Chaos Theory: Implications for Cost Overrun Research for Hydrocarbon Megaprojects

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Abstract: Cost overruns are a recurrent problem in hydrocarbon (oil and gas) megaprojects and whilst the extant literature is replete with studies on their incidents and causes, underlying theories that explain their emergence remain scant. To mitigate the occurrence of cost overruns, an understanding of 'why' and 'how' they occur must be accrued; such knowledge provides managers with the foundations to develop pragmatic techniques to attenuate them. This paper explains the nature of cost overruns in hydrocarbon megaprojects through the theoretical lens of chaos theory. The underlying principles of chaos theory are reviewed and its research implications for examining cost overruns identified. By conceiving megaprojects as chaotic or dynamic systems, the industry and research community are better positioned to develop 'innovative' solutions to mitigate cost overrun occurrence.

Keywords: Chaos theory, cost overruns, hydrocarbon projects, megaprojects

Introduction

Despite advancements in project management theory and practice, cost overruns are a leitmotiv within hydrocarbon (oil and gas) and other infrastructure (social and economic) megaprojects (Reina and Angelo, 2002; Eden *et al.*, 2005; Jergeas, 2008; Love *et al.*, 2011; Rolstadås *et al.*, 2011). In 2012, for example, Chevron announced a cost overrun of AU$9

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billion on its Gorgon Liquefied Natural Gas (LNG) project and a revised estimated project cost of AU$52 billion (representing a 40% increase in their original 2009 budget) (Kombargi *et al.*, 2012). Cumulatively during 2012, companies such as Chevron, Woodside, BG, Santos and Exxon Mobil lost approximately AU$25 billion in cost overruns (Ker, 2011). These staggering cost overruns can adversely impact an oil and gas company's financial profitability, as well as other organizations involved with project delivery. Moreover, cost overruns jeopardize a company's reputation and can trigger a significant fall in its share value. For example, cost overruns incurrred by Woodside for its Pluto Liquefied Natural Gas (LNG) project led to the company's share price plummeting by AU$1 billion (Ker, 2011). Such stark lessons have forced megaproject owners to acknowledge the negative implications of cost overruns and take action to mitigate them. A typical action employed involves placing intense pressure on operators, contractors and service providers to improve their performance and augment productivity (Ford *et al.*, 2014).

Persistent cost overrun problems discourage capital investors and already, infrastructural investments in Australia's oil and gas industry (expected to be > AU$150 billion within the next ten years) are in limbo due to prevailing doubts about financial viability (Daley and Macdonald-Smith, 2013). For instance, Woodside discontinued its plan to build onshore facilities for its Browse floating Liquifued Natural Gas (LNG) project in Western Australia due to cost burdens (Pearson, 2015); and Shell shelved its Arrow LNG project in Queensland, Australia due to potential cost blowouts and high investment risks (Macdonald-Smith, 2015a). Whilst in Canada, Suncor Energy Inc cancelled its proposed $11.6 billion Voyageur oil sands upgrader project due to rising costs (Lewis, 2013). Despite these adverse impacts, research examining the nature of cost overruns within hydrocarbon megaprojects has been limited.

The extant literature has explained cost overruns in hydrocarbon megaprojects as a consequence of an array of exogenous issues, which include logistical challenges in remote locations, wage costs, regulatory complexity, misdirected execution, misaligned objectives and technical challenges (Bloomberg, 2009; Jergeas and Ruwanpura, 2010; Ford *et al.*, 2014). One significant issue relates to the ineffectiveness of project management tools and techniques used for project delivery (Asrilhant *et al.*, 2006). According to Love and Edwards (2013), the push to produce oil or gas encourages decision-makers to become less risk averse. Consequently, errors are propagated and often manifest as rework during construction, therefore negatively impacting upon project cost and schedule performance, safety and the assets integrity. Indeed, the factors that can determine cost overruns in hydrocarbon megaprojects are almost limitless and difficult to measure.

Traditionally, the delivery of hydrocarbon megaprojects has relied on conventional project management theory yet, such projects are fraught with uncertainties that affect cost performance (Stinchcombe and Heimer, 1985; Van Thuyet *et al.*, 2007). Hence, hydrocarbon megaprojects are difficult to manage especially during the construction phase, and using conventional project management tools and techniques are largely ineffective because they are reliant upon highly defined components rooted in certainty (Asrilhant *et al.*, 2006; Loch *et al.*, 2011). Accordingly, more sophisticated perspectives are required to better understand how uncertainties can be managed (Cleden, 2012).

