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Understanding performance measurement systems using physical science uncertainty principles

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Abstract *Observes that performance measurement models are largely based on deterministic assumptions about the world. Suggests that it is time to re-align performance measurement with post-deterministic discoveries made in the physical sciences, especially quantum physics. In the physical sciences, scientists have (reluctantly) come to accept that the world has a fundamental uncertainty at its core. Asks the question of what lessons can be drawn for performance measurement from this knowledge of the physical world. Addresses this question first by describing the development and epistemological consequences of three post-deterministic (physical world) discoveries of: uncertainty, bounded instability, and self-organisation. Then traces the equivalent path to uncertainty in management. Concludes that it is time for the oldest management theories, which still underpin current performance systems, to be realigned with knowledge on uncertainty. Ends with a look at two current performance systems, activity-based management, and the Balanced Scorecard. In line with knowledge about fundamental uncertainty, these (and other) performance systems should focus on identification of the "aggregate system" critical few.*

Introduction

Strange experimental findings in quantum physics at the beginning of the twentieth century changed mankind's view of the physical universe for ever. Since that time, the physical sciences have moved on towards new understandings that accept fundamental uncertainty at their core (Wheatley, 1994; Kelly, 1994; Kauffman, 1996). In contrast, aspects of business practice, particularly the use of performance systems, continue to be largely based on a belief in fundamental certainty (Freedman, 1992; Quinn *et al.*, 1996; Kanigel, 1997). Such a deterministic view parallels the physical laws advanced by Isaac Newton, which assume that if the complexity of any system is understood then eventually every known interaction in it can be accurately predicted (Zohar, 1990). Current performance systems strongly hold on to elements of this view as outgrowths of Taylorism, which is the management equivalent of Newton's views (Dinesh and Palmer, 1998).

This belief in certainty leads performance systems to prescribe goal setting, documentation, and linkage of measures with one another as key to good management. However, this approach is under fire in the current business environment of fast change and uncertainty (Stumpf, 1995). As performance measurement researchers continue to struggle to find causal links between

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measurement and strategic performance (Neely, 1999), a reassessment of key assumptions is timely.

This article takes the view that it is appropriate to re-examine performance measurement assumptions in terms of physical science uncertainty principles. The purpose of the article is to ask the question: "What lessons can be drawn for performance measurement from findings in the physical sciences?"

To do this, the article starts with a review of some "uncertainty" discoveries made in the physical sciences, beginning in the early part of the twentieth century in quantum physics. This leads to a set of post-deterministic principles based on an understanding of uncertainty. The article then traces the path of twentieth century management model development. Comparisons are made with the physical world, illustrating how the paths to knowledge parted company, with the result that management has become split in its views on uncertainty. This is followed by a description of how current performance systems remain on the old path where certainty is still assumed. An examination of two popular performance systems:

(1) activity based management (ABM); and

(2) the Balanced Scorecard

provides anecdotal evidence that performance systems are most useful when they are used in a fashion consistent with uncertainty principles. The article finishes by summarising what this understanding means for managers.

The move to uncertainty in the physical sciences

When Isaac Newton published *Philosophiae Naturalis Principia Mathematica* in 1687 (Coveney and Highfield, 1996) scientists believed they had reached a point in knowledge whereby the fundamental rules of the universe were understood. Armed with knowledge of the effects of forces on matter, they believed that there was no limit to the predictive and explanatory power of their understanding. Like balls on a billiard table any system could be reduced to basic elements. Their interactions could be understood, modelled and predicted according to a basic set of linear equations (Wheatley, 1994).

Although scientists occasionally noticed unpredictability, they held fast to the belief that this was nothing more than complexity so great that scientists could not track it. ". . . But they were sure in principle that they might one day be able to do so. When that day came there would be no chaos . . . only Newton's laws. . ." (Wheatley, 1994, p. 29). Laplace wrote: "Such an intelligence would embrace in the same formula the movements of the greatest bodies in the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes" (Gleick, 1988, p. 14).

However, as technology caught up with scientific knowledge, gaps began to appear in the claims that this deterministic view could explain everything. The appearance of these gaps is linked to Einstein's 1905 proposal on the photoelectric effect of light, and diverse research into the behaviour of non-linear mathematical and physical systems. In retrospect, these discoveries set off a chain reaction of (uncomfortable) discoveries about the make up of the physical universe and, more to the point, our ability to measure and completely understand it. The physical sciences have gradually developed theories that incorporate a fundamental uncertainty of complex systems. These theories share three common, interrelated components that are detailed next under the headings of uncertainty, and bounded instability and self-organisation.

