analysis. Amadi-Echendu (Amadi-Echendu, 2006) has also shown that engineering professionals engaged in effectively managing physical assets subject to the continuum of constraints imposed by a rapidly changing business and regulatory environment need to adapt to new thinking styles and adopt effective cognitive and mental processes modes.

Given the complexity of the task of strategic life cycle management of engineering assets, it is important that the engineering asset manager be given a solid theoretical grounding in the skills required to manage the assets effectively and efficiently. From the point of view of the manager of engineering assets, this is best undertaken through specialised study. In particular, the strategic asset manager needs to understand the challenges in asset management, and understand how to focus on the larger picture as well as operational issues such as asset condition monitoring and maintenance.

Many engineering undergraduate courses now include courses (or subjects) that address engineering management and the responsibility of the engineer in society, and so partially meet the requirements of the education of the asset manager. This may commence with a compulsory first level course addressing basic engineering principles, followed by courses later in the curriculum that deal with concepts like the engineer and society, and engineering management.

The University of Southern Queensland (USQ), for example, offers the course Introduction to Engineering and Spatial Science Applications, typically taken during the first year of the engineering curriculum, which introduces students to engineering and spatial science applications to provide them with an understanding of the fundamental concepts of engineering science and develop in them the basic skills needed to effectively study in their discipline. Students are taught the nature of engineering, fundamentals of engineering science and their application; and are exposed to a range of professional skills (USQ, 2010).

For all Bachelor level engineering students, this course is followed by a course in Technology, Sustainability and Society, which is typically taken in the second year of the engineer's studies and builds on this foundation. It deals at an introductory level with a range of key topics such as the history of technology, sustainability, environmental impact assessment, politics, economics, models of society, social impacts of engineering, the legal framework and engineering management. A third level course, Engineering Management, then teaches management principles and practice for engineers and further develops the engineering student's appreciation of the social environment within which they will practice. A fourth level course taken by students in some engineering disciplines, Engineering Management Science, provides the engineer with a number of mathematical management tools, completes the undergraduate engineering management curriculum (USQ, 2010).

These courses, and similar courses at other educational institutions, provide the engineering undergraduate with a foundation in engineering and technology management and their social and environmental responsibilities. This can however only be partially achieved in engineering undergraduate curriculum courses, as the large number of courses required to be studied by the undergraduate engineering student and the need to focus in undergraduate study on technical competence mean that there are limitations with developing the skills of effective and efficient asset management during the education of undergraduate engineers. For example, in the USQ engineering curriculum, the courses described above comprise only about 12.5 per cent of the undergraduate curriculum (USQ, 2010).

Further dilution of the education of undergraduate engineers in the strategic management of assets occurs because the types of courses discussed above (with the exception of Engineering Management Science) are primarily verbally based rather than mathematically based, and therefore a number of students (particularly international students whose first language is not English) can find these courses difficult to understand, and do not achieve as well in some of them as they would in technically based courses. As an example, the Technology, Sustainability and Society course typically has a drop-out rate of about 15 to 25 per cent. While this course has been improved over the years to improve its acceptability to students and improve results, it is still not fully accepted by undergraduate engineering students, with a recent study showing that only 54 per cent of respondents to a survey saw a clear relationship between this course and their professional career pathway, and 19 per cent did not see such a connection (Thorpe, 2009b).

The other main issue with undergraduate courses are that although they address issues such as social and environmental responsibility, economics, legal issues and management principles and practices, they of necessity cover these areas only at an introductory level and do not really train engineers in the skills required to strategically manage assets. In addition, there tends not to be a very high emphasis on specific training in asset management and maintenance, and in key skill areas like risk management and innovation management.

While some universities do offer some advanced undergraduate courses in asset management, it is contended that undergraduate education achieves a basic understanding of management principles in graduate engineers, but falls short of developing the engineering management skills required by practising professionals. Because of this limitation, the best opportunity of providing engineers with the skills of effective and efficient life cycle strategic asset management is through dedicated postgraduate engineering education.

It is therefore necessary to develop the asset management skills discussed in this section through postgraduate courses. Such courses must be directly applicable to practicing professionals, and must been seen as a real asset to the corporations and institutions employing them.

5 Postgraduate Engineering Asset Management Study Programs

The preceding discussion demonstrates that engineering asset managers require not only sound engineering knowledge, but must also possess the necessary skills to have a sustainable whole of life view of the assets they manage; optimise the achievement of a range of life cycle asset management goals to meet the shared requirements of stakeholders in these assets; appreciate social and environmental concepts; and understand broader management concepts including those of economics, risk management, systems management, project management and human resources management.

In recognition of the desirability of developing these and other engineering management skills, a number of universities have developed study programs focused on the development of asset management skills.

For example, the University of Wollongong offers an eight subject Master of Engineering Asset Management, based in the Mechanical Engineering discipline, that teaches subjects in areas such as modelling of engineering systems, financial management, project implementation and outsourcing, life-cycle and risk management, maintenance requirements analysis, systems reliability engineering, plus either the selection of two elective subjects or a dissertation. The stated objective of this program is ‘to ensure continuous improvement in the strategic and tactical response of organisations and their managers to the management of infrastructure assets.' It aims to provide the knowledge for cost-effective asset organisation and management of engineering assets, and uses a strategic framework from which students progressively address problems in designing and managing assets, and learn concepts and techniques through evaluating potential solutions to challenges faced by organisations (University of Wollongong, 2010).

The Faculty of Engineering, Computing and Mathematics at the University of Western Australia offers a 12 unit Master of Business and Engineering Asset Management, taken over two years of full-time study or four years of part-time study, including an optional dissertation component. It is based on the achievement, through EAM, of achieving sustainable business outcomes and competitive advantage by applying holistic, systematic and risk-based processes to decisions concerning the physical assets of an organisation, and is targeted at asset management professionals. The study program has core units in systems reliability modelling, EAM and risk, reliability engineering, asset management planning, organisational behaviour, and data analysis and decision making. It offers optional studies in areas like accounting, managerial finance, leadership effectiveness, team leadership and facilitation, management of technology and innovation, and project management. There is an optional dissertation component (University of Western Australia, 2009).

In addition to postgraduate programs dedicated to asset management, there are also individual courses (or units) in EAM offered at both undergraduate level and postgraduate level. For example, Monash University offers the Master of Infrastructure Engineering and Management, which has eight units, of which there are four core units (infrastructure project and policy evaluation, infrastructure project management, two asset management units) and four specialised engineering and business electives (Monash University, 2010).