Historically, chaos theory has presented a useful theoretical lens that is able to reconcile the essential interdependencies of variables contributing to uncertain events (Levy, 1994). Singh and Singh (2002) and Remington and Zolin (2011) suggest that it can explain nonlinear and complex interactions that develop dynamically in megaproject systems. It is proposed therefore that chaos theory provides a contextual backdrop for understanding the emergence of overruns in hydrocarbon megaprojects. Consequently, this paper aims to reconceptualise the occurrence of cost overruns in hydrocarbon megaprojects as being the outcome of systems that obey the principles of chaos theory. Against this backdrop, the paper commences with an in-depth literature review to identify fundamental differences between the principles underlying chaos and conventional project management theory. The characteristics of chaos theory are then explained before discussing its relevance to hydrocarbon megaprojects. The application of chaos theory to explain 'how' cost overruns occur in hydrocarbon megaprojects is provided with practice-based examples. Finally, the implications of chaos theory for the management of hydrocarbon megaprojects is presented.

Chaos versus Conventional Project Management Theory

In simple terms, chaos is understood as a state of randomness, disorderliness or confusion/ uncertainty (Reichl, 2004). Chaos theory represents a study of dynamic systems that contain non-linear components and are usually unpredictable over time (Schuldberg, 2011). Unpredictability in dynamic systems stems from continuous changes that enable systems' stability or instability at different times (Haigh, 2008). Chaos theory positions itself in stark contrasts to conventional project management that is based on linear thinking and is described being regular, even, stable and predictable (Schuldberg, 2011). The difference between linearity and nonlinearity is the presence of nonspecific and disproportionate effects in the latter (Tsoukas, 1998). Chaos theory demonstrates that conventional models explain naturally occurring events in only limited cases (Thietart and Forgues, 1995). Linearity asserts that causes and effects within a system have a proportional relationship; that is, the impact of an action is directly proportional to the magnitude of the force producing the action (Schuldberg, 2011). In contrast, chaos theory seeks to understand the behavior of systems that fail to proceed in a traditional cause-and-effect manner (Murphy, 1996).

Many natural or physical systems disobey the traditional logic of science that underpins the basis of conventional project management (Checkland, 1999; Maani and Cavana, 2000; Sterman, 2000). Within complex projects, the relationships between their cause and effect phenomena are neither direct nor equal or proportionate. As previous studies suggest, chaos theory provides an ameliorated understanding of the issues influencing performance in complex projects and contradicts conventional project management theory (e.g. Singh and Singh, 2002). Conventional project management theory defines project management success as being dependent upon many variables, including: planning method; schedule management; quality control or management; use of technology; communication method or management; human resources management; and monitoring and control management (Cooke-Davies *et al.*, 2007).

Conventional project management practice utilizes top-down command and leadership structure, and utilizes methods and principles that are based on the assumption that stability, coordination, regularity, control and predictability can be achieved (Singh and Singh, 2002; Love *et al.*, 2011). Extant literature has relied on conventional management theories in analyzing what, how, when and why a project fails (Melgrati and Damiani, 2002). For instance, a project is deemed unsuccessful if objectives (e.g. cost, duration, operational performance) are not met (Lim and Mohamed, 1999). This crude definition of failure neglects uncertainty that may ensue at the conception phase. Conversely, chaos theory establishes that within a predictable system (such as a project), a parameter could react to small changes in its initial condition and then creates variations to ‘anticipated’ outcomes being observed (Frear, 2011).

Unless such changes to predefined initial conditions are known and managed efficiently, deterministic predictions using conventional tools and techniques will continue to under-perform or/ and fail (Cicmil *et al.*, 2006). Therefore, conventional project management are unsuitable for managing hydrocarbon megaprojects (Cooke-Davies *et al.*, 2011; Love *et al.*, 2011). Figure 1 illustrates the fundamental difference between chaos and conventional project management theory guiding the delivery of hydrocarbon megaprojects.