Uncertainty

Uncertainty is grounded in two properties:

(1) sensitive dependence on initial conditions; and

(2) the impossibility of measurement without participation.

These are interrelated, since the first renders accurate prediction of the behaviour of non-linear systems impossible unless every property of every element is precisely known, and the second states that this knowledge is unattainable, since the act of measurement influences the system under scrutiny.

Sensitive dependence on initial conditions, dubbed the “Butterfly Effect” by Gleick (1988), was first observed by Edward Lorenz. A mathematician cum meteorologist, Lorenz ran a computer simulation of a weather system (which is a classic non-linear mathematical system) and noticed that it produced vastly different results after only a few periods when the starting conditions were modified – even by rounding the starting parameters from six to three decimal places when re-starting his simulation (Gleick, 1988). For weather prediction, Lorenz’s discovery had far-reaching implications for those investigating non-linear systems: while we can trace a path backwards through time, we cannot do the same thing forwards. This suggests that prediction, especially long-term prediction, is pointless.

The Butterfly Effect was not merely a meteorological phenomenon. Lorenz’s research inspired similar investigations in a wide range of fields including turbulence, liquid-gas phase transitions, economics, and population biology (Gleick, 1988).

The other body of research that contributed to the demise of determinism centred on questions about the nature of light, particularly work by Albert Einstein and Werner Heisenberg. This work concentrated on the unusual capacity for light to act as both a wave and a particle, depending on what property was being studied.

Prior to Einstein’s 1905 photoelectric proposal that light is made up of virtual particles called photons (as was later verified by Robert Millikan), experiments had provided strong evidence that light is wave-based (Felder and Felder, 1998).

Confusion about the exact nature of light was exacerbated by the results of a double-slit experiment (Hawking, 1998; Gleick, 1992; Felder and Felder, 1998). In this experiment, light was shone through two slits onto a back wall, in an attempt to see if the resultant light patterns could be explained by both particle and wave behaviour. Four key difficulties related to measurement were discovered during these experiments and the ones that came after. These difficulties and their (often much later) explanations are described next.

The first difficulty arose from the fact that as the light particles being studied got smaller, waves of shorter wavelengths were required in order to study their equivalent wave properties. However, since a wave's energy increases as its wavelength decreases, the shorter the wavelength, the greater the impact on the particle being studied. This particle-wavelength relationship is believed to be at the heart of many of the confusing and unpredictable results seen during the double-slit experiment.

A second difficulty that the physicists discovered relates to the act of measurement itself. When a single light particle's path was studied, measuring it "forced" it to take a position, when prior to measurement it was just a "possibility". Physicists concluded from this that the results of our measurement will always be influenced by the act of measuring.

Prior to this view, it had always been accepted that you could disturb a system by measuring it in some particularly clumsy way, like feeling around with a large stick to figure out the position of a ping-pong ball. But the general view on measurement had always been that, if you were careful enough, you could do your measurements in such a way that they would barely disturb the system at all. Thus the system would continue to act as it would have without you there.

But Heisenberg's findings in particular revealed that the total uncertainty in any measurement will never be less than a certain constant (the uncertainty principle), due to the act of measurement affecting the result (Hawking, 1998). When the Butterfly Effect is applied to this uncertainty, the implications of trying to apply Newtonian "measure, build and predict" type logic to the understanding of a complex system is rendered virtually worthless.

A third key difficulty that arose from the double-slit experiment was that, no matter how the scientists carried out the measurements, if they knew which slit the photons went through, they got a wave interference pattern. If they did not know which slit the photons went through, there was no wave interference pattern.

Essentially, this placed scientists in a difficult position. With respect to light, there were two properties that they were interested in – velocity and direction of the particle under study. The act of measuring one property affected the other, so both properties could never be known at the same time. Thus, if scientists knew which slit the photon went through (the direction), they were unable to measure the velocity, and a wave interference pattern based on direction (position) measurements resulted. Likewise, if the scientists focused on measuring velocity rather than direction (did not know which slit the photon went through), they observed particle-like behaviour with no wave interference pattern.

In response to this inability to measure all properties of light at the same time, physicists came to the view that behaviour of matter is not precisely knowable or measurable, but rather it exists as a range of possibilities, taking shape only when the measurement is made. This idea is expressed in Erwin Schrodinger's famous conundrum called "Schrodinger's Cat", in which a cat is placed in a box rigged with a device that will (randomly and with equal probability) either kill or feed the cat when the box is opened. Since the cat's fate will only be disclosed when the lid is opened, the state of the cat inside the box is both alive and dead, or at least a function of the combined probabilities of each, until the act of measurement (opening the box) is made (Gribbin, 1984).

