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Chaotic Dynamics of Cost Overruns in Oil and Gas Megaprojects: A Review

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Abstract**—**Cost overruns are a persistent problem in oil and gas megaprojects. Whilst the extant literature is filled with studies on incidents and causes of cost overruns, underlying theories to explain their emergence in oil and gas megaprojects are few. Yet, a way to contain the syndrome of cost overruns is to understand the bases of 'how and why' they occur. Such knowledge will also help to develop pragmatic techniques for better overall management of oil and gas megaprojects. The aim of this paper is to explain the development of cost overruns in hydrocarbon megaprojects through the perspective of chaos theory. The underlying principles of chaos theory and its implications for cost overruns are examined and practical recommendations proposed. In addition, directions for future research in this fertile area provided.

Keywords**—**Chaos theory, oil and gas, cost overruns, megaprojects.

I. Introduction

DESPITE innovations in the management theories and practice, cost overruns persist as a major concern within oil and gas megaprojects [1]-[5]. In 2012, Chevron declared a cost overrun of AU$9 billion on its Gorgon Liquefied Natural Gas project and a revised estimated cost of the project to be AU$52 billion, which represented a 40% increase on their original 2009 budget [6]. In fact during 2012, companies such as Chevron, Woodside, BG, Santos and Exxon Mobil experienced a combined total of $25 billion in cost overruns in Australia alone [7].

As a result of cost overrun on its Pluto Liquefied Natural Gas (LNG) project, Woodside experienced significant fall in its share value and its assets worth declined by AU$1 billion. Experiences such as this have meant that owners of oil and gas megaprojects are now wiser. A common course of action in avoiding such eventuality has been to put extreme pressure on operators, contractors and service providers to enhance their performance and productivity in order to remain competitive in global markets [8]. Previous studies have described cost overruns by focusing on an array of exogenous factors, which include logistical challenges in remote locations, wage costs, regulatory complexity and technical challenges [8]. However, comprehensive understanding of cost overrun requires study on both exogenous and endogenous factors contributing to its development [4], [9]. According to [9], the push to produce oil or gas often results in decision-makers becoming less risk averse. Consequently, they commit errors that manifest themselves as rework and potentially impact on project cost.

Oil and gas projects are generally characterised with uncertainties and these impact their cost performance [10]-[11]. For this reason, they are difficult to manage. The use of conventional project management tools and techniques to deliver projects often leads to undesirable outcomes [12]. This is because these tools and techniques are designed to manage projects with highly defined components, rooted in certainty [13]. Accordingly, more sophisticated perspectives need to be developed to better understand how to manage uncertainties that are inherent within oil and gas megaprojects [14].

Chaos theory has long been suggested as a useful principle that reconciles the essential interdependencies within uncertain events' causatives [15]. It is proposed that the principles of chaos theory can provide contextual backdrop for understanding the emergence of cost overruns in oil and gas megaprojects. The paper commences with an in-depth review of extant literature on the chaos theory and its characteristics. Then, chaos theory is used to explain how oil and gas megaprojects experience cost overruns. Finally, the implications of this study for practice are discussed.

II. Chaos Theory

Chaos can be defined as a state of great randomness, disorderliness or confusion/ uncertainty [16]. In addition, chaos theory deals with the conduct of dynamic systems which contain non-linear components and cannot be predicted in the future [17]. A dynamic system has been defined as a system that is characterised by continuous change over time and can be stable or unstable [18].

Chaos theory is a direct contrast to linear or mechanistic thinking, which explains systems are regular, even, stable and predictable [17]. The difference between linearity and nonlinearity is the presence of nonspecific and disproportionate effect in the latter [19]. Chaos theory has challenged the world of linearity: it has shown that only limited naturally occurring events can be explained by traditional models [20]. Linearity asserts that causes and effects within a system have a proportional relationship i.e. the effect of an action is directly proportional to the magnitude of the force producing the action [17]. In opposite, chaos theory seeks to understand the behaviour of systems that fail to proceed in a traditional cause-and-effect manner [21].

Chaos theory contradicts conventional project management

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theory – where the latter defines project management success as depending on many variables which include: planning method, schedule management, quality control or management, use of technology, communication method or management, leadership, human resources management, and monitoring and control management [22]. It has been suggested that conventional project management theory is based on the mechanistic and deterministic philosophy of Newtonian physics, which asserts world equilibrium and a predictable structure that is orderly, stable, and rational [23]. However, chaos theory is radically different. Chaos Theory is based on the principle that within a predictable structure, an element of behaviour can never be predicted fully and is capable of causing disorderliness, instability and irrationality within the structure [24]-[25].