Such programs and courses meet a range of the needs in EAM discussed previously in this paper, including asset life cycle management, financial management and risk management. At the same time, they tend to be more focused on areas like reliability and asset maintenance than on wider issues like the impact of technology on society and the environment, management of asset networks and sustainability. Both the University of Wollongong and the University of Western Australia programs also tend to be sourced in the mechanical engineering discipline. Therefore, while these programs are intended to apply to a quite wide audience, they may tend to reflect the views of the mechanical engineering discipline rather than wider engineering applications. A similar argument could be advanced for the asset management units in the Monash University Master of Infrastructure Engineering and Management, which tend to reflect the needs of infrastructure management.

It is also noted that while study at Monash University appears to be off-campus, course delivery at many other universities, including the University of Wollongong and the University of Western Australia, appears to focus on on-campus study.

For these reasons, it is considered that a postgraduate program that incorporates the major components of EAM, but with a broader focus, that can be offered by distance education by an university experienced in such delivery, would have appeal to a broad range of students, both in Australia and internationally. Such a program, the Master of Engineering offered by USQ, is described and discussed in the following sections.

6 Postgraduate Engineering Programs at University of Southern Queensland

Postgraduate engineering education is offered within USQ by the Faculty of Engineering and Surveying, sometimes in conjunction with other Faculties such as Business and Science. Current Master level programs are the Master of Engineering, Master of Engineering Technology, Master of Engineering Practice, Master of Engineering Science, and Master of Engineering Research. There are also Engineering Doctorate and Doctor of Philosophy programs available.

In the Master of Engineering Technology, engineers and technologists develop increased technological skills through studying eight courses (equivalent to a year of full-time study) and undertaking a dissertation project equivalent in value to four courses (one semester of full-time study or equivalent). Students in the Master of Engineering Practice study a portfolio based program aimed at providing opportunity for experienced technologists to gain recognition equivalent to a four year professional engineering program. The Master of Engineering Science is a new program designed to provide an academic pathway to professional engineering for those who are qualified engineering technologists, or those who have a bachelor degree in a field allied to engineering (USQ, 2010). The above programs are not strongly geared to developing the skills of asset management. This deficiency is addressed in the Master of Engineering, which commenced as the Master of Technology Management in 2004. It is a coursework program that combines technological and managerial skills for practising technologists and engineers. A number of courses in this program are also available in the Engineering Doctorate and in other University courses such as the Master of Project Management offered by the Faculty of Business. Some are also offered as part of the Master of Engineering Technology program, as either a specialisation in their own right or an alternative to completion by students of the research dissertation.

This paper concentrates on the Master of Engineering, and in particular its Engineering Management Major, and to a lesser extent the Engineering Project Management Major.

7 Outline of the Master of Engineering

As stated above, the Master of Engineering commenced as the Master of Technology Management, the purpose of which was to produce graduates equipped with essential management knowledge and an appreciation of the latest technologies much broader than the initial specialisation, in order to equip them to manage complex technological or engineering businesses (USC, 2002). The Master of Engineering, which is co-ordinated by the author, has similar aims, and in addition provides additional flexibility through offering the three majors of Advanced Structural Engineering Design, Engineering Management and Engineering Project Management. The focus of the program is to provide graduates with knowledge of selected basic concepts and skills associated with engineering in areas such as sustainable development, technical risk assessment, and EAM. The program has an accompanying Postgraduate Certificate in Engineering, which in addition to the three majors in the Master of Engineering also has a Road Engineering major (USQ, 2010).

The Master of Engineering is available to students who have completed a four year Bachelor of Engineering degree awarded by an Australian university, or equivalent qualification. Students studying for a technical major are expected to have completed an appropriate major in their undergraduate program. Candidates who cannot enter the Master of Engineering may be considered for entry to the Postgraduate Certificate in Engineering subject to approval, provided they have five years of approved full-time equivalent work experience.

To complete the Master of Engineering, students are required to successfully undertake eight courses by distance education, in a standard duration of 1.5 to two years. Of the eight courses, two are to be the core courses of Asset Management in an Engineering Environment and Management of Technological Risk. The remaining courses undertaken depend on the major selected by the student, and consist of four compulsory major courses and two electives selected from a range of other courses. In the recommended study pattern, students firstly study the two core courses, then the four major courses and finally the two elective courses. The first specialised technology management courses were undertaken by students in 2004.

The structure of this program, for the Engineering Management Major, is shown in Figure 1. The Engineering Project Management Major differs from this Major by having a stronger emphasis on project management skills.

As previously stated, the Master of Technology program, which was the forerunner of the Master of Engineering, was developed out of the recognition that a large number of engineers and other qualified people aspire to managerial positions in a technology or engineering environment. It was also recognised that qualified managers of technology play a crucial role in technologically advanced as well as developing societies. This latter characteristic, which emphasises the crucial role of the technological manager in society, illustrates the importance of such a program in key technological functions like strategic asset management. This principle continues to be important in the Master of Engineering. The Master

2 × Core Courses:
Management of Technological Risk
Asset Management in an Engineering Environment

4 × Major Courses
Technological Impact and its Management
Towards Sustainable Development
Technology Management Practice
Technological Innovation and Development

2 × Elective Courses, selected from:
Accounting for Managers
Assessment of Future Specialist Technology
Project Requirements Management
Management of Environmental Technology
Whole of Life Facilities Management
Port Planning
Decision Support Tools
Management and Organisational Behaviour

Figure 1 Master of Engineering (Management) Structure

of Engineering is primarily aimed at attracting engineers who wish to develop management skills but want these to be in the field of engineering and/or technology management. They would come from both Australia and overseas, and would be likely to be ambitious and motivated, and see additional qualifications as a means of career enhancement.

In the next section, the key courses in this program that are related to strategic asset management are described in more depth.

8 Key Asset Management Related Courses in the Master of Engineering Management

The Engineering Management Major of the Master of Engineering Management contains a range of integrated courses that address the requirements of the strategic asset manager. Those currently offered include the specialised Asset Management in an Engineering Environment course, Technological Impact and its Management, Management of Technological Risk, Technology Management Practice, Technological Innovation and Development, and Assessment of Future of Specialist Technology. Whole of Life Facilities Management and Towards Sustainable Development are expected to be available in 2011, and Management of Environmental Technology in the future. To show how this program meets the requirements of strategic management as discussed above, the courses of Asset Management in an Engineering Environment, Technological Impact and its Management,

Management of Technological Risk, Technological Innovation and Development, and Technology Management Practice, all of which are available in both the Engineering Management Major and the Engineering Project Management Major of the Master of Engineering, are discussed below in more depth. This is followed by an overall summary of how the program addresses the development of strategic asset management leaders.

8.1 Asset Management in an Engineering Environment

Asset Management in an Engineering Environment, which was developed by the author, is the main course in the Master of Engineering from the point of view of developing the leadership oriented strategic asset manager. It recognises that in the modern world one of the highest expenditures for any government is the cost of developing and maintaining infrastructure.

