Managing Ports and Harbours as Sustainable Complex Systems

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Abstract. Ports and harbours are very large infrastructure projects which have great impact on the community, environment and the economy of a country. Ports are not only a vital lifeline link between water-side and land-side traffic, but are also sources of national wealth, pride and concern. Stakeholders now want requirements to be described in a creative, rigorous, and policy-relevant manner and for critical issues such as sustainable development to be incorporated into developments. This paper looks at the issue of sustainable development for ports and harbours as potentially being one of managing complexity, and it considers how holistic system requirements may be accommodated in this process. It also suggests that currently not enough use is being made of stakeholder data – economic, social, and environmental - and that significant operational improvements could result from closer attention to this issue.

Most of the problems related to sustainability and sustainable development are typically complex and inter-related. It has been shown that the more complex a system the harder it is to manage, although a certain system complexity is needed for both short and long-term functionality. By having insights into the causes of complexity in systems enables decisions to be made and actions to be taken where otherwise there may be lost opportunities and ultimately reduced profits, or damage to social and environmental networks. Ports have to achieve a harmonious balance between the local community, the environment and economic issues. By applying systems engineering techniques and ideas surrounding complexity management this paper looks at the designing and subsequent management of ports & harbours and in so doing to develop better overall strategies. Research work into a number of operational sub-processes is used to gain insights into where measures of complexity may be further developed.

Introduction

Ports operate within an environment that is driven by natural processes such as tides, currents, and climate, as well as marine biology, society and man-made processes. Within the last six years the literature shows that there has been a rising interest in environmental issues relating to ports and harbours, (ESPO 2001a; ESPO 2001b; Sutherland & Gouldby 2003; Pontee et al. 2004; Morris 2007). Port activity is coming under scrutiny, both in terms of capital projects and ongoing operations. For example, the European Commission's transport policies are now expressed largely in terms of their potential impact on the environment and expected levels of pollution. In 2002 David Jamieson, the UK minister of shipping, stated that modern ports must be '*successful, sustainable and safe*', (UK DTLR 2002). There are also a number of European

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research institutes and international organisations that are promoting the sustainable development of ports such as “Ecoports”, “Espo”, “New! Delta” and “UNEP – regional seas programme”.

Ports are traditionally designed and built based on the specified maritime and channel design, quay design, the expected port operations and cargo handling, the terminal layout, and also to the expected marine traffic and type of cargo. Simulation models are used extensively for the analysis and planning of ports, and there are a wide range of published research reports. Existing literature includes simulation models of full container terminals (Nam et al. 2002; Agerschou 2004), container movements to and from trucks (Sgouridis et al. 2003) and to and from vessels (Sgouridis et al. 2003), vessel traffic (Pachakis & Kiremidjian 2003; Asperen et al. 2003), and ship handling at the port (Bruzzone et al. 1998). Arena software (Kelton et al. 2004) is a well known simulation package, and is used extensively in commercial operations, including port planning and analysis, (Sharpe et al. 2005; Goldsman et al. 2002).

We are however witnessing an inexorable increase in complexity in all spheres of social life and problems relating to sustainable development are typically complex, interconnected and ‘messy’, (Brown-Santirso & Peet, 2005; Holmberg & Karlsson 1992; Giallopin 2003; Cabezas et al. 2005). ‘Messy’ problems are challenging traditional approaches to problem solving, such as reductionist approaches. Ports, and the problems they seek to solve, are becoming more complex. It is not possible to design part of the port system in isolation without considering the problem and solution as a whole. Simulation models, such as ARENA, can accommodate the dynamic or transient effects seen in port and shipping operations in unexpected situations, such as adverse weather conditions or equipment breakdown. However, they are limited to relatively straightforward problems and cannot cope with complex, inter-related factors such as, the degradation of the local environment through dredging, loss of support from the local community, the effect of more extreme and unpredictable seasonal variations, and the potential effects of a new development on the physical and biological marine environment. Many of the emergent behaviours from these complex relationships are unknown, such as not being able to guarantee cargo handling efficiency, i.e. demurrage payments, which are notoriously difficult to predict. Simulation models and other predictive methods are based on data where ‘outliers’, i.e. unusual operations are removed from the data sets due to the possibility of creating misleading results, (Khatitashvili 2006). These models then often fail to provide insight into the complex and hidden linkages established between system inputs and system elements. Nassim Taleb in his bestseller, “Fooled by Randomness” warns of the dangers of ignoring outliers, or more exactly the potential for randomness in systems (Taleb 2004).