III. CHARACTERISTICS OF CHAOS THEORY

Plethora views of the characteristics of chaos theory have been discussed in different ways by different authors. However, Table I presents most common attributes of chaos theory found in the literature. They are: (i) sensitive dependence on initial conditions; (ii) positive feedback mechnism; (iii) bifurcation and catastrophic phase changes; and (iv) strange attractors.

A. Sensitive Dependence on Initial Conditions

Sensitive dependence on initial conditions, otherwise known as the *butterfly effect* assumes small influences can cause significant consequences which cannot be predicted [17]. An oil and gas megaproject is highly sensitive to change [26]. A small change to the system such as a delay in the completion of an activity may have significant effect on a company's financial performance. A particular change in the oil and gas megaproject system may easily be overlooked because it is perceived as insignificant. However, long-time effects of such change may be difficult to predict in a megaproject where there is a high degree of reciprocal interdependence between stakeholders and activities are undertaken concurrently. For instance, where a change is effected from a partner in the joint ventures, the change may produce a domino effect on the other partners and eventually lead to extra costs being incurred.

TABLE I
CHARACTERISTICS OF CHAOS THEORY

Attributes	Descriptions	Authors
Sensitive dependence on initial conditions	A situation whereby small change in a system causes major and unpredictable consequence	[20], [17]
Positive feedback mechanism.	A process by which negative consequence in a system is amplified by actions taken otherwise to reduce it	[21], [20]
Bifurcation and catastrophic phase changes	A process of sudden qualitative modifications in the nature of a system caused by radical shifts in the system's conditions	[17], [20]
Strange attractors	A process by which a system self-organizes into order after undergoing series of changes	[17], [21]

B. Positive Feedback Mechanism

System stability is achieved by means of negative feedback in which corrective action is needed to prevent deviation from a system's static state [21] . Contrastingly in chaos theory, a system is built up by means of positive feedback, that is, where the future state of the system is dependent upon the initial or earlier conditions [19]. Activities such as those that are performed within a project (e.g. cost management, risk management, communication management, scheduling and quality management) continue to support themselves, leading to positive reinforcing cycles or positive feedback loops [27].

Negative (i.e., regulates or corrects) and positive (i.e., amplifies deviations) feedback can cause major changes to the existing conditions of a system as well as continuously introduce new patterns of behaviour [28]. In the case of oil and gas megaproject, its implementation within specified environmental objectives may lead to the selection of technology that can contribute to the occurrence of cost overrun. For example, according to the North Caspian Operating Company Business Ventures (a company acting on behalf of Consortium partners including KMG, Eni, Shell, ExxonMobil, Total, Conoco and Inpex.), environmental concerns caused the use of special technology to trench, lay and backfill simultaneously in Kashagan oil and gas megaprojects [29]. The application of such technology is presenting the consortium partners with an array of technical challenges that are increasing the cost of the project.

C. Positive Feedback Mechanism

Bifurcation can be defined as "a process of sudden qualitative modifications in the nature of a system, which are caused by continuous variations in the system's conditions p.259 [17]. Sellnow et al. [30] 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). Bifurcation occurs when a system moves from a periodic to a chaotic state as a result of changes being made to its initial conditions [17].

Murphy [21] suggests a dynamical system such as a construction and engineering project evolves from an apparent state of orderliness to randomness, and that such system often appears to follow characteristic patterns, which may trigger a state of 'total' disorder. A system achieves a state of 'total' disorder when it no longer follows characteristic change patterns. This often takes place when bifurcations occur at intervals, and the system lacks the resources to accommodate the developments arising from its uncharacteristic change patterns [31]. Before a project system bifurcates (i.e. a system in its original state), it often manifest a stable pattern, that has underlying conditions, which cannot be altered simply by making changes to its original state (e.g. the schedule) [32]. At such stage, deterministic actions may be used to return the system back into its original order. Initial bifurcation occurs when changes made to the project create two new patterns in which it settles into. For example, a new partner joining a megaproject could alter the existing project arrangement and

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create two arrangements. Also, the two patterns created during the first bifurcation split further into additional stable patterns during a second bifurcation. At this state, the system may still adapt to changes made to its initial conditions until it reaches a point known as the 'edge of chaos'.