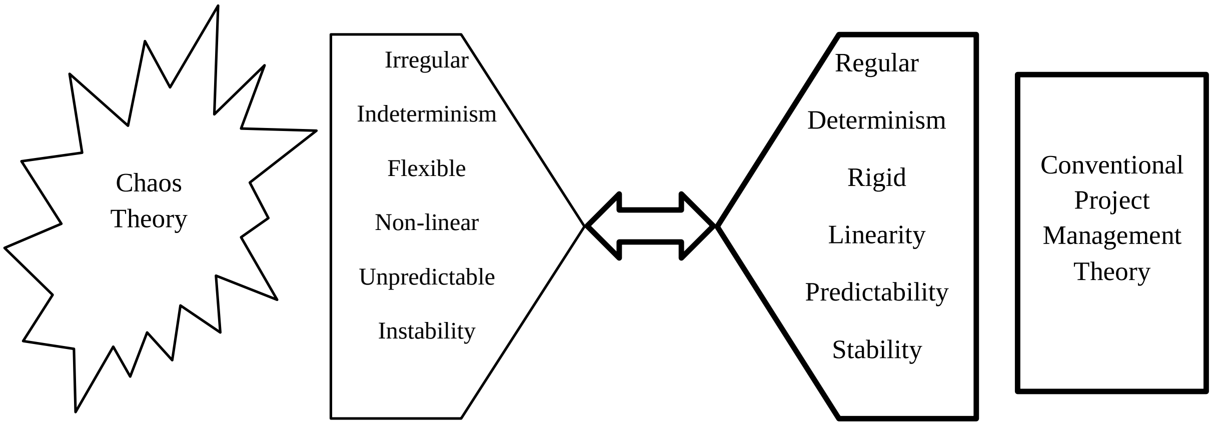

Figure 1. Difference between chaos and conventional project management theory

Chaos theory is a pervasive science that widely affects other fields of study, yet its application to construction and engineering project management remains scant despite studies such as Singh and Singh (2002) and Remington and Zolin (2011) extolling its merits. Thus, demands to rethink current management practice have been widely espoused (Melgrati and Damiani, 2002; Cicmil *et al.*, 2006).

Characteristics of Chaos Theory

Various views of chaos theory found in the normative literature are presented in Table 2. Where's table 2? However, the key attributes of chaos theory can be summarized as: (1)

sensitive dependence on initial conditions; (2) positive feedback; (3) bifurcation and catastrophic phase changes; and (4) strange attractors (Kiel and Elliott, 1996). These attributes are discussed hereinafter.

Sensitive Dependence on Initial Conditions

Sensitive dependence on initial conditions, otherwise known as the *butterfly effect*, assumes small influences cause significant consequences (positive or negative) that cannot be predicted (Schuldberg, 2011). This was illustrated by Lorenz's (1993) study of a deterministic model of the earth's atmosphere (Kellert, 1994; Tsoukas, 1998). Kellert (1994) suggested that unstable behavior within the system is sensitive to small changes in its initial conditions. A hydrocarbon megaproject in the construction phase is highly sensitive to change (Asrilhant *et al.*, 2004). For example, a drawing omission of an electrical component can easily be overlooked when perceived as insignificant at the point in time the event occurred. The long-term effects of such error are difficult to predict particularly where there is a high degree of reciprocal interdependence between stakeholders and where activities are undertaken concurrently. For instance, a minor detail missed creates an error in a component design and then initiates a *domino effect* on other activities across the entire project. Consequently, high-levels of rework are required at a later stage to resolve problems created by that error, thereby generating significant cost overruns.