Sustainable development is probably not possible without due consideration to the phenomenon of complexity. In fact, this line of reasoning is not at all new (Odum 1953; Elton 1958; May 1972). Indeed it would seem common sense to assume that the complexity of a given system will have an influence on functionality, robustness, stability and indeed its ultimate survivability, or sustainability. Studies of social systems recognise that the problem of sustainability is one of recognising the subtle, long-term influences of complexity and of developing ways to mitigate and control it, (Tainter 2006).

Understanding and defining the problem correctly is crucial when defining a realistic representation of a system. It’s also clear that new outcomes will not result unless new procedures are employed. We must then look to improving the way we look at problems and the processes by which things are made, (Godfrey 2006). One approach is to adopt a holistic perspective and to adopt a methodology that enables the system to be driven from the requirements of the key stakeholders. Systems thinking provides such a framework for problem solving. Recent research has shown that a systems approach can define a wider problem boundary than those limits traditionally adopted by engineers, (Fenner et al. 2006). Systems thinking requires whole-life thinking, i.e. consideration of the implications of every decision, and recognition that what happens in one part of a system may affect other parts. Thus this can then lead to the creation of a wider design space in which more holistically conceived solutions can be formulated to any given problem, (Fenner et al. 2005). Systems thinking intrinsically captures complexity and thus the aim of this paper is to explore how, in the real world of Ports and Harbours, a practical solution for sustainable development may be achieved.

Setting the Scene

Sustainable Development. There has been an enormous amount of work on issues relating to sustainability since the rise of environmental consciousness in the 1970s (Mazmanian & Kraft 2002), and by far the most common usage of the word “sustainable” is in combination with the word “development”, (Mazmanian & Kraft 2002). According to Parkin et al. (Parkin et al. 2003) there are over 200 definitions of “sustainable development”, and the term has now penetrated planning and various other academic disciplines, and has become one of the pervasive icons of modern times, (Jaberdeen 2004). Some researchers see sustainable development as an emerging meta-discipline that is beginning to define a whole new subject area, (Mihelcic et al. 2003).

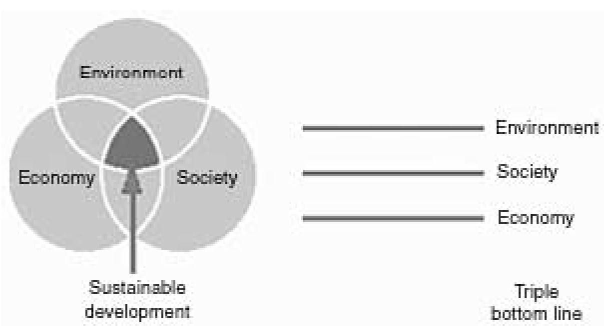

Figure 1. Sustainable development: Venn diagram & triple bottom line, (Parkin et al. 2003).

As already indicated definitions of sustainable development vary widely (Robinson 2002; Jaberdeen 2004), however most call attention to the need to maintain resilience in environmental and social systems by meeting a complex array of interacting, environmental, social and economic conditions, (Swart et al. 2004). These dimensions have complex inter-linkages and are often conceptualised as overlapping circles in a Venn diagram, see Fig. 1, and have also been characterised as the Triple P concept: Planet, Profit and People (Serageldin 1994), which emerged out of the Brundtland report on sustainable development (Brundtland 1987), and is characterised by industry in particular as ‘triple bottom line’ accounting.

The life cycle initiative is a response to the call from governments for a life cycle economy in the Malmö Declaration (2000). It contributes to the 10-year framework of programmes to promote sustainable consumption and production patterns, as requested at the World Summit on Sustainable Development (WSSD) in Johannesburg (2002). Life cycle thinking is an approach that is closely tied to the concept of the product life cycle. It expands the traditional focus on manufacturing processes to incorporate various aspects associated with a product over its entire life cycle and integrates existing consumption and production strategies, preventing a piece-meal approach. Life cycle approaches thus avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium to another. The Life Cycle Initiative expands these ideas to extended producer responsibility, design for environment and supply chain management, and to communication and outreach efforts to promote the environmental performance advantages of a product or service.