A fourth and final difficulty with the double slit experiment was that replication of initial conditions led to different results (Felder and Felder, 1998). That is, although scientists did their best to run the same experiments more than once, they were unable to find any correlation between the results and the starting conditions. Furthermore, the experiments suggested that it is possible for an individual particle to take any number of different paths from the same initial conditions. In retrospect, this was also a demonstration of what Lorenz observed in his weather patterns – the Butterfly Effect.

These multiple and confusing discoveries about the make-up of light were not only verified many times, but also replicated with non-light matter. As the evidence mounted, quantum physicists were forced to the conclusion that, at an individual (particle) level, all of matter possesses a fundamental uncertainty. The overall outcome of these findings essentially turned Newtonian certainty on its head. The explanations for the strange behaviour of light given above are the result of many physicists' discoveries over a long period of time, and show an acceptance of fundamental uncertainty across the entire spectrum of physical science which is very different to pre-twentieth century Newtonian ideas.

Bounded instability and self-organisation

The advent of computer technology in the mid-twentieth century furthered knowledge of an uncertain and non-Newtonian physical universe. One especially profound insight into this uncertain world came from Edward Lorenz's computer simulation of weather patterns. Prior to this time, weather patterns had always resisted both prediction and understanding.

Lorenz's work was based on modelling the location of a particle moving subject to atmospheric forces. Lorenz used a system of elementary differential equations, which, by virtue of their non-linearity, caused his simulated particle to move about wildly and apparently randomly. However, Lorenz noticed that while the momentary behaviour of the particle was chaotic, a general non-linear pattern now known as an attractor system appeared when its path was studied over time (Ott, 1993). This modelled system resembled weather patterns that Lorenz himself had noticed time and again in the real world. The pattern that appeared had a butterfly shape to it, and is now generally known as the Lorenz attractor (Gleick, 1988).

The aggregate view of particle movement that resulted in the Lorenz attractor illustrates a further post-Newtonian principle known as bounded instability. Lorenz's butterfly gives a shape to this bounded instability, which comes about from the paradoxical existence of both randomness (at the individual level) and order (at the aggregate level). Bounded instability results from describing a system of individual movements which, when we take a step back, are random, yet never exceed finite boundaries (Wheatley, 1994).

Lorenz's model showing a bounded unstable system based on the iteration of a few simple non-linear equations has been replicated and verified by many other scientists and mathematicians. Catastrophe theory (Thom, 1989) expands Lorenz's findings to include other non-linear sets of equations thought to underpin the bulk of systems in the universe. To explain, catastrophe theorists postulate that (with qualifications) all non-linear systems (which are thought to account for most systems in the universe (Jencks, 1997)) can be modelled by one of seven elementary topological forms. Lorenz's particle movements, that result in the butterfly topology, is one example of a non-linear system that fits within one of these topological forms. The other six elementary topological forms (the seventh is actually called the butterfly) are: the fold, cusp, swallowtail, wave crest, hair and mushroom (Guastello, 1995, pp. 33-42).

The boundaries of these topological systems are not symmetric, but rather are governed by attraction (both positive and negative) to single sources, or sets, of "strange attractors" (Guastello, 1995). The greater the number, and the more different the types of attractors in the system, the more unpredictable the behaviour of the individual particles moving in that system. Systems fall apart when the number of attractors becomes too great or the wrong types of attractors are present, leading back to the view that the seven attractor systems (topologies/shapes) developed by catastrophe theorists can explain the bulk of systems present in the universe.

Catastrophe mathematicians have also noted (Guastello, 1995), that these strange attractor, non-linear systems represent the bulk of living, as well as non-living, systems. For instance, each bee in a swarm appears to act randomly and with autonomy. It is hard to imagine any form of order or organization arising from such apparently individual behaviour. It is only when viewed from afar that the ordered behaviour of the swarm is noticeable. Living systems such as bee swarms are commonly known as "distributed beings". Biologists support the catastrophe theorists in noting that non-linear systems (such as distributed beings) make up the bulk of the living universe, and further note that these living non-linear systems have the same properties of "bounded instability" described in non-living systems by physical scientists (Kelly, 1994; *Journal of Business Strategy*, 1996).

Catastrophe theory (Thom, 1989) not only deals with the aggregate topological shapes that exhibit bounded instability, but also furthers knowledge about change in these non-linear systems. Change in these non-linear systems is believed to happen suddenly and unpredictably, and can be triggered by either small or large events. Any slight change in the environment is thought to have the potential to cause a massive shift in the entire system.