It is designed to enhance the ability of managers in making better economical and financial decisions for the construction and maintenance of engineering infrastructure assets. Such decisions, if properly made, will mean better use of resources in obtaining optimum performance and longevity of engineering assets. This course addresses this requirement by taking a strategic view of asset management; discussing the principles of the asset management process and asset management economics; and applying the principles to the asset management process.

Initially, this course discusses the asset management context as discussed in Section 2 of this paper and establishes the need for the asset manager to optimise the requirements of the main stakeholder groups – owner/manager, user (where the user is not the owner), local external community and wider community. Building on this foundation, it then discusses the strategic asset management framework including the asset life cycle and its issues, performance requirements and deterioration, and the role of the strategic asset manager. Following a module on asset management economics, the course then applies these principles to asset operations, renewal and maintenance; integrated asset management including investment decisions for both individual assets and asset networks; and asset management systems. It concludes with a discussion of future issues in asset management, such as developments in asset management systems, data collection, sustainability and globalisation, and management practices.

The course aims to develop a multi-skilled strategic asset manager who is conscious of sustainability and globalisation issues and able to interact with a range of people from many facets of society (Thorpe, 2009a). The Whole of Life Facilities Management, which as discussed above is expected to be developed in 2011, will complement this course by focusing on the tactical and operational process of asset operation and maintenance.

8.2 Technological Impact and its Management

The Technological Impact and its Management course is based on the understanding that that the world of today is one in which there is dynamic change in the creation and development of technology. Therefore, it is necessary for managers of technology to understand the impact of technological development and the ways in which it can affect the society in which we live and the controls necessary to achieve a positive impact on mankind.

This course reviews current technological development, evaluates its impact on the world we live in, examines the relationship between modern society and technological development, and discusses the role of technological development on wealth creation and business. It also assesses the overall social need to manage such development as well as technology creation, transfer and exploitation. While it does not specifically focus on asset management, it introduces the asset manager to the principles of strategically and innovatively managing technological development in a world that demands increasing social and environmental responsibility in the technological management process.

8.3 Management of Technological Risk

As previously discussed, risk management is a priority area for the strategic asset manager. It is particularly important for the asset management leader. This course concentrates on the management of technological risk with respect to both taking advantage of opportunities and minimising the effect of negative impacts. There is a financial incentive, as well as community and corporate responsibility, to achieve the best results from an asset management point of view and to improve reliability. Increasingly, there are statutory requirements to address reliability and safety issues explicitly. In addition, there may be opportunities to manage risks to the benefit of the organisation. Consequently, strategic asset managers need to be aware of the tools and techniques used for the identification, assessment and treatment of technological risks.

In the first part of the Management of Technological Risk course, which was originally developed by the author, risk management is discussed in the context of the Australian/New Zealand Standard for Risk Management AS/NZS 4360:2004. In the second part of the course, learners apply risk management principles to technological and engineering projects and processes, and discuss the future of risk management, which is an important tool in evaluating the likely benefits and costs of alternative approaches in the asset management process. Of particular interest to asset managers are sections on risk management in project management; health safety and environmental risks and their management; and a discussion on risk management in asset management, which is based on the principles in the International Infrastructure Management Manual described in Section 3 above.

8.4 Technological Innovation and Development

Technological Innovation and Development builds on Technological Impact and its Management, and is designed to enable learners to understand the commercial research and development process; appraise the factors which impact on innovation and its development from a managerial point of view; understand and apply the organisational, social and environmental factors which impact on product and process innovation; appreciate and manage the relevant risks; and understand key issues such as intellectual property management and commercialisation.

From a strategic asset management point of view, this course develops the skills in the asset manager of not only being creative in the asset management process, but also seeking and adopting advances in technology to optimise the life cycle planning, development and ongoing operation and maintenance of the assets for which the manager is responsible.

8.5 Technology Management Practice

Technology Management Practice, which was partially developed by the author, covers a range of engineering management topics. In particular, it covers the principles of management, project and works management; engineering economics, probability and statistics, law (as related to engineering), contracts and project delivery, accounting and personnel. It complements other courses taken as part of the Master of Engineering through teaching specialised engineering aspects of the management process. For example, the project and works management section takes the learner through the basic principles of good project management; then introduces the principles of planning, estimating and scheduling; and discusses procurement, quality management, plant and equipment management, and office management. The contracts module deals with contract management and the management of project activities, and will in future deal with modern forms of project delivery such as public private partnerships and relationship contracting.

This course provides the tools to enable all engineers, including asset managers, to effectively manage the engineering function.

8.6 Summary

While the Master of Engineering does not specifically target one particular discipline, its Engineering Management Major and Engineering Project Management Major have specific courses designed for the strategic asset manager and a number of complementary courses that use a similar theme of combining technological, economic, social and environmental issues in a strategic framework aimed at developing engineering leaders. From the asset management viewpoint, this program meets the requirements of EAM discussed in this paper; and provides courses that enable managers of assets to better implement whole of life strategic asset management, manage individual assets and asset networks in a sustainable manner with consideration of stakeholder requirements, manage related risks, understand project management principles, be innovative and apply engineering management principles to the asset management function.

The development of this program has therefore carefully considered the needs of the strategic asset manager, both now and in the future.

9 Challenges in Developing the Master of Engineering

9.1 Considerations in Development

The Master of Engineering is designed to meet the needs of both potential learners and industry. It is anticipated that most learners will already be practising professionals, located in both Australia and overseas, many of whom will be working in organisations that are dynamically changing and will have different levels of technological maturity. While most students will be engineers and technologists, some (including some asset managers) may have other qualifications. Hence the courses in this program have been written to be understood by a range of professionals.

In developing the courses in this program, it therefore has been necessary for the author in his co-ordination role to appreciate that learners will have differing needs, and will come from a range of organisations. These organisations, and the people in them, will have differing understandings of the concepts in this program, and will also have differing geographic and cultural backgrounds. As an example, asset management in an engineering environment is likely to be quite different for a person in a developed country whose main concern is to ensure that an expected standard of service from a particular asset (such as a four lane asphalt surfaced road) is met, and a person in a less developed country, whose main concern might be justifying the construction of a road to a reasonable standard for its expected traffic and community needs. Course material needs to meet both sets of requirements.

Similarly, requirements and expectations may differ across geographical and political regions. Therefore, course development has needed to consider both Australian and overseas practice. For example, Management of Technological Risk is primarily based on the Australian/New Zealand Standard for Risk Management. However, the course developer has had to appreciate that there are also other equally valid risk management methodologies which need to be considered. For example, see Chapman and Ward (Chapman and Ward, 2003).