Life cycle management, (LCM) has been developed as an integrated concept for managing the total life cycle of products and services towards more sustainable consumption and production patterns. It is the application of life cycle thinking to modern business practice with the aim to manage the total life cycle of an organization's products and services towards more sustainable consumption and production. It is the systematic integration of sustainability, e.g. in company strategy and planning, product design and development, purchasing decisions and communication programs and it is not a single tool or methodology but a flexible integrated management framework of concepts, techniques and procedures incorporating environmental, economic, and social aspects of products, processes and organizations. Life Cycle Assessment (LCA) is an analytical tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. The drivers and benefits to managing sustainability through life cycle management are broadly seen as follows in Table 1:

Table 1. Summary of drivers and benefits for managing Port operations sustainably through life cycle management .

Corporate strategy • Improve public reputation, image and general relations to stakeholders; • Competitive advantage: being at the forefront of development & new technologies; • Reduce costs: Increased operational and resource efficiency; • Enhance port & harbour innovation: development, design & operation; • Increased port value (a 'sustainable' port). Recognised port leader in sustainable development.	**Market requirements** • Compliance with relevant authorities, e.g. conservation agencies, port & harbour authorities, environment agencies, etc; • Increased market share: advantages to 'first movers' on sustainability issues within ports; • Ability to focus on sustainability and go beyond a port service.
Financial sector requirements • Inspection, maintenance and repair costs determined according to the economic optimum life-time and risk of failure of the structures concerned; • Reduced financial risks and significant cost savings in insurance rates and fines, achieved by decreased liabilities; • Increase shareholder value, to get a 'Dow Jones Sustainability Index'.	**New regulations or legislative demands** • Anticipate future legislative demands, e.g. dredging sanctions, port emissions, ecological preservation; • Joining sustainability schemes and green public procurement programmes, e.g. EcoPorts, Espo, UNEP; • Joining corporate social responsibility programmes.

It is clear from Table 1 above, if evidence were needed, that issues of sustainability are to dominate strategic thinking in the future. It is also clear that efforts are already underway to implement tools and methodologies to enable business to design and manage systems sustainably. A key problem however is that the models devised represent an aggregated view of expert opinion and there are probably few, in fact none know to this author, of holistic measures for tracking systems during their life-cycle. To find answers to this problem it is perhaps necessary to look to other disciplines.

Complexity. The contemporary science of complexity extends an intellectual tradition developed in older fields of system theory and information theory (e.g., Shannon & Weaver 1949; Ashby 1956; Brillouin 1956; von Bertalanffy 1968). The underlying concept of complexity science is that any system is an ensemble of agents that interact. As a result, the system exhibits characteristics different from that of each agent, leading to collective behaviour (Gell-Mann, 1994). This property is known as emergence (Morowitz, 2002). Moreover, complex systems can adapt to changing environments, and are able to spontaneously self-organise, (Sornette, 2000).

One of the challenges with studying the mechanisms and history of complex systems is the lack of a working definition of complexity itself. There have been numerous attempts to define the complexity of a given system or phenomenon, usually by means of a complexity *measure*. The first and still classic measure of complexity is that introduced by Kolmogorov at the end of the 1950s, (Kolmogorov 1965). This is, generally speaking, the shortest computer programme capable of generating a given string. This quantity is in general incomputable, in the sense that there is simply no algorithm which will compute it. Nevertheless the research field shows that Kolmogorov's theorem plays an important role in the history of measuring complexity.

Generally speaking, complexity measures either resemble the Kolmogorov approach, and involve finding some computer or abstract automation which will produce the pattern of interest (e.g. Bennet 1985), or they bear a resemblance to information theory and produce some value for entropy, i.e. noise in the system, which while in principle is computable, can also be very hard to calculate reliably for experimental systems, (Shalizi, 2007), (e.g., Lloyd & Pagels 1988). To date researchers have been trying to define complexity as an abstract process, whereas engineers need something more tangible, and a more practical definition is needed. The approach suggested here is to obtain a complexity metric through analysing the entropy of process data.