This type of change is known as self-organisation, and is based on a process of destabilisation, followed by reconfiguration. That is, once a bounded system is disturbed, it will self-organise to a new state of bounded instability (Guastello, 1995). The important features of change in such self-organising systems are (Gleick, 1988; Kauffman, 1996; Kelly, 1994; Parker, 1998):

- Reorganisation triggered by either a significant change in the external environment or a minor variation at an individual level which is then amplified throughout the system.
- Failure of the existing system followed by reconfiguration to a new state where it is better able to deal with its environment.

Guastello (1995) posits that this process of self-organisation (also known as bifurcation) takes place as sets of strange attractors are competing within a single system. A small change can throw a particle (or equivalent individual element) out of the boundary (basin of attraction) of one attractor and into a new path around another attractor. This change in relative attraction upsets the stability of the system, creating non-linear feedback until the entire system shifts to a new pattern.

As the system itself is believed to be most stable when in a state of bounded instability (which is really not very stable at all) such a system is extremely sensitive to variation in its components (Jencks, 1997). It is liable to suddenly swing back into a state of chaotic change, before stabilising once more.

Summary

The trend in science described in detail here suggests that both living and non-living systems in the universe, while appearing to have some form of order at the aggregate level, have at their core a fundamental uncertainty. Already this uncertainty suggests that at the individual level measurement can be seriously flawed, as initial conditions, inability to measure all properties at once, and inseparability of the observer from the system cause major problems. It is only when an observer steps back from the individual level, that he can see a "strange" (aggregate) and non-linear order, which is where the system is in a state of bounded instability. Change at this point can happen rapidly and unexpectedly, and results in self-organisation to a new state around a new attractor at the aggregate level.

Newtonian determinism in management moving to uncertainty

This section traces the path of certainty to uncertainty in business. Unlike their physical science counterparts, management scientists have not yet accepted or understood fundamental uncertainty assumptions across all business models. Although the most recent management model (the open systems model) is based on a knowledge of a non-linear universe, this model sits alongside (rather than replaces) the older models of Taylorism and human relations, which still hold more generally to certainty principles.

The conclusion of this section is that, if management theory as a whole is to move onwards to new understandings that fit with knowledge of a generally non-linear universe, then, as well as introduce and accept new non-linear models, earlier management models also need to be re-aligned with knowledge of uncertainty.

Taylorism: the oldest management model

The first formalised industrial-age organisational theory, known as scientific management, was developed by Frederick Taylor in the early part of the twentieth century (Quinn *et al.*, 1996; Guillen, 1994; 1997). Scientific management, or Taylorism as it came to be known, matches (in an organisational setting) the deterministic physical principles of Isaac Newton. The Taylorist view holds that organisations are like large machines, which can be broken down into subparts until the complexity of the structure is understood. Likewise, all jobs can be broken down into steps, and workers can be trained in "one best way" approaches that will increase the efficiency of work, and hence drive the organisational "machine" faster and more cost effectively (Freedman, 1992; Kanigel, 1997).

These Taylorist views have been heavily criticised at periods throughout the twentieth century, coinciding with evidence of uncertainty in the business universe. However, despite these attacks, Taylorist theories remain largely fundamental to the development and use of current performance measurement systems. This fit of Taylorist assumptions to current performance measurement systems is described next.

Two management models, known as the rational goal model and the internal process model, depict Taylor's views on management in detail (Quinn *et al.*, 1996). The first of these models, the rational goal model, is based on the central idea that a firm should strive to make a profit (Quinn *et al.*, 1996). The basic assumption in this approach is that clear direction (from top management) leads to productive outcomes. Using this model, there is a continual emphasis on goal clarification, rational analysis, and intervention.

This "rational goal" emphasis on goal clarification is a key basis of both early performance measurement systems such as management by objectives (MBO), as well as more recent measurement systems such as the Balanced Scorecard (Dinesh and Palmer, 1998). To explain, the Balanced Scorecard measurement system is based on determination of an overall strategy (goal) and, from this, the development of a set of lower level matching measures that are consistent with the overall goal or strategy (Kaplan and Norton, 1992).

The second management model directly aligned with Taylorism is known as the internal process model. The internal process model is complementary to the rational goal model, and came about largely through the work on "professional bureaucracies" by Max Weber and Henry Fayol (Quinn *et al.*, 1996). The central idea in this model is that stability and continuity provide effectiveness, and that routinisation leads to stability. The internal process model's emphasis is on defining responsibilities, measurement, documentation, and record keeping. The model focuses on efficient workflow and coordination.