Positive Feedback

Positive feedback occurs when actions taken to regulate or normalize a system cause further disintegration within (Reigeluth, 2004). In a linear system, stability is achieved using negative feedback in which corrective action is needed to prevent its deviation from its ordinary course (Murphy, 1996). From a chaos theory perspective, a system is dominated by positive feedback in which its future state is dependent upon the initial or earlier conditions (Tsoukas, 1998). Attempts to influence the system increase the likelihood of its collapse. In a megaproject, any change made to an activity undertaken (e.g. cost management, risk management, communication management, scheduling and quality management) creates conditions that continue to support themselves, leading to positive reinforcing cycles or positive feedback loops (Remington and Zolin, 2011). A positive feedback loop could include an occurrence of further project delays due to fast tracking. Negative feedback (i.e., regulates or corrects) and positive feedback (i.e., amplifies deviations) can cause significant further changes to the system's existing condition as well as continuously introduce new patterns of behavior (Hilborn, 2000). In hydrocarbon megaprojects, its implementation within specified environmental objectives often leads to the selection of technology that contributes to cost overruns. For instance, environmental concerns within North Caspian Operating Company Business Ventures (a company acting on behalf of Consortium partners including KMG, Eni, Shell, ExxonMobil, Total, Conoco and Inpex.) prompted the use of specialised technology to trench, lay and backfill simultaneously in Kashagan oil and gas megaprojects (Delpont, 2012). The use of conventional technology would have left trenches open over the three stages and led to an environmental catastrophy (Delpont, 2012). The application of such technology presented consortium partners with several technical challenges that significantly increased the project's cost.

Bifurcations and Catastrophic Phase Changes

Bifurcation represents a situation where slight changes in the system's parameters trigger a succession of continuous variations that culminate in a radical and sudden physical transformation or reorganisation of a system's behaviour (Robertson and Combs, 2014). Sellnow *et al*. (2002) state that bifurcation "represents the flashpoints of change where a system's direction, character, and/or structure are fundamentally disrupted" leading to formation of new ones (p.271). As some parameters in a nonlinear system are varied, the system responds or adapts to the variations by undergoing physical modifications repeatedly or at regular intervals. Bifurcation is established when a nonlinear system can no longer adapt to changes and the system becomes chaotic (Schuldberg, 2011).

Bifurcation is best illustrated by considering a slight variation of situation of a parameter (such as project scope) which then generates a need to adjust the original conditions of other parameters such as schedule, integration, quality and stakeholders' management plans. Such action is necessary to ensure that a project is positioned to accommodate that change. It is likely therefore, that as a changes are being affected, errors are committed due to the interplay between endogenous and exogenous variables. For example, an erroneous forecasted inflation rate leads to financial pressure exerted upon contractors who cannot supply materials at costs originally quoted due to an unexpected hike in prices. Fast tracking may be employed to address the ensuing delays and ensure project completion within the approved schedule. However, such action may not permit sufficient time to plan for the smooth and efficient execution of some project activities. Consequently, unqualified workers may be forced to undertake some tasks further exacerbating the propensity for errors being committed. Changes continue to reinforce themselves until the project lurches from an apparent state of orderliness to randomness or total disorder. A system achieves a state of 'total' disorder when it no longer follows characteristic change patterns (Seeger, 2002).

When a system experiences repeated changes, it becomes saturated with an infinite number

(n^{th}) of potentially stable patterns. This outcome indicates that the system will continually oscillate from one mode to another and is unlikely to settle down until it lapses into a chaotic state. At every bifurcation point, a system rearranges itself into a new hybrid order that may significantly differ from its prior order until disorderliness ensues (Murphy, 1996; Sellnow *et al.*, 2002). For instance, unexpected changes in environmental regulations of a country where an hydrocarbon megaproject is being executed may neccessitate a change in drilling operations and strategies. This change will equally stimulate further actions such as the recruitment of new drilling specialists and coconmittant process changes. Such a situation positions the project in a region between order and chaos, in which it attempts to settle into different steady states until it eventually reaches chaotic situation

Bifurcation implies change scenarios, but there are different types in engineering and construction management systems such as emergent, strategic, planned and unplanned (Bamford and Forrester, 2003). Bifurcation occurs in various forms, depending on the nature of change but sudden changes or radical shifts in a system are referred to as catastrophic changes or ‘tipping points’ (Schuldberg, 2011). Murphy (1996) indicates that while the occurrence of bifurcations can be predicted, their outcomes cannot be. Thus, while project participants may foresee the impending crisis, predicting the result is impossible.

Strange Attractors

Not everything about dynamic systems is erratic; they are also attracted to an idealized state known as an attractor (Robertson and Combs, 2014). An attractors is the characteristic pattern of the process by which “a system self-organizes into coherence and adapts to maintain, sustain or recreate order when subject to change from either internal functioning or external influence” (Pryor and Bright, 2007). According to Murphy (1996), an attractor represents an organizing principle that a system settles into a particular form irrespective of the level of randomness it may experience. Strange attractors indicate that while dynamic systems can move into an orderly pattern for a short duration, they still exhibit chaotic characteristics and never settle down (Robertson and Combs, 2014). For instance, they do not repeat the same model twice and are hence, unpredictable (Tsoukas, 1998; Robertson and Combs, 2014).