This work focuses on providing a system level measure for complexity based on Shannon entropy, (Shannon & Weaver 1949). This measure intuitively provides a measure of the uncertainty remaining in the system after an observation has been made (Cover & Thomas 1991). The Shannon entropy of a discrete random variable X, that can take on possible values $\{x_1 \ldots x_n\}$ is defined as:

$$H(X) = -\sum_{i=1}^{n} p(x_i)\log_2 p(x_i) \qquad (1)$$

where

$p(x_i) = \Pr(X = x_i)$ is the probability mass function of X

Shannon entropy provides a useful framework for describing and quantifying the dynamics of systems. For example, economists have used the entropy measure as a more realistic and rich explanation of the complexity within the stock market, (see Fig. 2). Entropy, in the case of this study, is used for assessing the amount of order and disorder in systems and for assessing the complexity of transitions, as well as determining how past states, or trends, may influence systems. In Fig 2 we see classic complex system behaviour before catastrophic events where the rate of change of change of information content markedly increases.

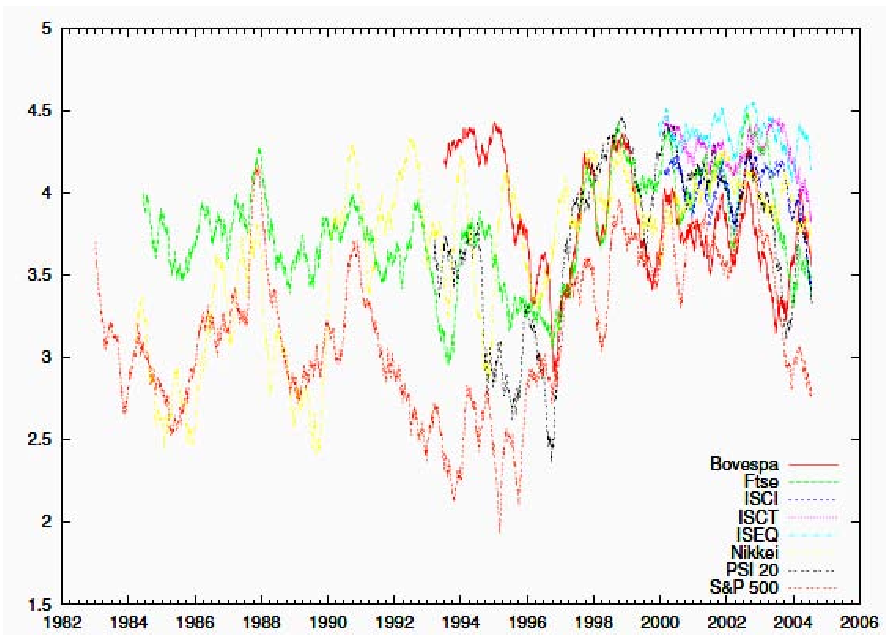

Figure 2. Weekly entropy for various market indexes from 1982 to 2006, (Matos *et al.* 2006).

The entropy measure employed in this paper is based on the idea that for a given process variable and a series of recorded values, equation (1) can be used to compute the maximum permissible uncertainty (i.e., entropy) of the variable. An average, entropy may also be calculated based on the spread of values within the recorded range. The difference between the maximum and the average value of entropy can then be taken as a measure of the reserve of uncertainty available to the system. This provides a definition for system Robustness as follows:

$$Robustness(\%) = \left(1 - \frac{(MaximumEntropy - AverageEntropy)}{MaximumEntropy}\right) \times 100 \quad (2)$$

Values summated across all system variables will provide a measure reflecting the overall system complexity. It is reasonable to assume that a system displaying a lower overall complexity against its maximum achievable will be more capable of long-term survival than one operating at its upper thresholds of disorder, but also conversely we can assume that there must be some complexity for operational capability. In this paper this idea is extended to a realisation that for a sustainable system its overall complexity must be a trade-off between functionality and manageability.

Systems Thinking. Within the last five years there has been a drive by the UK government, the Institution of Civil Engineers (ICE) and the Royal Academy of Engineering to increase the awareness of systems approaches within the Civil Engineering sector, (The House of Commons 2004; RAE 2007). There are several examples of its potential benefits in highly published infrastructure projects, and a small group of researchers who are also advocating its use, (P Jowitt from the Scottish Institute of Sustainable Technology; Karl-Henrik Robert from the Natural Step; K Marmen from the Oakland Institute; The Sustainability Institute in Hartland, U.S.; The Polyurethane Industry). In various literature resources, systems and their complexity are now viewed as an essential 21st century science (Living Roadmap for Complex Systems Science), and are predicted to be at the heart of the future Worldwide Knowledge Society. There is also now a "living roadmap" for systems in order to help consultants implement what are considered "big ideas" into European projects, (Bourgine & Johnson 2006). Additionally, since the first major attempt to teach systems was in 1950 at MIT by Gilman, there are now numerous systems engineering centres throughout the world and new systems courses.