Again, tenets of the internal process model remain core to current performance measurement systems. For instance, in the measurement system known as activity-based costing (ABC), there is a focus on detailed documentation and record keeping that is expected to lead to improved allocation of resources (Mabberly, 1992). ABC operates by detailed documentation that traces direct and indirect costs from specific product or service lines back to the activities involved in production (Cooper and Kaplan, 1988). These activities of production are then linked to factors (or inputs) that "drive" them. The drivers that result from this are believed to be input measures that correlate positively with needed resources (Mabberley, 1992).

This short review suggests that Taylorist assumptions of goal clarity and direct (linear) links between cause and effect remain in evidence in current measurement systems. The following sections describe how other management models have developed in response to noticed uncertainty in the business environment, which could not be explained by goal clarity or linear links. However, these models have developed alongside, rather than replaced, the certainty assumptions that still provide the basis for current performance measurement systems.

The human relations model

The first evidence of uncertainty in management, which highlighted problems with trying to correlate cause and effect directly, came from a set of experiments carried out by Elton Mayo between 1927 and 1933. The phenomenon known as the Hawthorne effect came from this well-known productivity study, which involved the observation of a group of workers from Western Electric's Hawthorne Plant near Chicago.

In this study, attempts were made to measure and correlate worker productivity with their physical working conditions (such as degree of lighting or noise). However, findings from the study were completely unexpected, as no correlations between productivity and conditions could be found. Regardless of (positive or negative) changes in working conditions, resultant productivity of the workers went up. Elton Mayo and his researchers concluded that it was their own presence that affected the outcome of the study (Bartol and Martin, 1991). As long as the study was in progress productivity increased.

These findings have strong parallels with the findings of the double-slit light experiment described previously. Results were different even with the same initial conditions, and researchers concluded that the act of measurement itself had an impact on the results.

However, it seems that this is where the scientific and management epistemologies parted company. While the physical sciences went on (albeit reluctantly) to embrace the paradox seen in the double-slit experiment, management, when faced with the Hawthorne results, simply developed a new subset of factors to explain the unexpected findings.

These newly developed "intrinsic motivation" factors became the basis of the human relations model of management (Quinn *et al.*, 1996). The human relations explanation of the Hawthorne effect is that the goodwill that the workers experienced through being the focus of attention (an intrinsic motivation factor) overcame the impact of detrimental changes in extrinsic motivation factors (e.g. lower lighting levels).

Thus, although management scientists had now noticed unpredictability, they held fast to the belief that the Hawthorne findings were due to nothing more than a greater than expected complexity. Once these new (human relation) factors were added to the management toolkit, prediction would eventually again become accurate.

The open systems model

By the 1960s, both Taylorist and human relations models were well entrenched in management (Dinesh and Palmer, 1998). However, at about this time management researchers were also beginning to write yet another model (Quinn *et al.*, 1996). This model, known as the open systems model, had in its roots an awareness that the external business environment was less predictable than either the Taylorist or human relations models had allowed for.

The development of the open systems model came from a variety of sources. One source was the growing amount of empirical work that provided evidence that managers live in highly unpredictable environments and have little time to organise and plan (e.g. Mintzberg, 1975). This empirical approach generally concluded that job structure had little to do with being able to pre-plan through goal clarity or develop direct links between cause and effect. Instead this work (e.g. Quinn *et al.*, 1994) led to a contingency theory perspective, in which appropriate managerial action depended on key variables of the system (such as organisation size, technology type, or environment predictability). Adaptability and flexibility, as well as quick response to change are the goals of contingency theory.

A second source of development for the open systems approach was computer modelling work initiated by Jay Forrester at the Massachusetts Institute of Technology (Forrester, 1975). The field of system dynamics arose from Forrester's work, which is based on modelling the business world as a series of feedback loops with non-linear characteristics. In parallel to Edward Lorenz's findings that his non-linear modelling of weather patterns fit observed physical patterns, Forrester's work was used to model many business situations successfully. Eventually the field of system dynamics gave rise to a set of common business system "archetypes" (Senge, 1994; Kim and Anderson, 1998), analogous in their descriptive intent to the topological forms derived from catastrophe theory.

The field of systems thinking (a less quantitative, and more "holistic" approach to non-linearity) also developed in response to this non-linear modelling (Ackoff, 1999). The systems thinking field also recognises and accepts uncertainty in the business world, but is less prescriptive than system dynamics and generally concerns itself with the avoidance of reductionism. The key difference between system dynamics and "soft" systems thinking is that system dynamics assumes that a system can be modelled (using non-linear assumptions), whereas soft systems thinking assumes that a system cannot be modelled or fully understood.