A practical example of a strange attractor is the ability to make correct predictions about particular parameters (such as risks on a short-term basis) but the inability to indicate the stability of a project system. There is a point during a project's implementation when system stability can be achieved whether through actions taken or otherwise; albeit, the system never settles permanently into that stable condition. For instance, an onshore facility with specific engineering design flaws that may threaten the project's sucess could be detected during quality checks; at this state, the project behaves as a chaotic model. A particular set of experienced design engineers could be drafted in temporarily to resolve this problem or realise a reasonable level of system equilibrium. This process represents a transition from a chaotic model to a stable pattern for the project system. However, the decision to employ experts may result in unwanted tension and crisis of confidence for the original design team. This outcome could polarise design engineers and create conflicts trhoughout the project team thereby instigating the production of a faulty component that may require a complex solution. The possibility of relating to the project's future patterns in this particular situation captures the essence of a strange attractor. Yet, such understanding of the design problem is ephemeral as those associated risks may still adversely affect the project's performance. This scenario demonstrates that it is hard to predict the next behavior of a system that now appears stable especially as new unexpected changes may arise later due to continuous interactions of components or factors connected with the system (Grassberger and Procaccia, 2004).

Chaos Theory and the Megaproject

Principles of chaos theory are applicable in many fields of science. For instance, choas theory has explained events in economics (Kelsey, 1988; Federici and Gandolfo, 2014); cost accounting (Tse and Robb, 1994); organisation (van Eijnatten and Putnik, 2004; Daft, 2012); marketing (Doherty and Delener, 2001; Gummesson, 2006); built environment (Lu *et al.*, 2010); management (Frear, 2011); and engineering (Strogatz, 2014). Despite its ubiquity, its application to megaprojects is embryonic probably because chaos theory is widely associated with natural systems such as meteorological conditions (Levy, 1994). Nonetheless, megaprojects exhibit features of chaotic theory in which their behavior cannot be easily modelled and predicted (Newell *et al.*, 2008; Whitty and Maylor, 2009).

While studies such as Newell *et al.* (2008) and Whitty and Maylor (2009) referred to a megaproject as a system incorporating components that are closely interrelated, it remains unknown as to whether data sets exist, which encapsulate a web of interconnections embedded within them. Outcomes of hydrocarbon megaprojects, reflect systems that are characterised by essential principles of chaos theory. For example, they exhibit unpredictable and systemic changes that are influenced by complex interactions of numerous variables (Merrow, 2011). Such variables may include human error, stakeholders, cultural diversity, environmental and safety complications, site conditions, logistics complexities, political climate, technological and technical intricacies and workers' incompetence.

For one ongoing LNG megaproject development in Australia, obtaining access to an adequate number of experienced workers required for the timely and efficient running of the project represents a major challenge. Strict immigration visa rules, local content regulations and professional registration barriers have hampered the drive to recruit experienced overseas workers. This situation led to operators and contractors increasing wages for people to work on busy rosters to enhance their performance. However, workers voiced their frustrations regarding these unfavorable rosters (despite increases in remuneration to appease their dissatisfaction) and industrial action was taken (Macdonald-Smith, 2015b). This incident decelerated the work progress and compounded the project's already poor performance; according to one worker: "…it's not all about money." Inclement weather conditions together with environmental requirements have also presented obstacles to labor productivity. The project is now several months behind schedule with a cost overrun of at least 60% experienced so far and is under severe pressure from its sponsors and investors. Under such conditions the possibility of further errors occurring remains high. This case demonstrates how complex interactions often affect the execution of hydrocarbon megaprojects, which bring about unpredictable changes to these systems.