The core of systems thinking requires whole-life thinking, i.e. consideration of the implications of every decision, and recognition that what happens in one part of a system may affect other parts. Within a sustainable development context this primarily means understanding that the three elements comprising sustainable development are all inter-related and cannot be considered in isolation, e.g. an alternative electricity source such as wind energy installed in a plant must not negatively impact the bottom line, and a new port development cannot be built in an area where air quality and noise emissions negatively impact a local community. Systems approaches begin by understanding the broader system within which problems occur and the principles governing success within that system. This upstream approach means problems are addressed at the source and are turned into opportunities for innovation and business success.

Lessons from Operational Sub-Processes

Equipped with ideas of sustainability, systems thinking and complexity we look at the operational sub-process of Ports in this section. From the analysis of these sub-processes where insight will be gained into novel ideas for managing complex systems, it's possible to infer a larger process, already intimated above, for overall system analysis and management of sustainability.

For the sake of this paper the stakeholder requirements for Ports and Harbours will be considered to be similar to those for Airports, although with obvious differences in scale, cargo handling capability and operational frequency. In each case the key stakeholders are the investors in the capital equipment and land, the service providers who operate the infrastructure, the local community and the governmental and regulatory authorities, and of course the end users themselves. For both Ports and Airport terminals owners require a maximum return on capital investment, whilst operators and service providers require optimal use of assets. The local and wider communities insist on minimum impact, while still serving business needs predictably and robustly with operations that meet legislative demands, and also while meeting environmental considerations. In summary, the principle operations of a marine port and an airport are fundamentally similar. They are both transportation hubs, act as interchanges between transport modes, and adhere to regulatory consent in terms of customs and excise. Additionally, both need to dock vessels, offload and load cargo, and are dependant on weather and other indirect social and environmental influences.

An Airport Example. A recent study into stress levels of aircraft traffic controllers, and the approach to the problem from a holistic systems perspective, may hold interesting clues to an expanded systems approach. The safety of air traffic systems is directly related to the workload and the availability of resources necessary to manage the traffic. For example, a given number of air traffic controllers can efficiently and safely manage only a certain maximum amount of traffic. The goals of the study and the ensuing analysis were to identify non-intuitive but distinct patterns of behaviour which governed the overall airport-system processes, and to examine external influences on the airport system from a holistic systems and complexity perspective, and to potentially, in the long-term, outline design and management improvements for the sustainability of airport infrastructure.

Analysis of the data using the complexity metric derived from entropy calculations, and the tracking of this complexity metric with respect to time, revealed that wind velocity was a key influencing factor of main significance within the system, i.e. as the wind increased the workload on the air traffic controllers also increased due to increased uncertainty injected into the system initiated by the wind velocity. This data analysis was confirmed by interviews with operators and supported existing tacit knowledge and intuition, but which had previously not been formally recognized as a key process variable. It's probably worth noting that conventional statistical measures of variance tended to "smooth" and mask the chaotic influence of the Wind Velocity, whereas the complexity metric highlighted this effect.

In addition to determining the key source of system complexity, a metric was established to monitor, in real-time, critical traffic density against an agreed baseline. This complexity metric enabled the establishment of a holistic safety-trip for airport workload and also enabled the "a priori" identification of critical periods at different airports in a given traffic sector. Critical complexity of air traffic becomes measurable and therefore manageability and overall operational safety is increased. Also, knowing "a priori" of critical system complexity, and its causes, provides operators with a powerful new tool for planning truly robust operational performance.

There are two significant outcomes from this study. Firstly, process data can be used to drive, reinforce, confirm, and provide additional insight for informed expert opinion. Secondly ideas of complexity can be used as a holistic measure to track and monitor system performance.

The Port Example.