Rather, soft systems thinking focuses on engaging in a learning process by which the limitations of perspectives can be known and incorporated into decision making (Checkland, 1999). Just as the system dynamics archetypes developed through computer modelling are analogous to physical system non-linear topologies (also developed through computer modelling), so the concepts of synthesis and emergence introduced through a systems thinking perspective (Ackoff, 1999) are analogous to the concept of self-organisation (Gleick, 1988; Kelly, 1994). That is, synthesis and emergence assume that aggregate order arises from interactions at the component level.

These open system approaches (contingency theory, system dynamics and systems thinking) are beginning to influence strategy research (e.g. Hamel and Prahalad, 1994; Hamel, 1998; Brown and Eisenhardt, 1998; De Geus and Senge, 1997; Senge *et al*., 1999). This is largely because recognition of a non-linear universe is even more apparent now than it was in the 1960s and 1970s, as unpredictability in the world of business has grown (Tetenbaum, 1998).

However, despite the clear parallels of these open systems approaches with the physical fields of post-deterministic science described previously, the open systems model has not yet replaced the earlier models of Taylorism and human relations in business. This is especially apparent in the continued use of Taylorist assumptions associated with current performance measurement systems, as described at the beginning of this section. Rather, it seems that the epistemological trend in management has been to develop separate management models over time. The "best" approach that some management researchers are now advocating is a "both/and" approach (Quinn *et al*., 1996), whereby open systems, human relations, and Taylorist approaches are used together, even while recognising the difference in their assumptions.

An alternative approach to the better use of management models may be to re-explore the older models in light of new understandings. The rest of this article focuses on a re-examination (in light of uncertainty principles) of Taylorist assumptions in terms of the practice of performance measurement and the development of performance systems.

Measurement systems

This section starts by describing recent debates about whether or not measurement development is appropriate in a "non-linear" world of fast change (Tetenbaum, 1998). This debate represents a larger debate between the linear assumptions of Taylorist models versus the non-linear assumptions of open systems models, and, at a meta-level, the ongoing conflict between certainty (determinism) and uncertainty principles. The description of problems related to measurement system appropriateness in a non-linear universe is followed by anecdotal evidence which suggests that, when managers "accidentally" use performance measurement systems in ways that match uncertainty principles, organisational success results. The section concludes that performance measurement systems can be very useful in a fast changing (non-linear) environment, as long as non-deterministic assumptions are understood and practiced. From this, value can be gained through the deliberate practice of measurement with knowledge of uncertainty.

Are performance measurement systems useful?

Despite the continued widespread development and use of MBO, the Balanced Scorecard, ABC, and other performance measurement systems, questions are being asked about the relevance of performance measurement systems in general in the information age (Hoffecker and Goldenberg, 1994; Stumpf, 1995). Under the influence of open systems thought, managers are now questioning whether or not a firm can, or even whether it should try to, set a clear course in an environment of rapid change (Hamel, 1998; Kelly, 1999). This view directly contradicts the rational goal assumption of goal clarity that still underpins popular measurement systems such as the Balanced Scorecard, as described earlier.

In this open systems view, adaptability concerns also override efficiency concerns. This shift in focus leads to the questioning of the relevance of the internal process model assumptions based on documentation and record keeping (Kelly, 1999; Hoffecker and Goldenberg, 1994). That is, if the current work environment is changing faster than the time taken to develop measurements, then trying to bring about stability through documentation is pointless.

These arguments about the worth of measurement systems illustrate the problems that have come about from the epistemological development of management models as alternatives, in contrast to the integrated approach to uncertainty seen in the physical and biological sciences. Rather than throwing measurement systems entirely out of the window, as some authors (e.g. Kelly, 1999) would argue, a better approach may be to re-examine measurement systems in terms of the findings that were detailed previously with respect to uncertainty in the physical universe. Using this knowledge, it may well be that measurement systems *are* useful, as long as their use fits knowledge of fundamental uncertainty. The next section details the "accidental" success of some current measurement systems, which provides evidence that this is the case.

Review of the success of current measurement systems

This section provides supporting evidence that measurement systems, when used (even accidentally) in such a way that they match the uncertainty principles of the physical sciences, lead to greater success. Specifically, the change from ABC to activity based management (ABM) is examined briefly, as is the successful (and unsuccessful) use of the Balanced Scorecard.

The drivers of activity based management

In a previous section, ABC was used as an example that highlights the use of internal process model assumptions, which in turn reflects Taylorist assumptions, which in turn reflect certainty principles (belief in a predictable universe). That is, ABC is based on detailed documentation that links together specific product and service lines to their specific "drivers". However, this ABC use for accurate product costing has had limited, if any, success (Cooper *et al.*, 1992).