When a system experiences repeated bifurcations, it becomes saturated with an infinite number (n^{th}) of potentially stable patterns. Such system is not likely to settle down until it lapses into a chaotic state. At the bifurcation point, a system rearranges itself into a new hybrid order which may be significantly different from its prior order [21], [30]. Bifurcation implies change scenarios; but there are different forms of change in engineering management systems. Change could be emergent, strategic, planned and unplanned [33]. This means that bifurcation occurs in various forms, depending on the nature of change. Sudden changes or radical shifts in a system are referred to as catastrophic changes or 'tipping points' [17]

Speakman and Sharpley [34] describe major changes in a project system as potentially catastrophic crisis events that trigger major shifts in project management processes. Murphy [21] indicates that whilst it is possible to predict the occurrence of bifurcations, their outcomes are impossible to predict. Thus, by induction, while project participants may foresee impending crisis, predicting the end results is far less certain.

D.Strange Attractors

Nonlinear system is unpredictable, however, it does not completely lack pattern [35], [36]. Attractors are 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" p. 831 [36]. According to Murphy [21] an attractor is an organizing principle that a system will always metamorphose into a specific form irrespective of the level of randomness it may experience. A change to the original plan of a project, such as an error in the engineering design, can lead to series of other changes. For instance, it can cause changes in the construction plan and subsequently disrupt the entire project system. Despite being in a state of chaos, a project system may still manage to organize into an order in between the chaotic condition. Although the project system may appear orderly, it can still be difficult to predict its next behaviour especially as new changes may arise [37].

IV. OIL AND GAS MEGAPROJECTS AND CHAOS THEORY

Large Project management processes in mega-hydrocarbon projects are usually predetermined long before construction commences [12]. For example, cost and schedule estimates are invariably established during Front Engineering End Design (FEED), and are expected to be managed and controlled throughout the project implementation cycle [38]. Mega-hydrocarbon projects are characteristically long in duration, complex and expensive in nature and are dependent on high levels of technical and technology usage. In some cases, technologies applied are either untested or bespoke. When technologies adopted are 'off-the-shelf', they need to be integrated into the project system in order to deliver its core goals [39]. For example, in the Kashagan oil and gas field development, conventional drilling and production technologies such as concrete structures or jacket platforms resting on the seabed (steel jacket) could not be used due to geological and geographical constraints. Instead, offshores facilities are installed on artificial islands (drilling islands and hub islands) to protect them harsh weather [40].

The essence of planning is to ensure that the activities necessary to achieve project objectives in terms of time, cost and quality can be identified ahead to determine appropriate implementation management process [41]. Nonetheless, long range planning increases the probability of inaccurate cost forecast occurrence [42], [43]. Such inaccuracies can negatively influence stakeholders' confidence and their consequential decision to invest in such projects. It is suggested that the greater a project's duration and complexity, the more likely that deterministic factors (used to make decisions such as those relating to cost) will vary. For instance, small changes in the initial conditions of a project's cost system may result in dramatic changes in a system's behaviour.

As planning is discrete, it is a separate and distinct effort that is usually completed before the commencement of project execution [43], [44]. On the other hand, implementation and monitoring/controlling of activities established during planning phase are deemed to be continuous [38].This is because changes in plans are intermittently checked and corrected continually during implementation and monitoring/controlling phases in order to ensure that overall specific objectives are being achieved [38]. As such, problems created during planning phase may become catastrophic during project implementation [45]. The initial conditions of cost are usually determined by the information made available via the project management plan, charter, enterprise environmental factors and organisational process assets [13].

The changeability of these conditions is more magnified during the project's implementation phase. If a project's budget conditions derived from the plans are not acted on during implementation, they will most likely remain in their state of inertia (inactivity). Although an initial error could occur during cost planning, this error is normally escalated during construction. In alignment with Chaos Theory, an error in the initial cost estimate for a mega-project could spark a chain reaction that generates a series of errors leading to an unforeseen escalation in project cost [46]. As a number of variables influence the initial conditions of a project's cost, it is difficult with to isolate and effectively control their rate of change using traditional project management approaches [23]. This 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 [22].

Variables that can create a disturbance in the initial conditions of a cost estimate for a typical mega-hydrocarbon

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project are myriad and include: unknowable error during the cost estimation; unpredictability of project team behaviour; 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 spontaneous changes to initial conditions of the project cost thereby increasing the difference between estimated and actual project cost [25]. For example, a sudden and sharp rise in the value of currency of the project's domicile country means foreign stakeholders may have to commit additional funds to ensure the asset is delivered.

The decisions about the cost of a megaproject are usually based on the conditions identified during its gestation period [23]. At this stage, it may be difficult to ascertain or foresee any future change in the conditions. Project cost is usually estimated using established tools and techniques such as expert judgment, analogous estimating, parametric estimating, bottom-up estimating, three-point estimating and/ or, reserve analysis [47]. Estimating tools and techniques are only helpful in predicting the expected behaviour of cost elements in the future but they cannot actually prevent their changeability [33]. Any change to project's initial conditions especially during the construction phase may catalyze a chain reaction. Such change could lead to unexpectedly significant changes to the cost and time dimensions of the entire project cycle [48].