Port operators and shipping owners conduct their business on agreed rates for port usage and cargo handling capacity that can largely be pre-modelled by various standard procedures. One recurring problem is that of demurrage. In commercial shipping, demurrage is an ancillary cost that represents liquidated damages for delays, and occurs when the vessel is prevented from the loading or discharging of cargo within the stipulated lay time, i.e. when Port resources are not available to ship operators at agreed levels then operators incur a penalty. That many sophisticated modelling packages have been used to lessen demurrage, and yet it is still a persistent problem reveals what is already quite intuitive, namely that ports are collection of people, equipment and services that are inter-related in a complex set of relations. They are in fact complex systems and as much as we would like to try and simplify and rationalise our approach to them, they remain fiendishly difficult to manage

If we consider the approach used for the Airport example we can gather process data characterizing the system to try and obtain a new insight into Port operations, and then use the same methods to monitor complexity with time. In fact, what first becomes apparent is that most Port and Shipping operators only collect data that is relevant to immediate economic targets. The amount of cargo loaded, and the time at berth are clearly logged but little else. For weather conditions, air temp, harbour sea conditions, wind velocity, labour conditions, equipment breakdowns, or any number of other measures of potential influences, it is necessary to look piecemeal for sources – if they exist at all.

Using basic measures of Port handling, berth activity in a given Port over a 3 year period was analysed from a holistic complexity perspective. The results proved interesting and the analysis is summarised in bar graphs below. From the analysis, Fig. 3 shows that from years 2002 through to 2004 there was a general trend within Berths 1 and 2 for the complexity to increase. It is speculated that this was due to the gradual inefficiency of the Port operations, i.e. overstretched facilities, or in complexity terms, increasing system noise. Also, Berth 1 for the year 2004 does not follow the overall increasing complexity trend. Fig. 3 also shows that Berth 1 is generally less complex than Berth 2.

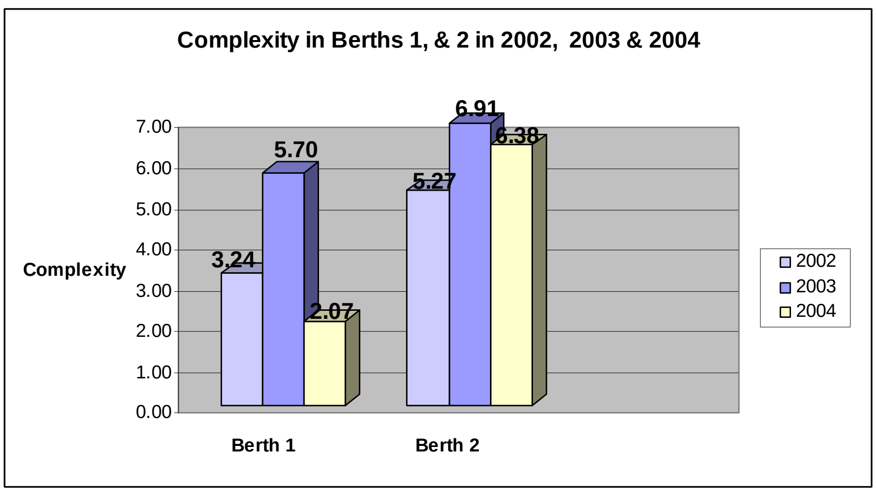

Figure 3. Complexity in berths 1 and 2 from years 2002 to 2004

Computing a value for berth robustness which here is the percentage difference between the maximum and average system complexities shown in Fig. 3 it's possible to arrive at a measure, inferred from system complexity, which refers to a system's ability to maintain its functionality in the presence of uncertainties. Comparing Figs. 3 and 4 it's seen that Berth 1 in year 2004 would clearly be the berth of choice for a shipping operator, i.e. where there would be most certainty of operations performing as planned and required, and for the port operator this may be where to place high-value customers, although operational questions must be posed as to the reasons for the differences.

The power in this analysis was the ability to unveil in holistic, and clearly labelled manner, what was known to operators within the Port but not explicitly captured within existing data capture frameworks, i.e. trends and patterns within complex systems are difficult to openly identify and discuss. In this example it was also possible to identify a clear disconnect between times at berth and amount of cargo loaded/unloaded. This led to further investigation as to the causes.