In the early 1990s a new use for ABC systems was developed. Increasingly it became used as a performance *management* system known as ABM (Cooper *et al.*, 1992; Lyne and Friedman, 1996). Instead of accurate product costing as the focus, ABM uses ABC to manage the performance of an organisation by identifying the one or two "critical" input drivers that, when focussed on, result in large gains in organisational performance. This critical few approach has proved successful in several instances.

For instance, John Deere Ltd has used this critical few approach successfully (Stevenson *et al.*, 1993). In their use of ABM, John Deere management noticed that design modularity was an input connected to many other costs in the system. By assigning arbitrarily high cost penalties to non-standard design solutions, John Deere management used ABM to encourage their design teams to focus on parts rationalisation and modularisation. This focus in turn resulted in cheaper, faster production, and higher conformance quality. Returns from this decision to penalise non-standard design solutions were much higher than expected. Hewlett-Packard has also successfully used this critical few ABM approach, with similar significant organisational improvements (Landry *et al.*, 1997; Merz and Hardy, 1993).

The success of ABM compared to the earlier failure of ABC can be explained by the findings in the physical sciences discussed earlier. That is, whereas ABC focuses on linking individual products and services to their individual drivers, ABM focuses on the main (aggregate) causes of cost to a firm (Luxton, 1998). As has been seen in the physical sciences, trying to tie individual measures to individual inputs (as is the case with ABC) is pointless for a multitude of reasons. However, ABM's aggregated approach of the critical few better matches knowledge of uncertainty, as possibilities have more order, and hence show patterns more predictably, than at an individual level.

The focus of ABM on an aggregated critical few also parallels the concept of Lorenz-type attractor systems in the physical sciences. In the case of both John Deere and Hewlett-Packard, a focus on the "strange attractor" of design modularisation resulted in the emergence of entirely different production systems. Management at John Deere and Hewlett-Packard did not prescribe these new production systems, but rather they "self-organised" themselves around the focus on design modularisation.

The new production systems also look surprisingly like the "best" production systems that are promoted in current management literature (Schonberger, 1996; Kasarda and Rondinelli, 1998). To explain, the resultant production systems of both organisations have a focus on prevention rather than cure, have decreased time to market, and promote mass customisation (Suarez *et al.*, 1995).

This ability of these production systems to emerge, or self-organise around an aggregate indicator set by management shows that order is not necessarily the same thing as control (Diggins, 1994). In other words, success comes from correctly identifying an aggregated critical few measurements that act as strange attractors to trigger self-organisation. Just as trying to link individual measures to one another is pointless, so is trying to micro-manage or specifically prescribe a new production system. Management in both John Deere Ltd and Hewlett-Packard stepped aside from the implementation and allowed the new system to emerge randomly and unpredictably around the strange attractor of design modularisation. Yet the resultant systems are naturally "bounded", with remarkable similarities to other best of breed production systems. However, management in these instances did not try to impose a "perfect" production system on the workers, but rather allowed the workers to develop their own systems which have self-organised as good matches to their specific environments.

The Balanced Scorecard

As detailed previously, a central tenet of the Balanced Scorecard system is a tie-in with the rational goal model through its focus on goal or output congruence (Hoffecker and Goldenberg, 1994; Newing, 1994; Dinesh and Palmer, 1998). The objectives and measures for the Balanced Scorecard are developed directly from the organisation's vision and strategy.

The Balanced Scorecard has become the most popular measurement system in business, with predictions that over 50 percent of *Fortune* 500 companies currently use some form of it as a measurement framework. Despite its widely touted success, some literature describes the Balanced Scorecard system as inappropriate for organisations with short-term cash flow problems, and for organisations undergoing restructuring (Birchard, 1996a). Rather, the Balanced Scorecard is believed to be successful because of its ability to define the critical success factors, or targets, important to a firm in situations that focus on growth and long-term success (Birchard, 1996b).

This focus on critical success factors or targets strongly resembles ABM's "critical few" approach. That is, putting forward a potential target acts as a strange attractor around which the system can reorganise itself at a new level of suitability. This resemblance has been taken a step further with some organisations placing aggregate input drivers derived from ABM directly into the Balanced Scorecard framework (Daly, 1996). This merging of input drivers with output targets supports the view that a common factor of success in both ABM and the Balanced Scorecard is the identification of aggregate level measures.

Reinforcing this view that aggregation is the way to use measurement systems are findings that, at the individual level, the Balanced Scorecard approach has been unsuccessful. For instance, findings from a study on a grocery supply chain in New Zealand show difficulties in developing specific worker-level measures that match higher level ones (Lucas, 1995).