The application of chaos theory to natural systems is different from that of a hydrocarbon megaproject as the source of unpredictability is dissimilar (Levy, 1994). Unpredictability in natural systems can be attributed to spontaneous interactions, nonlinearity, and lack of ability to determine initial conditions and structure of the system with infinite accuracy (Singh and Singh, 2002). In hydrocarbon megaprojects, unpredictability results from interactions of components subjected to interventions by individuals and organizations (Levy, 1994); human agency contributes to the chaotic behaviour (Heylighen, 2006). During the Rabigh oil refinery megaproject, an oversight by the design team led to errors in its preliminary engineering design which only became apparent when over-sized equipment arrived and could not be fitted into the space allocated (Luciani, 2007). Engineering issues and scope changes were identified as major factors that contributed to the project cost's increasing from US$3billion to US$9.8billion (Luciani, 2007). In another oilfield development project, carelessness of the project team resulted in them making decisions on Front End Engineering Design (FEED) packages that failed to capture a specific engineering requirements and resulted in costly changes ocurring.

Applicability of Chaos Theory to Cost Overruns

The disorder and nonlinear characteristics of hydrocarbon megaprojects share many similar principles associated with chaos theory. These characteristics include: long-term unpredictability; high probability of sudden change occurring; short-term stability and predictability; and aggravation of pre-existing conditions with corrective actions. Hence, chaos theory can help to explain how cost overruns develop. Each of these features and their applications to cost overruns are discussed in turn.

Long-term Unpredictability

Emergent overruns can be explained by their sensitivity to initial conditions. In hydrocarbon megaprojects, small variations in initial conditions create multiplying effects over time due to nonlinear relationships that exist between their different project parameters (e.g. risks, scope, and quality) and activities. Consequently, accurately predicting the possible consequences of minor changes to a system is problematic. In the case of an LNG facility, an omission in the piping and instrumentation diagrams produced in the FEED package had negative implications for the execution of key project components much later (Hwang *et al.*, 2012). Due to the error, pipeline construction could not proceed without rectifying the problem. In addition, the problem resulted in delayed completion of LNG jetty and storage tanks thereby instigating low labor productivity and cost overruns. This case stresses some of the difficulties of forecasting the long-term effects of a minor change.

Hydrocarbon megaprojects are usually grounded by the long-term forecasts predetermined long before construction commences (Asrilhant *et al.*, 2004). For example, cost and schedule estimates are invariably established during, and are expected to be managed and controlled throughout the project's implementation cycle (Burke, 2013). More often, forecasts are unreliable by the time they reach the construction phase (Castillo and Dorao, 2013). Multiple cases of significant cost and schedule overruns in hydrocarbon megaprojects support this assertion. Notwithstanding, it is believed that careful planning and clear-cut definition of initial conditions would help make better future predictions (Berends, 2007). In fact, lessons learned from previous related megaprojects are usually incorporated to establish such predictions (Berends, 2007). This approach aligns with conventional project management thinking which assumes that projects can be known thoroughly from the very beginning and achieving success is a matter of active applications of standard tools and techniques. Yet, conventional project management neglects latent uncertainties that usually manifest themselves during the construction phase (Cleden, 2012).

According to chaos theory, the benefits of forecasts in regards to achieving project success may not be as remarkable as believed. The theory suggests that the future of a megaproject cannot be built entirely on experiences gathered from similar past megaprojects (Doherty and Delener, 2001). This situation arises as each megaproject is unique and lessons learn are not transferrable to another (Levy, 1994). The non-repeatability of lessons can be explained by the fact that issues interact and the manner in which interfaces differ from one megaproject to another. Chaos theory therefore, suggests that in addition to lessons learned, the unique and dynamic nature of interactions that exist between different components should also be focused upon.

Predictability is practically infeasible in megaprojects as they are characteristically long in duration, complex and dependent on high levels of technical content and technology usage. In some cases, technologies applied are either untested or designed specifically for the project. When ‘off-the-shelf’ technologies are adopted, they need to be integrated into the project system to deliver its core goals. In the case of oil and gas field development in Kazakhstan, conventional drilling and production technologies such as concrete structures or jacket platforms resting on the seabed (steel jacket) were unuseable due to geological and geographical constraints (NCOC, 2013). Instead, offshores facilities were installed on artificial islands (drilling islands and hub islands) to protect them from harsh weather (NCOC, 2013). Consequently, it was difficult to determine how the projects would evolve over time. Uncertainties that dominated the project environment, therefore, provided fertile ground for cost overruns to germinate and massive cost overruns were experienced (Barinov, 2007)

High Probability of Sudden Change Occurring

Conventional project management suggests that small changes in parameters should only produce a reciprocal change in the project. For instance, a minor addition to scope should only incur a commeasurable cost. Such paradigm in conventional project management forces project managers to underestimate the possibility of a particular small event producing significant upsets. In the case of the Sakhalin megaproject, a slight change to the drilling fluids due to government and environmental regulations was not expected to cause major well construction challenges (Thorogood et al., 2006). That supposed small change, however, eventually led to equipment failures and affected the wellbore stability; in culmination, sudden prolong delays in the drilling operations were experienced which contributed significantly to the project's cost overrun.