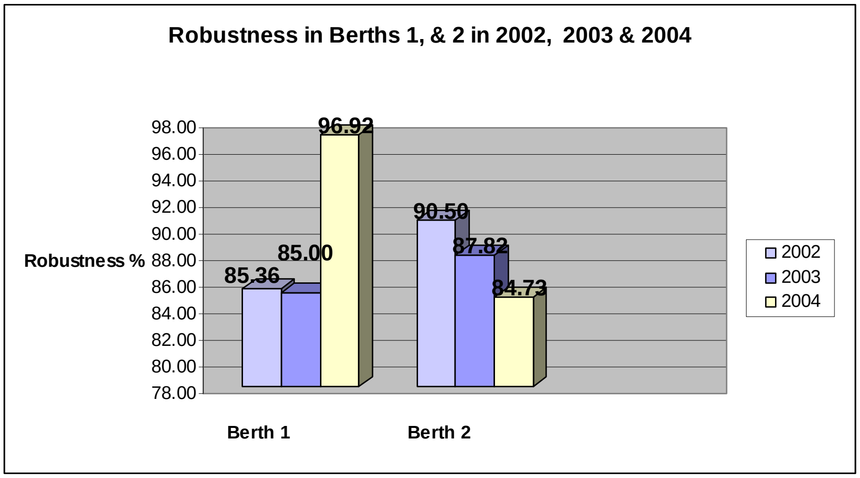

Figure 4. Robustness in berths 1 and 2 from years 2002 to 2004.

Clearly in this example, as port or shipping operator there are financial incentives to tracking complexity and there are perhaps increasing gains from the gathering of wider data. The analysis suggests that there could be value in widening the system under analysis to include additional external influences into the model, such as dollar rate, weather patterns, equipment breakdown, world port ranking for shipping trade, etc.

Discussion

What can we learn from all of the above? We have seen in the initial discussion that ideas of sustainability are vital to the future of industry and we see conventional life-cycle management being extended to include environmental and social issues and being placed within new methodologies and processes such as Life Cycle Management (LCM) and Life Cycle Analysis (LCA). We look to Systems Thinking and the Systems Engineering processes for holism and to capture the complexity of interrelating system components and we, by implication, define sustainability as being the “correct” functioning of a product, service, systems, organization, infrastructure or community, over its planned life cycle. Then, of the many initiatives and tools available to capture expert opinion in order to build models for the successful design of these sustainable systems it is clear that these models are difficult to validate, and that not much thought has been given in the literature to how these systems may be actively monitored. The paper looks to an easily computable measure of complexity and demonstrates how this measure may be used to gain system insight and how to approach the trade-off between required functionality and system manageability. In the Airport example it's seen how Wind Speed emerges during analysis as a key influence upon Air Traffic Controller stress levels. It's also mentioned in that example how a measure of complexity can be used as a holistic system measure to monitor overall system health with a threshold being established as an early warning to system instability. In the Port berth example it's shown how complexity may be used to track operations and provide a comparison of services. It's shown how complexity can be used as an intrinsic system property that describes the health, or otherwise, of operations and enables overall trends to be monitored.

The paper claims to offer an approach to managing Ports as complex systems and in so doing provide economic, social and environmental advantages, in fact to offer an overall approach to manage very complex systems sustainably. Firstly it's clear that Ports, and for that matter, many large infrastructure systems are complex with many interconnecting elements with internal and external sources of perturbation. We have realised that we need to look at all the processes within a port system and to find the data that is either available or can be measured to characterise those processes. A range of measures could be analyzed say from dredging metrics to ship movements, cargo handling rates, pilot hours, container movements, number of staff, number of maintenance interventions, rail exports, road movements, exports, and anything else that can be measured and which stakeholders would feel relevant to port operations and that would characterize, in an overarching view, the processes. By not being tempted to drill deeper into the minutiae of highly non-linear relationships and in trying to define interactions with ever greater modelling detail, an alternative approach is to employ a global framework, reframe to the vision of the observer, and track the complexity of the system and thereby gain sufficient insight to enable strategic planning and effective management.

The systems side of the analysis means drawing the system boundaries as widely or narrowly as needed to define the problem (i.e. reframing the vision) and looking at, and learning from the encapsulated real world events, such as the rise in sea water levels, the loss of marine habitats, and freak weather patterns. The idea is not to look at only one focused part of the system, say the harbour silting model, but to try and look at the system as complete with all the interconnecting elements in order to try to discover emergent properties and also the variables that might influence the behaviour in ways not fully apparent at the present. Traditionally this type of analysis is not pursued because there aren't the tools available for this kind of work. The complexity metric provides us with an alternative strategy.