The manifestation of chaos theory in project cost management means small changes in the initial cost conditions generate the need to make other changes to the estimates and baselines [49]. These changes may also necessitate other changes within the cost until the overall impact of the changes in project initial conditions on the cost estimates becomes very considerable. Uncertainty in project cost increases with time. This is expressed mathematically as:

$$U = U_0\, e^{\lambda t} \tag{1}$$

where: U_0 is the initial uncertainty that grows with time (t); e is the exponential constant that is an irrational number; and λ is the Lyapunov exponent which measures the rate of loss of information about the initial conditions of the project. The higher the value of Lyapunov exponent, the more chaotic the project system is. Lyapunov exponent is expressed as:

$$\lambda = \frac{1}{\mathrm{tn}-\mathrm{t0}} \sum_{k=1}^{n} ln \frac{\delta\,(t)}{\delta 0(t-1)} \tag{2}$$

where: t0 is the time before the start of initial uncertainty in the project i.e. time before the loss of information about the project begins; tn is the time at which the uncertainty in the project becomes unmeasurable; k is the degree of independence of project initial conditions; and δ (t)/δ0 (t-1) is the measure the divergence as a result of small change in the initial conditions of the project.

The evidence that cost management (which comprises cost planning, estimation, budget determination and cost controlling processes) is sensitive to initial conditions of a project can be expressed mathematically as:

$$\dot{P} = f\ [P] \tag{3}$$

where: $\dot{P}$ is a function of an instantaneous state of the cost management (i.e. the rate of changes within the cost management process). This nonlinear and deterministic equation can be applied to predict the future state P_f of the project cost from the initial state P_0 if only all future changes that will occur in the system can be determined in advance. Originally known information about a project is often explored to construct an overall cost estimate including provision of a contingency for uncertain costs that may occur [50]. Such cost estimates often include a determined contingency percentage that is assumed to provide buffer for unforeseen costs that may arise. However, it has been reported that traditional deterministic percentage approach is not be effective at selecting a cost contingency and the use of probability theory to calculate a cost contingency is more effective [51]. This is because projects are generally prone to errors of unanticipated commission or omission [52]. The consequential uncertainty (U_f) in the project's initial conditions can be denoted by the probability density function (PDF) as:

$$U_f = \rho\ (P,\ t_0) \tag{4}$$

Considering the phase space of the project life cycle S, then the probability that the true initial state P_{true} of the project at the initial time t_0 of the project lies within the phase space of the project life cycle S is given as:

$$P_{true} = \int_s \rho\ (P,\ t_0)\ dS \tag{5}$$

where dS is the change in the phase space of the project life cycle; ρ represents the value of two or more projects that cost the same amount and operating within the phase space of the project life cycle. From the determinism of equation 4, the probability that P_{true} lies within S is time constant.

V. IMPLICATIONS FOR PRACTICE

Professionals within the oil and gas sector can take some vital lessons from applying chaos theory to their megaprojects. This can assist them in understanding how cost overruns emerge in their megaprojects and then in designing as well as selecting practical strategies for managing the syndrome. On the first premise, practitioners undertaking hydrocarbon megaprojects should be aware that chaos theory demonstrates that such huge projects hardly obey simple linear rules because they are governed by close interactions of several events that are hard to know and manage. As a result, there is limit to which events within or around hydrocarbon megaprojects can be predicted and managed.

In practice, chaos theory implies that the future state of a megaproject is sensitive to the small change in the initial condition of the megaproject [19]. This is so because megaprojects as a dynamic system consist of several components, processes and tasks that are continually interdependent. These components, processes and tasks, having being predetermined long before the construction phase commences, cannot be predicted well enough. For instance, it would be difficult to establish from onset their behaviors right through the project life cycle. Despite that, those components, processes and tasks are expected to be managed and controlled throughout the project implementation cycle according to the requirements generated during the planning stage of the project process. As noted by [14], the long duration of megaprojects predispose them to increasing uncertainty that may hinder the achievement of the project objectives. The aforementioned circumstance can only be managed if the industry can design a validated strategy for assessing the long range behaviour of such change and its long term impact on the project.