Finally, learners are likely to have different levels of access to the courses. In Australian and world urban centres, for example, most learners will have access to fast Internet access, and therefore they are likely to both expect and be provided with interactive on-line teaching materials. People in remote areas of Australia and other countries may well have minimal Internet access, and those in remote parts of the world could have little or no access to the Internet. Assessment (such as assignments) from students in some more remote regions of the world may need to allow for good hand-written assignments as well as the normal typed assignment expected of a person who has ready access to computers, and may need to allow for slower postage from some locations. Therefore, delivery of the course delivery needs to cater for all of these needs and expectations. This is particularly important for asset managers, many of whom will be managing in a range of geographical locations, with differing levels of equipment, expertise, and access to labour and equipment.

Therefore, when developing the courses in the program, it has been important to be aware of the differing academic and professional backgrounds of learners, their needs and expectations and those of their employers, and the best way in which they can receive course materials and interact with lecturers.

9.2 Challenges in Developing the Courses

Because of the range of student interests and backgrounds undertaking the Master of Engineering, the courses in both this program and its predecessors have been developed so that they provide sufficient material in the course material to give basic information while maintaining a strong focus on a balanced management approach. This needs to be balanced by providing sufficient challenge for people who want to learn a topic in depth.

There is also a need to meet the requirements of people with differing levels of mathematical background. For example, people who have a bachelor level degree in engineering technology (and would therefore be candidates for the Postgraduate Certificate in Engineering provided they have suitable work experience) are likely to have less training in formal mathematics than people with a four year engineering degree. Asset managers can come from both groups, and also from people with business and other backgrounds with a lower level of mathematical skill than fully qualified engineers. Therefore, the level of mathematics in the courses in this program has been kept to a minimum, subject to ensuring that necessary standards are maintained. This requirement has been met by guiding learners through the necessary basic process while giving them access to learn the necessary basic quantitative skills (such as the use of statistics).

At the same time, the needs of advanced learners have to be considered. Therefore, courses in the Master of Engineering have covered the necessary background material at outline level only, and then moved fairly quickly to applications. Those learners who need to know the theory in more detail have been directed to appropriate books and websites.

This type of approach has also been used in other aspects of this course, such as writing of English expression.

Developing courses to meet the needs of diverse learners is best illustrated by the example of developing Asset Management in an Engineering Environment, which is relevant to the needs of the asset manager. In this development, it was necessary to decide on what would be the focus of the asset management context (as discussed in Section 2 of this paper), assess what material should be included in the course, identify the likely profile of potential learners, and decide how course material should be delivered and assessed.

A particular challenge was to decide on the way in which the course should be organised and presented to meet course objectives and to challenge learners. Thus, while the thrust of the course is on the strategic aspects of managing technological assets, operational aspects of asset management have also been addressed, both to ensure that they are fully considered and to lay the platform for the Whole of Life Facilities Management course that will cover tactical and operational management of assets in more detail. In addition, material relating to sustainable development, a whole of life focus, risk management, innovation and technological management have been included and have been designed to link to other courses in the program.

A modular design has been employed, both for ease of study and to allow selected modules to be offered as future short courses suitable for possible industry training purposes. Therefore, the first modules that students study deal with theoretical issues, while later modules in the course focus on application of these principles. Current and emerging issues like sustainability, risk management and optimising multiple asset management goals are addressed throughout the course. The course uses guided research – reflection, research into key issues (supplemented by a series of questions to prompt the research process), development of opinions and problem solving. Extensive use is made of on-line research to supplement written material. As with most courses in this program, a textbook is used to supplement study resources prepared by university staff.

To assist learners with mastering the amount of material in the course, it has a number of activities that are classified into differing ranges of importance. The first level is essential tasks, which provide basic knowledge of the course material. Tasks classified as 'important' are designed to provide further understanding. They include reading and understanding explanatory course or text material, or undertaking a reading or exercise that aids understanding of the principles being explained. Learners may also optionally further research course material ('background tasks') or undertake in-depth research to understand it in more depth ('other tasks'). Material in essential and important tasks is examinable and is accordingly structured to enable learners with minimal mathematical background to succeed in the course.

10 Implementation of the Master of Engineering Courses

The Master of Engineering and its predecessors (Master of Technology Management and Master of Engineering Management) have now been offered since

2004. The first courses, offered in Semester 1 of 2004, were Asset Management in an Engineering Environment and Technological Impact and its Management. These were followed in the second semester of 2004 by Management of Technological Risk. A further three courses (Technology Management Practice, Technological Innovation and its Development, and Assessment of Future Specialist Technology) were added in 2005. A further course, Project Requirements Management, was added in 2008. As previously stated, it is expected that Whole of Life Facilities Management and Towards Sustainable Development will be added in 2011. Students enrolling for these courses are from diverse academic backgrounds, including engineering, project management and technology management.

While there can be some variation between individual courses, course material usually consists of an introductory book, a study book, and a book of readings. The introductory book contains information about the course; the study book contains the course material; and the book of readings a number of readings to aid understanding.

Written learning material has been enhanced with on-line discussion using online teaching tools. This allows online discussion, notices, and posting of supplementary course material on the web for those with web access (the majority of students). This increasing use of on-line teaching aligns with studies in the literature that support on-line teaching and learning. For example, Macdonald (2002) reported on the use of on-line interactivity in assignment development and feedback in Britain's Open University; Deeks (1999) discussed the use of web-based assignments for structural analysis; and Ferris (2003) used web-based teaching for management engineering management.

As systems and communications continue to improve, online learning facilities are being enhanced with discussions, quizzes and other interaction with students. At the same time, it is recognised that it is necessary to meet the requirements of learners in remote locations, and therefore it is expected that there will be a paper based system of study materials for some time.

Comments to date have been positive, and enrolment numbers for most courses, and in particular those courses that are offered in more than one program, continue to grow because of demand. For example, the number of students completing Asset Management in an Engineering Environment has grown, after allowing for drops, from five in 2004 to 40 in 2009. There are 49 students currently enrolled in 2010. Similar growth has been experienced for Management of Technological Risk, Technology Management Practice and Technological Impact and its Management. Project Requirements Management has also experienced strong growth (from four students to 20 students after allowing for drops) in the two years in which it has been offered. Because of this strong growth and generally positive comments from students, it is therefore concluded that the major courses in this program appear to be meeting student requirements.

11 Discussion

Educating strategic asset manager leaders requires a combination of understanding technological and economic asset management in a strategic global sense; consideration of stakeholders; the management of sustainability, risk management and innovation management; within an overall engineering management framework. While purpose designed postgraduate EAM programs such as those offered by the University of Wollongong and the University of Western Australia meet a number of these requirements, it is contended that the Master of Engineering best meets the overall need of asset management education through combining a range of skills and knowledge required by the asset manager into an integrated package aimed at the innovative management of today's and tomorrow's technology assets and organisations, and which is being developed in response to a changing world and changing demands. It is a distance education program aimed at attracting dynamic engineering and technology professionals worldwide.