If hydrocarbon megaprojects were regarded as chaotic systems, small changes would not be expected to yield small reciprocal effects throughout its life cycle. With this mind, a project manager may anticipate that every action in the course of a project's implementation can potentially change its results beyond logical expectation. In a typical hydrocarbon megaproject in which several changes are expected, the chance of it overrunning or underrunning its cost are high. The continuous and close interactions between numerous variables (such as those related to procurement, stakeholders, technologies, specific country laws, technicality, environmental, logistics and leadership) make hydrocarbon megaprojects more sensitive to every event or change (both positive and negative) that occurs within the system. For instance, ignoring or failing to recognize stakeholder demands may galvanize significant problems. This was illustrated in the Sakhalin LNG project were failure to employ practical strategies for managing stakeholders' demands to protect 100 whales fueled protests and delays that contributed to massive cost overruns (Ray, 2008).

As some variables influence the initial conditions of a megaproject, it is difficult to isolate and effectively control their rate of change using conventional project management approaches (Singh and Singh, 2002). This circumstance is due to conventional project management practices not having been sufficiently designed to track and control numerous changes that are capable of derailing projects' objectives (Cooke-Davies *et al.*, 2007). Variables that can create a disturbance in the initial conditions of a cost estimate are myriad and include: unknowable error during the cost estimation; unpredictability of project team behavior; unanticipated changes in climatic conditions; political unrest; geographical conditions; exchange rate fluctuations; changes in legislation; and unaccounted loss of productivity. These aforementioned variables can trigger sudden spontaneous changes to initial conditions thereby increasing a project’s cost (Bardyn and Fitzgerald, 2005). For example, a sudden and sharp rise in the value of the currency of the project’s domicile country means foreign stakeholders have to commit additional funds to ensure the asset is delivered.

Short-term Stability and Predictability

Despite the general belief that nonlinear or chaotic systems are unstable and unpredictable, they do not always lack a pattern (Murphy, 1996) and can be orderly and predictable over a short period (Levy, 1994). However, such orderliness and predictability may lead the project teams to become unaware when the system happens to be chaotic and unpredictable. Due to a megaproject system settling down into a particular and temporary order, it is possible to make precise near future predictions about the project (Robertson and Combs, 2014). Understanding and knowing about environmental risks due to a project system being attracted to a short orderly pattern, may be useful in making forecasts about their possible effects and developing appropriate mitigating actions (Asrilhant *et al.*, 2004). If project teams are aware that environmental rights groups could escalate an issue, then they can make provisions for addressing their demands. Project teams could determine what actions may be required to douse any tension that the groups might want to generate. But the project teams are unable to predict the consequences of such actions in the future.

Chaotic megaprojects systems experience a certain level of order, despite thriving in disorderliness, due to the interrelatedness of their components (Lu *et al.*, 2010). In the case of the East of Shetland Pipeline (EOSP), for example, a seam weld failure in gas pipelines during their fabrication was not detected until a final hydrostatic test was conducted (Macdonald, 2007). The detection of gas pipeline leaks was attributable to the interactions of several factors such as quality assurance activities and integration management procedures within the project system. The ability to detect the pipeline failure represents a trace of orderliness. Without the system's patterns being stable, it would be difficult to detect the fault. The interaction of multiple actions helped stabilize the project system and led to the failure's discovery (Macdonald, 2007). At this point, much of the attention was on fixing the faulty gas pipelines with no comprehensive strategies developed for managing possible problems that could arise from dependent activities such as installation of compressors. As quality checks were not carried out on the installation of certain integrated reciprocating compressors, they were misfit and rework was needed thus engendering further delays and project costs.