As the components, processes and tasks interact, they constantly create a continuum that is prone to changes. The ability of the megaproject team to follow up within the continuum is essential to monitoring and controlling several small changes that may pose threat to the objectives of the megaproject [53]. For example, an error in engineering design of a particular component of an oil and gas megaproject may be left undetected for a long period. As a result of this error, several other components of the megaproject will be affected because they are all closely interrelated. In this situation, an error in one component will manifest and affect several other ones until it results into catastrophic changes within the whole of megaproject system. Such changes will have cost implications for the megaproject and consequently triggering cost overruns. This is the backdrop against which practitioners within oil and gas megaprojects must pay attention to the issue of sensitive dependence that has been discussed within this paper. To address the issue of sensitive dependence in the oil and gas megaprojects, it is suggested that the practitioners continue to reinvent within their projects. By reinventing continually, practitioners may be able to detect and address issues before degenerating into substantial problems.

Practitioners within the industry should also be aware of practical implications of positive feedback mechanism for hydrocarbon megaprojects. As discussed throughout this paper, megaprojects are undertaken within atmosphere of uncertainties. Several actions are usually incorporated to ensure active management of different components of megaprojects. While in the conventional management thinking, actions taken are expected to address the uncertainties inherent in megaprojects. This is known as negative feedback mechanism. In megaprojects setting, however, actions taken may lead to negative impacts or they can amplify problems. This is referred to as positive feedback mechanism. Hydrocarbon megaprojects are vulnerable to positive feedback mechanism because of many unknowns that are present in them. For instance, use of challenging or unproven technologies is normal in hydrocarbon megaprojects because they are technically complex and as such require novel approach for their successful delivery. Often times, applying these challenging or unproven technologies to megaprojects can be problematic thereby causing increased uncertainty and risk in them. This is because the technologies are new and as such there are uncertainties about their behaviour. In such situation, there is high probability of misapplication of certain areas of the technologies which can further magnify the existing uncertainties with the megaproject environments.

Apart from sensitive dependence on initial conditions and positive feedback mechanism, bifurcation and catastrophic phase changes also have implications for hydrocarbon megaprojects. Radical shifts of changes made to the conditions of the megaprojects may cause qualitative modifications to the system. At this flash point, the megaprojects may either become stable system or chaotic one. For instance, change orders may create profound alterations to the flow of the processes within hydrocarbon megaprojects. Such sudden shifts can lead to several changes across many other components of the megaprojects. However, the hydrocarbon megaprojects will maintain their original stability for a certain period until they transit into total disorder. Total disorder will only occur when the megaprojects can no longer maintain their stability as a result of change orders being made at intervals that the systems cannot accommodate.

Finally, implications of strange attractors for practice in hydrocarbon megaprojects cannot be overemphasized. Despite the chaotic behaviour associated with megaprojects, they also have capacity to self-organize into order. For instance, error in the offshore reservoir definition can lead to selection of wrong technology and consequently causing catastrophic change to the megaproject. After undergoing this chaotic change, new delivery pattern will be created for the megaproject. In this case, new order is created and the megaproject can still progress towards achieving its objectives although via different delivery pattern or strategy from the one planned originally. In megaprojects, such situation can be repeated many times during their implementation thereby increasing the chance of different outcomes within the systems. As a result of changing delivery patterns in the megaprojects, cost overruns may be experienced. This is because extra cost is incurred to manage changes in the delivery pattern of the megaprojects.

VI. CONCLUSION

Several studies previously undertaken produced promising results as to why cost overruns occur in megaprojects, however, the literature fails to cover how cost overruns develop within mega hydrocarbon projects. Understanding how cost overruns emerge in mega hydrocarbon projects is a challenging task that needs to look beyond conventional reasons often attributed to cost overruns in megaprojects. The critical literature review conducted in this paper, has highlighted the implications of chaos theory as a tool to be used in developing strategies to manage cost overruns across megaprojects. To understand how cost overruns develop within mega hydrocarbon projects, the behaviour of megaproject system must be first understood. It has also emphasized the need for both academic and industry communities to reappraise their understanding of how cost overruns occur within megaprojects through the lens of chaos theory. Although chaos theory is yet to be studied within construction and project management field, there is anecdotal evidence to suggest that the development of cost overruns is impacted by this theory.

Future research is now required to focus upon empirical study that can identify how cost overrun can be predicted and its risk mitigated using the lenses of chaos theory. Studying how cost overruns develop through the concept of chaos theory will not only provide the 'outside' view but 'inside' view of how cost overruns develop within megaprojects. Developing better understanding of the origins of cost overruns is the first step towards combatting this recurrent problem in practice. Not only will such research potentially raise profitability margins for contractors but could also increase profit margins for other stakeholders.

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