Because it is required to be delivered by distance education to motivated professionals, this program has needed a tight focus as well as suitability for learners with a range of backgrounds and experience. The needs of these learners will continue to drive the development of this program and its courses into the future. For example, the requirements of stakeholders will change, new materials and methods will emerge, better systems will be developed, social and environmental issues will take an increasingly significant role in shaping engineering endeavours, and more will be understood about asset management. In addition, improved web based systems for teaching asset management principles will continue to develop. In this context, it will therefore be important to continue to refine the Master of Engineering to develop innovative asset management leaders who are also strategic thinkers. This will require continuous updating and upgrading of the types of courses offered, their content, and their mode of delivery.

A significant component of this change process will be in meeting the needs of worldwide approaches and demands in asset management. Doing so will require better understanding and appreciation of international requirements and of the diverse expectations of many communities across the world, each with differing social, environmental and economic values and needs. Incorporation of this information into the course delivery process would be expected to improve the relevance of course material to learners in local communities and at the same time improve understanding of global issues by all learners.

One of the key challenges ahead within the whole engineering profession will be the extent to which a traditional engineering undergraduate program, with its strong emphasis on technical training, will be able to produce the graduate who can effectively manage technological assets in a world expecting sustainable engineering practice. The Master of Engineering and similar programs would be expected to fulfil this need by offering a diverse postgraduate engineering management education that considers current and emerging issues in strategic asset management, with a view to developing leaders in this field who have a combination of business and technological expertise, as well as a solid grounding in current and emerging issues such as sustainable development, globalisation and risk management.

In the future, the courses in the program are likely to also be delivered as specific industry based programs as well as through academic courses. Therefore, courses like Asset Management in an Engineering Environment are likely to develop to meet a range of specific industry and community based educational and training needs, thus transferring the knowledge and skills taught to industry and the wider community.

12 Conclusions

While there are limitations in the management education of strategic asset management leaders at the undergraduate level because of the need for students at this level to focus on technical issues rather than the broader issues associated with strategic lifecycle asset management, postgraduate education provides the opportunity to develop the broader skills necessary. Through aiming to meet the requirements of the modern engineering manager, and targeting a range of modern asset management requirements such as sustainability, social issues, risk management and innovation, the Master of Engineering (and in particular its Engineering Management and Engineering Project Management Majors) aims to provide a program to develop and empower the strategic asset managers who know how to balance diverse stakeholder goals. This thrust, along with the detailed course development required to effectively deliver the courses in the program by distance education worldwide will, it is believed, continue to advance the education of engineering asset and engineering managers globally.

While there are a number of challenges to be overcome, this program and its related initiatives are therefore expected to provide the opportunity for such managers to obtain a level of postgraduate engineering management education that enables them to possess the skills to be leaders in their field.

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Experience with Education in Maintenance and Reliability Engineering by Off Campus Learning

Ray Beebe

Abstract Physical plant assets are tending to remain in service for beyond their design lifetime. Arguably, a greater professional input is needed into the maintenance and reliability engineering of these assets, yet few universities, if any, offer such content in undergraduate engineering degrees. Accordingly, postgraduate programs have been developed. Those offered by off campus learning are more likely to meet the needs of engineers, many of whom work remote from the possibility of regular attendance on a campus. In over 25 years since their inception, hundreds of engineers and other technical professionals have completed the Monash University programs. These have continued to evolve, and take appropriate advantage of advances in learning technology. This paper describes the development and lessons learnt during the Monash experience.

Keywords Maintenance and reliability engineering, Distance learning, Asset management education

1 Introduction

Many industrial assets are being required to not only remain in service beyond their intended design lifetime, but also to improve in performance. The focus of asset management has therefore moved beyond merely keeping plant functioning into the area of reliability improvement. A clear impact on the bottom line of

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a business must be shown. The term 'maintenance' unfortunately implies a reactive role, but today it is increasingly seen as an investment in production capacity rather than just a cost to be borne.

Maintenance and Reliability Engineering (MRE) is, therefore, clearly a professional engineering role offering great career challenge and excitement. Reliability Engineering is well developed in the military and in some technical areas such as electric power transmission. For the above reasons, these techniques are now relevant to industry in general. In Australia, the need for education of practising engineers in these areas led to programs taught by off campus learning.

Some universities around the world have recognised the need for such education, and have developed programs to suit. Some examples are: Hines (2005), Champaneri (1998), Knezevic (1997), Kerlin and Shannon (1997).

Off campus learning (also known as distance education) is the only practicable way of providing continuing professional development to those in this field, many at remote sites. It matches the needs of engineers wherever they live in the world. Also, research shows that:

> *"Flexible learning is private learning based on course materials, providing access to teaching staff and two-way communication. Self-motivation is required, but the integration with the work scene leads to a higher capability outcome than if classroom-based" (Townsend & Cairns, 2003).*

2 Origins of the Monash MRE Program

The Graduate Diploma was developed in the mid-1980s by Len Bradshaw (who later left to create and publish *Asset Management and Maintenance Journal*). The units of study were written by School staff, and differ in style in accord with academic initiative. Later, a Graduate Certificate was created for completion of the first four units.

In 1989, Dr Yousef Ibrahim developed a second graduate certificate: in reliability engineering. Funding supporting the development was from available government and industry sources. It was written and is taught entirely by practising reliability engineers. The Master's degree was first offered in 1999, and was designed to combine more reliability engineering material with the engineering maintenance management topics.

In 1999, an agreement was reached with the University of Tennessee at Knoxville, USA (*i.e.* UTK), to collaborate in offering these programs in North America. The UTK Reliability & Maintainability Center acts as the Monash agent. UTK has since developed its own master's program, which is complementary to the Monash degree.

3 The Programs Today

The aim of the programs is to equip people with the knowledge, skills and attitudes to improve the life cycle performance of plant assets and thereby improve the performance of their business.

Study by off campus learning is usually taken as half the study workload of on-campus students, but students can take a lesser load. For postgraduate continuing education, universities in Australia and the UK generally require one year of full-time study or equivalent for a *Graduate Diploma,* with a *Graduate Certificate* half of that. Requirements for Masters' *degrees* vary. A few students have completed the Master's degree in one year full-time, and this possibility may be attractive to others in a break between full-time work. The Monash programs in this field are:

- Graduate Certificate in Maintenance Management (GradCertMaintMgt);
- Graduate Certificate in Reliability Engineering (GradCertRelEng);
- Graduate Diploma in Engineering Maintenance Management (GradDipEng-MaintMgt);
- Master of Maintenance and Reliability Engineering (MMaintRelEng).