Methods currently abound as how to establish these complex sustainable systems, over 700 models recently covered in a report by the Building Research Establishment in 2006 (BRE 2006), but most solutions lack the ability to validate and monitor and validate the theory. This paper suggests the following managed approach for a sustainable system as outlined in Fig 5 using the Managed Sustainability Model (MSM).

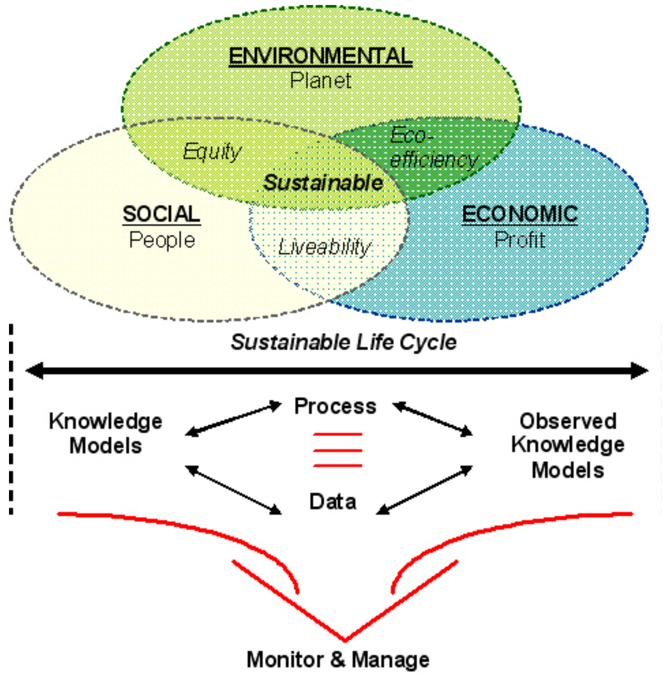

Figure 5. The Managed Sustainability Model (MSM).

1. Knowledge models are created from empirical evidence and expert opinion.
2. System processes are studied with a view to establishing metrics.
3. Observed data is accumulated.
4. Observed knowledge models are created and compared with initial expert opinion and model adjustments are made as appropriate.
5. The system is monitored and subject to appropriate management interventions.

Conclusions

The scale of the new global challenges demand an alternative approach to engineering problem solving. Systems engineering includes a process of continuous learning about the systems in question and their interactions with the dynamic environments with which they are connected. Port authorities are necessarily engaged in a complex global role within business, environment and people. Engineering for sustainable development requires whole-life thinking and consideration of all the implications of every decision.

Systems thinking has much to contribute to improvement in sustainability by helping to create a line of sight from individual activity to emergent properties. A holistic systems approach is a potential way of incorporating real world events into port processes and thus of managing sustainable development. In this context sustainability is seen as directly related to system complexity, i.e. a system reaching unmanaged critical complexity will by definition be unsustainable, fragile, or random in behaviour.

Sustainable development presents new problems for port authorities while at the same time presenting opportunities. Appropriate and practical solutions offer massive commercial and social gains. The key finding in this paper is to treat sustainability as a branch of complexity science and to bring tools and technologies already available from other fields and to use them as an adjunct to systems thinking. For reliable tracking of sustainability system operators need to pay more attention to the gathering and dynamic use of data.

Further Work

The future challenge is to convince the various Port stakeholders that provision of data sets will ultimately benefit all parties. Additionally tracking of complexity in real and theoretical models needs further research in order to understand signs and trends towards system extinction.

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Biography

Lucy Allan is the Sustainable Infrastructure Systems leader within DRTS Ltd. She holds a MEng in Civil Engineering from The University of Sheffield, and is currently studying for an Engineering Doctorate at Bristol University. She has three years experience in environmental systems, managing systems for enhanced performance, civil engineering with an environmental engineering context, and marine structures and managing their complexity. The background to this experience was gained after an eleven month research scholarship at Yamaguchi University, Japan, and during a twelve month scholarship at the Technical University of Catalonia, Spain.

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