Aggravation of Pre-existing Problems with Corrective Actions

The conventional method of managing projects is grounded in reductionism, determinism and perfectionism (Heylighen, 2006). This approach suggests that actions or interventions can be taken to ensure the realization of a stable system. In the context of conventional project management, corrective actions are expected or designed to regulate or normalize faulty system. It is against this thinking that several methods have been designed to check and correct changes in a project during implementation and monitoring/ controlling phases. This action is to ensure that overall specific objectives are being achieved (Burke, 2013). For instance, schedule compression techniques such as fast tracking and crashing are usually employed to address project delays (Swink, 2003). These techniques are expected to return a project back to its original schedule in the face of delays.

Multiple interfaces exist between variables that affect the performance of megaprojects. As such, corrective actions aimed to address problems may aggravate them without being realized (Badiru and Osisanya, 2013). A case in point is the application of project crashing to deal with apparent delays. Such action, although designed to address schedule problems, may influence errors or omissions to occur because of the effects of crashing activity on the project system (Howick and Eden, 2001). In the process of undertaking a crashing exercise, workers may be subjected to lengthy overtime that can reduce labor productivity due to exhaustion, absenteeism, decreased work rates, increased injury rates, increased error rates and increased turnover rates. So more hours are expended to complete overtime tasks and labor costs rise beyond expectation. This scenario demonstrates how corrective actions can worsen problems and add to project costs. Chaos theory implies that corrective actions may exacerbate problems they are expected to address (Murphy, 1996). Considering this notion, project teams must vet every corrective action they intend to implement for addressing problems if they are to avoid complicating issues further. Although corrective actions are useful and unavoidable in the successful completion of a megaproject, chaos theory suggests they must be carefully selected and used to achieve desired results.

Implications for Research

The implications of this research are threefold. First, there is an implied degree of ambiguity with current conceptualization of hydrocarbon megaprojects which are conceived as linear systems. A new reconceptualization is needed to better understand why and how they perform; a superficial understanding of their characteristics and cost overrun causation currently exists due to the assumption of a stable system. Without a better understanding of the dynamics, behavior and nature of these projects, cost overruns will unfortunately remain an innate feature of their existence. More research studies are needed to incisively define hydrocarbon megaprojects and assist in the development of best-in-class practice and solutions to improve project performance.

Second, while this paper has generated new and important conceptual categories concerning the implications of chaos theory for cost overruns in hydrocarbon megaprojects, these require validation via empirical evidence. The current paucity of empirical evidence has contributed to a misunderstanding of practice. An empirical study conducted through the lens of chaos theory will foster better understanding of management practice suitable for hydrocarbon megaprojects subject to the richness of data accrued. However, researchers should be cognizant that oil and gas companies are often reluctant to provide data regarding cost overruns for fear that it could potentially provide a negative view of their projects and adversely influence their share price and/or their ability to raise future capital investments.

Third, a model is required that explains the nature of chaotic dynamics (e.g. labor, logistics, technology and external factors) that contribute to cost overruns. The model could be used to determine whether the influence of factors such as labor , structure and culture, logistics, technical and technology on cost overruns is mediated by the principles of chaos theory. It will also assist in generating a greater understanding of the importance or otherwise of chaos theory in the management study of megaprojects.

Undoubtedly, the significant consequences of cost overruns in hydrocarbon megaprojects requires a research agenda that strives to develop strategies to mitigate them using the lens of chaos theory. Providing recommendations for improving cost performance is a pressing issue within the industry especially considering the falling price of oil and gas. Such suggestions would improve a project’s viability and instill confidence in oil and gas investors.

Conclusion

Research on cost overruns within the context of hydrocarbon projects has been limited and practitioners are largely reliant upon consultancy firms’ reports. These reports typically include information on instances of cost overruns but rarely state ‘how’ they occur. The behavior of complex project systems must be first comprehended to understand how cost overruns develop. This paper has proposed that emergence of cost overruns in hydrocarbon megaproject systems can be explained through the lens of chaos theory. Developing and field testing theories on cost overruns in hydrocarbon megaprojects would be a useful step towards augmenting knowledge on this problem. Such actions would also assist in formulating cost-optimal preventative techniques or solutions to this persistent problem. Reduction of cost overruns in hydrocarbon megaprojects will increase capital investments in the sector and raise profit margins for all parties involved in these ventures.

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