Direct admission into the Master's is available to engineers with a four-year degree in engineering. Admission into the Graduate Diploma is available to lesser-qualified graduates in engineering and graduates in other professions, who may articulate into the Master's degree following completion of the Graduate Diploma with high grades.

There are many non-degreed engineers and others working in maintenance and reliability, often with significant responsibility for staff management or planning of maintenance. Anybody enrolling direct with Monash can study units on a 'not-for-degree' basis. On completion of two units with an average grade of 65 per cent admission into either of the Graduate Certificates is allowed with full credit. Completion of either Graduate Certificate with 65 per cent grades entitles articulation into the Graduate Diploma and later the Master's degree. Many such people are of high calibre and some have completed Master level.

Assessment varies with the units, with all having progressive assessment via assignments submitted through the year. Most have an examination as well, arranged anywhere in the world. Some units have assignments done in groups on-line.

Students usually study two units per semester, but some choose less. Several hundred people have completed the programs, and their feedback is overwhelmingly positive. Typically, most come from every state in Australia, but also from up to 15 other countries. In one year, the programs had students in every inhabited continent. Wherever they live, students interact with teaching staff in exactly the same way as those living in Australia.

4 Study Materials

Based on feedback from students, the study materials continue to be produced in print based format, updated each year and rewritten regularly as appropriate. Most items are also posted on unit Blackboard websites (see later).

There are generally three parts, with some units also having a CD of images, short videos or other resources:

- Unit Guide: which contains information about unit administration and gives the assignments and other assessment detail (many assignments relate to the student's workplace);
- Unit Book: which contains the Study Guides. These are detailed guidance to the subject matter, referring to the textbook and Reader/s where appropriate. The style of these varies with the topic and text;
- Reader: consisting of selected relevant technical papers and articles. Although items are reviewed annually, some items remain that are regarded as classic in the field.

Some units require a textbook, which is usually bought by the students. An exception to the above is the Maintenance and Reliability Engineering Project subject, which is workplace-related, and has only an on-line Unit Guide.

5 Teaching

Unit Advisers comprise full-time academics, who also have other teaching, management and research commitments, and sessional staff, who are practising engineers. Some have international reputations in their field. The author has led the programs as Co-ordinator since 1996, joining in 1992 following 28 years in the power generation industry.

Students maintain contact with the Unit Advisers via e-mail, and rarely by telephone. Assignments are submitted by e-mail, and are responded to with feedback by the Unit Adviser after grading.

The program offers a graded coverage of subject content, designed to provide students with knowledge, skills and attitudes in each subject area. Students are expected to read widely, and present responses to assignments which indicate their understanding and appreciation of the application of the material. Sometimes there are no clear right or wrong answers!

Up to 2009, Residential Schools were conducted: one in each semester in Australia, and one each year in Knoxville, Tennessee. Students were required to attend and took part in lectures, discussions and site visits. Given the concerns about greenhouse impact of travel and cost, it was decided to cease conducting these and build on Blackboard functionality.

Electronic resources are a rapidly growing source, with electronic journals and databases enabling access anywhere in the world at a time that suits the students.

Many books are available in electronic versions, where each 'copy' held can be accessed on-line by one person at a time. Continual additions are made to the Monash Library collection in the MRE field. Most students can access the Library's mailing out service. Use of other libraries is available where co-operative arrangements have been agreed with several other institutions. Some students have access to texts and other resources held by their companies.

6 The Move to Web-Enhanced Teaching

As with many other aspects of life, the computer and internet also provide great possibilities for teaching, with the aim of improving quality (Benson, 2003). Our associates at the University of Tennessee developed six units of study in this field and trialled them successfully (Hines and Shannon, 2000), and now offer a complete master's degree in a closely associated field. Teaching takes place synchronously, *i.e.* with the students all logged on at the same time. Students and teachers can communicate with each other online. The teacher's presentation is recorded for later access by students.

Monash University has adopted the Blackboard™ learning management system for all units, following initial use of WebCT CE. In the interests of extending off campus delivery, development funding was provided for this program. Each Unit Adviser as the content specialist was assigned an Educational Designer, qualified and experienced in teaching. The Unit Advisers and Educational Designers worked together to learn the software and develop the detail of the units.

The three broad pedagogical approaches identified for development of Blackboard templates rely jointly on adult learning principles and resource-based learning, and are (Bruhn, 2004):

- basic collaboration – where teaching is complemented with some basic collaborative tools (*e.g.* discussion groups);
- case-based or problem-based – where these philosophies are used in a unit to give selective release of cases and flexibility in organising learning environments to support students working in small groups, and the style adopted here;
- mixed mode – for on-line interaction, provision of content offered on campus or via off campus print formats, and uses various tools to support learning: the approach taken with these units.

7 Formulation of Minimum Standards for Web-Enhanced Delivery

In devising a minimum standard that should apply to the units when adopting a mixed mode approach to the delivery of units on-line the following criteria (Bruhn, 2004) were developed for the Blackboard site(s):

- Easy to navigate and be strong on ‘visual signposts’, that is, graphics and/or text on the web pages should be self-explanatory as to what will be presented if the student clicks on that icon.
- Have clearly expressed objectives or learning outcomes to define content, assessment tasks (both formative and summative) and on-line learning activities.
- Provide content in a form appropriate for online delivery, or give directions/guidance as to where it is located.
- Complement/enhance any print materials and not just duplicate them.
- Provide opportunities for ‘active learning’ through the careful integration of interactive learning tasks (which may include interactive multimedia), that is, the students should engage in activities which require them to do something (*e.g.* role play within a game, manipulate models by changing a range of variables, visit a website and do a critical appraisal of its features).
- Provide opportunities for students to assess their progress in acquiring knowledge and skills through the use of quizzes and other online self-assessment activities (formative assessment) and as preparation for summative assessment tasks.
- Provide an efficient means of linking to other on-line resources both within and external to the University and have the capacity for the academic to provide up-to-date information that becomes available during the semester.
- Provide the means by which students can communicate with the academic or fellow students, either informally or through structured discussion groups.
- Provide the means by which students can access important information about the unit and critical dates during the semester [*e.g.* unit structure, prescribed texts, assignment details (including assignment and examination dates)].
- Be flexible in design to allow for changes to be incorporated as required during the semester based on the identified needs of particular cohorts of students and/or variations or additions to the content.