As an example, Lucas's study shows that a worker level (individual) measure of "number of bottles processed" on a manufacturer's production floor cannot be easily correlated with a higher level measure of "product shipped for the entire production unit". Likewise, when individuals focus on their own productivity measures, there is no correlation with overall unit productivity measures. Sometimes the two measures move together, but at other times they do not.

These findings reinforce the view that measurement at the individual level (in this case individual workers) is generally pointless. Thus, both the ABC-ABM and Balanced Scorecard results provide anecdotal support for the view that reasonable predictive patterns appear only at aggregated levels.

Lessons from the physical sciences

We now come back to the question put forward at the beginning of this article: "What lessons can be drawn for performance measurement from findings in the physical sciences?" As detailed previously, this question represents a larger issue that has been described here through the comparative epistemological development of twentieth-century physical science and management theories. The conclusion from this comparison is that while the physical sciences have come to wholly accept uncertainty, management science has not. Rather, management theories have evolved as competing alternatives. One result of this compartmentalised approach has been an ongoing "either-or" debate about the usefulness of performance systems in business. Our approach here has been to re-examine the use of performance systems in light of the uncertainty principles discovered in the physical sciences. The results of this examination suggest that performance systems can be extremely useful if used in line with uncertainty principles. This view is explained in detail next.

The successful use of measurement systems described in this article show good alignment with the three physical science principles of:

(1) uncertainty;

(2) bounded instability; and

(3) self-organisation.

Evidence from this limited review suggests that aggregation of measurements is far more useful than attempts to measure at an individual level.

It is worth noting that strategic literature has long stressed the ideas of aggregated level measures as providing a focus for business success. Development of critical success factors, determination of aggregate forces (internal to and external to) an organisation, and development of key performance indicators have been present in measurement literature since the late twentieth century (e.g. Porter, 1986; Kaplan and Norton, 1996). Likewise, problems with individual measurements have been known since the Hawthorne experiments (Bartol and Martin, 1991). Attempts to cascade measures down to the lowest level of an organisation have continued to bring problems (e.g. Lucas, 1995).

So, in one sense, the examination here just reinforces what management already knows. What is new here is that these findings suggest that management can use performance systems successfully in an uncertain environment. What is essential is that they use these systems deliberately in a way that is consistent with uncertainty principles.

To explain, a key understanding here is that measurements are best kept to an aggregate level. Individual measurement is, and will always be, unknowable at a precise level, incapable of being measured without the observer becoming part of the system, sensitive to initial conditions, and non-predictive (we can trace an individual path backwards but not forwards). The sum of this understanding is that individual measurement is generally pointless. However, the collection of individual measures may be worthwhile if the focus is to aggregate the information. Rather than trying to correlate inputs with specific results, the better approach seen here is to use an aggregation of individual elements to help determine which inputs (or outputs) are linked to many other elements within an organisation. This leads to the concept that the order of magnitude of links from a single element to other elements in a system is an indicator of an element's importance. This idea (of identifying individual elements that are linked to many other elements in a system) is an idea that is gaining favour in open system-based management literature (Kelly, 1999; Senge *et al.*, 1999). This suggests that performance systems themselves can be used (as ABM was in John Deere) to provide a pathway for the determination of the aggregate critical few. If this is the performance measurement system's focus, then it can be very helpful in an uncertain world.

Likewise, it seems that if these aggregate, multi-linked factors (or measures) are correctly identified and then encouraged, such a focus can initiate spontaneous self-organisation. Knowledge of the bounded instability and self-organisation principles in the physical sciences suggests that management should attach clear benefits to focusing on this aggregate information, but should not try to control or micro-manage what individual workers do. Self-organisation will result in a system better suited to the environment, with its own implicit order, caused by reorganisation around the strange attractors of the critical few by the workers themselves.

John Deere Ltd's and Hewlett-Packard's experiences suggest that allowing self-organisation based on identification of the aggregate critical few can work well. In both of these cases, the resultant production systems are unique to their context, and yet resemble best-practice advice taken from recent management literature.

Conclusions

The proliferation of performance measurement systems occurring worldwide (Neely, 1999) suggests that more study into the underlying principles that make these systems strategically successful in a non-linear world is of immense value to management. Empirical studies examining the uncertainty principles presented in this paper, to see if more evidence exists that these principles hold in the successful use of performance measurement systems, would be especially worthwhile.

On a more abstract level, what this paper posits is that, given the epistemological path taken through the development of alternate management models, there is now, more than ever, a need to re-align the older models with knowledge of uncertainty. This represents a re-alignment of the underlying paradigms of science and management (as was the case when Taylorism arose to match the Newtonian model), and it might well be called the development of the new scientific management.

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