8 The Development Process

It was decided early that Internet use would be *non-synchronous*, as the students are spread across many time zones. It was also firmly established that the development was fundamentally being made to improve the quality of teaching and learning, not to save money, nor to just appear to be progressive. Active learning was the aim, through careful integration of learning tasks, so that a student would be required to do something, rather than be a passive reader. In some cases, the existing materials included these features, and enabled ready adaptation into a web-enhanced approach. Multi-media expertise was utilised where appropriate.

It was also decided that the study materials would remain in print-based format, supplemented with CDs for sound, images, and some documentation. All students are required to have Internet access, although it is still not expected yet that all students have broadband access. Merely transferring the study materials away from provision in print to having them on-line, such that the student needs to

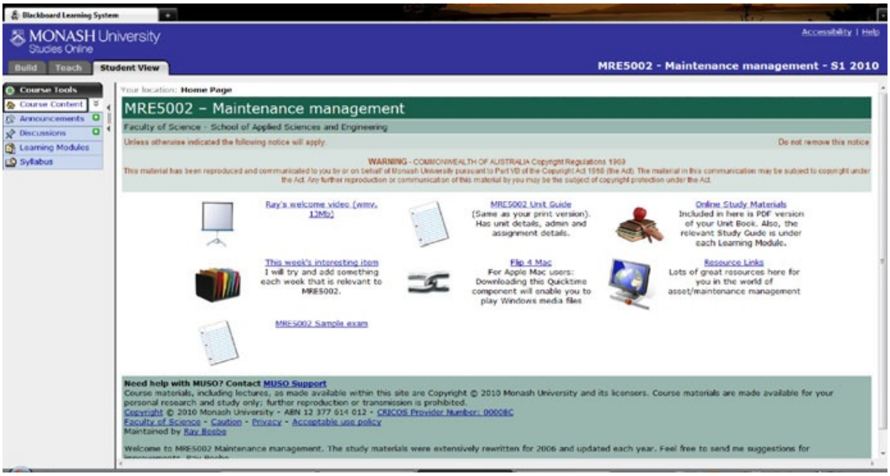

Figure 1 Screen view: opening page of a typical Maintenance and Reliability Engineering unit

download and probably print them, is not the best use of the Internet. High quality images open quickly from a CD, but can take some time to download if on-line.

The opening page of one unit is shown in Figure 1. The material content can be built up and readily modified by the Unit Adviser, who has "Designer" access.

Content pages vary with unit and teaching style, but may comprise:

- Syllabus or Unit Guide: an outline of the aims of the unit, its assessment and administrative details.
- On-line study materials: a section corresponding to appropriate Study Guides (up to eight, depending on the unit).
- Self Assessment Questions: each Study Guide contains Learning Activities, with responses given at the end of each print section. Self Assessment Questions are available for each Study Guide, and are answered on-line. After the student enters a response, the 'official' answer is shown. These can be graded, but it was decided not to do this, but to use them as opportunities for students to assess their progress in acquiring knowledge and skills.
- Resources: a display of hot links to selected web sites with information relevant to the unit material. These can be chosen to open in a new window.
- Discussion section for interaction between students.
- Assignments: a summary or repeat of the requirements given in print.

9 Experience

The extent of site development and particular features varied between units, as it was not desired to have the teaching pattern standardised, but to allow for individual teaching and presentation styles, as with all university teaching.

The varying number of students was also a factor, such that experiences differed between units. It took some time for both teachers and students to get familiar with Blackboard, and several had some difficulty utilising all the required features. Blackboard provides an on-line facility for drafting and eventually submitting assignments. However, submission by email direct to the Unit Adviser has proven to be simpler for all concerned and is now our most common method. The intent was that Unit Advisers read the assignments, added comments and assessment grade on screen without printing them. Most managed to obtain this skill.

Towards the end of the second year of offering the units this way, formal evaluation was performed by a Senior Education Designer who had not been involved. A questionnaire was used to evaluate student experience in each of five units. For one unit, a two-hour focus group was also held. Sixteen of the 30 students in this unit responded, with some points that emerged as follows:

- Time is needed to obtain sufficient familiarity with Blackboard and the unit site. Several teething troubles were encountered, and most overcome as the year progressed.
- The on-line resources were inconvenient to access compared with the print materials, and some saw as merely being a repeat of the paper materials and not adding value to them.
- Not all could access the Internet when away from home when they wished to do some study.
- The volume of reading concerned some, and it is possible that this may be less of a problem for those who had previous tertiary study. Some felt that the site should include add-on information to the print materials. Student-selected resource links were suggested by some.
- Discussion groups did not occur because students did not raise issues. These need to be set up by the Unit Adviser. In some units, students are asked to post introductory information about themselves (as most had never met). Although there are several public discussion boards in the MRE field, these are apparently not used as widely as it appears. As many students travel away from Internet access in the course of their employment, structured discussions may be difficult to introduce.
- The self assessment questions were used by some for revision prior to the examination (which was conducted in the normal fashion: *i.e.* handwritten). Some felt that if they had been graded and thus included in the overall assessment for the unit, they would have been given earlier attention. General experience seems to be that these items will not be attempted unless they are required to be completed, whether assessed or not.
- Many favoured an introductory video to accelerate the learning curve for the start of the unit.
- Overall, the students rated the unit as 'very good', and much was learnt to improve it for future years.

Later, all of the units were rated against the formulation criteria. This unit fully met the criterion in 7 of the 10, and partially in the others.

10 Who Takes Up MRE Studies?

In 2005, a questionnaire was developed in conjunction with Dr Melinda Hodkiewicz of UWA and sent to a range of current and recent students. Eighty-seven responses were received and analysed. The average working life of respondents was 16.7 years.

The **discipline** of engineering *etc.* most strongly represented was Mechanical (66 %), followed by Electrical (16 %), Electronic/mechatronic (7 %), Management (3 %), Other (6 %) and Chemical (2 %). 25 % of respondents **described their jobs** as 'reliability engineers', 47 % were in 'maintenance' (Engineer, Planner, Supervisor, Technician) and 23 % were 'managers'. Industries that students worked in are shown in Table 1. The two occupational terms are not used consistently. Hodkiewicz *et al.* (2004) built on O'Malley *et al.* (2003) and suggested that the distinction should be:

- Reliability engineers are not governed by day-to-day operations, but have a strategic focus. They develop programs that provide the framework for maintenance.
- Maintenance engineers are responsible for immediate equipment functionality and implement strategies developed in co-operation with reliability engineers.

Table 1 Industry where students in this sample work by percentage

Mining/mineral processing/refining	37	Petrochemical	5
Defence (military & civilian)	17	Government	2
Manufacturing	15	Warehouse/logistics	2
Utility (gas, water, power)	10	Timber/pulp & paper	2
Service Provider/Consultant	8	Transport (air, road, rail)	2

11 What Do Students Consider Should Be Included in MRE Courses?

The topics considered were in two categories. Each topic had some students who considered that they were competent already (remember that these are not raw engineers). The survey results are shown in Figure 2 (technical topics) and Figure 3 (management topics). Note that some of these are not included in traditional bachelor degree programs.

The Top three technical were:	Reliability and Risk Based Inspection methods
	Failure modes and effects analysis
	Failure mechanisms & Root cause analysis
And the Top three management:	Life cycle costing and NPV methods
	Risk assessment
	Budgeting and capital expenditure

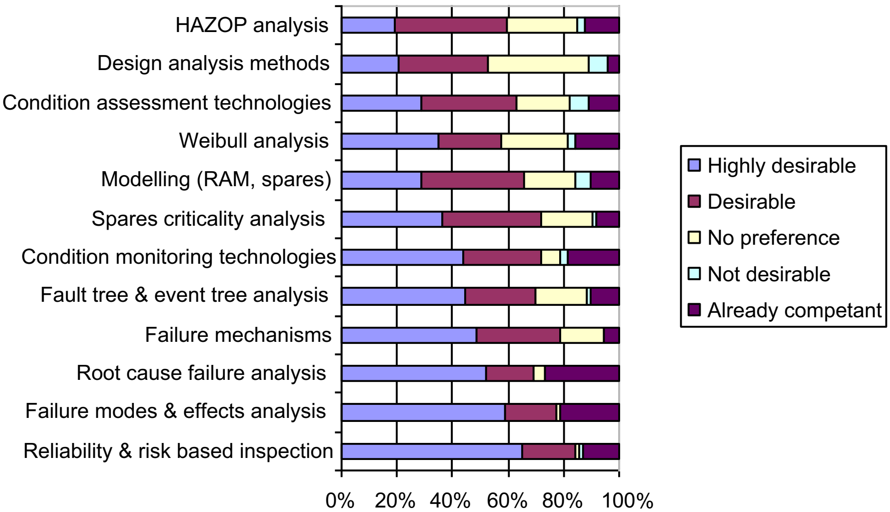

Figure 2 Value of technical topics in MRE study according to student survey (N = 87)

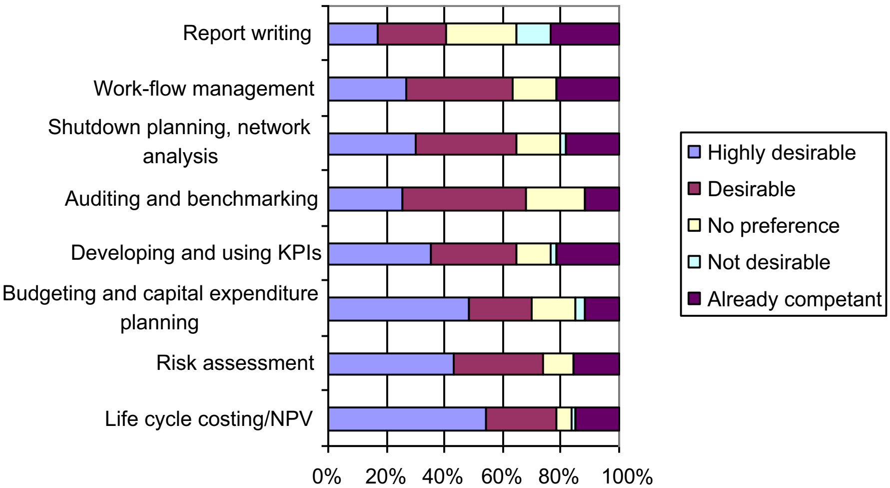

Figure 3 Value of management topics in MRE study according to student survey (N = 87)

12 What Outcomes Have Graduates Experienced or Expect to Experience?

Students had not been asked this until the survey, but reports have been received over the years of promotion and new jobs where the studies have been a major factor. Figure 4 shows the survey results. Worthwhile outcomes were apparent across the board, although the data could be interpreted as showing an individual highly satisfied in all areas, or in only some!

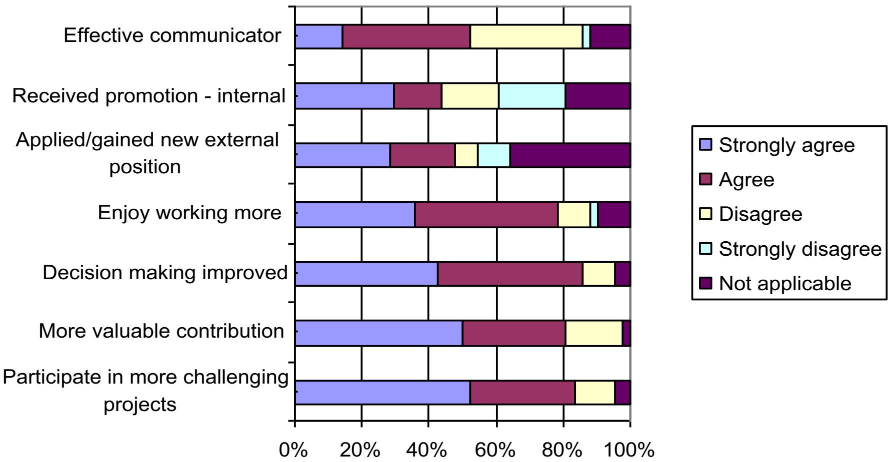

Figure 4 Outcomes experienced or expected from MRE study according to student survey (N = 87)

13 Conclusions

Experience with web-enhanced delivery of off campus learning in MRE shows that improved learning is possible, but significant overall benefits should not be expected initially when compared with paper-based print materials alone. This should improve as higher performance Internet access becomes more widely available.

In developing a unit of study for web-enhanced delivery, the academic must try to use opportunities possible on-line that cannot be provided easily in other ways. These must be integrated fully with all the other components of the study materials in a unit in line with the overall objectives of that unit: the only reason for having web-enhanced learning is to do a better job.

The survey gave some insights into what students consider about the value of topics in MRE programs, as well as the value of postgraduate study itself. It is overwhelmingly thought to be worthwhile, and gives the basis for further research into topics that should be included or emphasised. Some points:

- Reliability is a job people 'move' into, not an early career choice.
- Those in the reliability field have a wide variety of educational backgrounds and experience.
- Considering the population of engineers, relatively few have undertaken postgraduate reliability education.
- Many reliability professionals undertake targeted education in the form of university-coordinated postgraduate studies, vendor-supplied or institution organised training.

14 Future Research Possibilities

Useful research would be to compare the formal programs available across the world, both on campus and off campus. An aim would be to find if the workplace performance of graduates differed as a result of this further study, as well as between the courses. Non-award courses should be included in the evaluation. The outcome of such a study would be a valuable guide to providers and potential students.

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