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Simplifying complexity? On quality decision-making and non-conformance outcomes of megaprojects

Index Terms—**Construction, Cynefin framework, uncertainty, lessons learned, quantitative method, root cause analysis (RCA)**

Abstract— **Research in quality management has provided much insight into the challenges construction projects face with non-conformance and rework. However, most rework research has focused on most prevalent and costly avenues that desire improvement, rather than the capabilities of quality problem solving and appropriate decision-making in uncertain situations. Quantitative method is adopted whereby 1205 non-conformance report (NCRs) from a £1.45bn highways megaproject are analysed using a cognitive decision-making framework to determine real-time and retrospective action pathways employed to rectify non-conformance problems. We identify that the interventions to address quality problems are typically premature and do not fully consider the wider picture of non-conformance failure. The findings revealed many cases of oversimplification, resulting in premature quality problem solving outcomes. This causes NCRs to be ineffectively addressed and does not eradicate future occurrence. We show that with the assistance of a cognitive decision-making framework and a categorisation ruling, projects can improve decision-making by determining when to switch intervention pathways to ensure the correct outcomes. There cannot be a one-size-fits-all approach to quality problem solving. Project teams must be more aware of the differing complexities with NCRs that require different courses of action. We close with the limitations of the paper and suggest avenues for further research.**

I. INTRODUCTION

The term 'megaproject' refers to large-scale, complex ventures that typically cost in excess of $1 billion [1]. Collectively, these schemes make up 8 percent of the total global GDP and offer unique opportunities to understand the interplay of uncertainty, complexity and value outcomes in the development of infrastructure. Such schemes generate significant interest to explore operations and supply chain issues [2]. There are a wide range of reported challenges with respect to the planning, design and delivery of megaprojects, as well as the value they provide to clients and wider society. Complexity is a central issue in management theory [4], but also, and especially so, in the case of megaprojects. Flyvbjerg *et al.* [5] suggest that risks in large projects are typically assessed based on the assumption that there are clear and stable cause-and-effect patterns, rather than the highly stochastic outcomes that are seen in reality.

A more recent view of projects is emerging that accepts their inherent complexities, and is more aligned with the challenge of managing the unexpected, or so-called 'unknown unknowns' [6]. Furthermore, complexity has been directly linked to innovation on megaprojects and seen as a contingency factor to influence innovation on project performance [7]. Important research challenges for the engineering management discipline include the appropriate responses to ever-changing project complexities, where an underlying theory of explaining how to respond is still absent [8], and to better understand different kinds of complexities [2]. In addition, it has been noted that the 'conceptualisation of complexity and response as a linear system was *[is]* no longer adequate' [61]. In the case of rework, Love *et al.* [9] suggest learning from failure data to improve our understanding of the nature and likelihood of rework costs, and reprofile complexity from a position of being a 'known-unknown' to becoming a 'known-known' to give more certainty to schemes.

In the search for operational improvements, over recent decades, the construction sector has striven to adopt a right first-time culture, following the successful application of lean practices within the automotive industry [10]. However, as noted by Tezel *et al.* [11], this has been a mixed success. One possible reason for this, as noted by Browning and de Treville [12], is that such an approach was developed in stable, predictable and repetitive contexts, and this is where it is most effective. However, the desire to minimise variance and uncertainty levels, and to strive for simplicity, persists in construction operations. This is typical of a broader phenomenon, the cognitive miser effect, supported by psychological studies, which suggests that human social cognition has a bias towards simple and less effortful routes to problem solving, decision-making and risk management [13].

Typically, the success of a construction megaproject in delivering without error is measured against non-conformance. Non-conformance and rework play a critical role in quality management and have been extensively researched over the last few decades [14]–[18]. However, quantifying the impact, risk and cost of non-conformance has proved challenging, due to the commercial sensitivity and stigma associated with poor project performance [19]. With regards to this paper, understanding NCR failure patterns is not our intent. Our intentions are to understand how project teams make decisions about how to detect, analyse, report and resolve NCRs (i.e quality problem interventions). Early detection of non-conformance, along with the successful determination of its underlying cause, should enable projects to eradicate possible future recurrence and facilitate continuous improvement [14]. It should be noted that the focus in this paper is on the quality dimension of the project 'iron triangle' (cost, time and scope) and assessing the impact of the simplicity paradigm, specifically for non-conformance in megaprojects. As quality represents a significant segment of the iron triangle, negative outcomes can lead to major cost and time overruns that impact handover and extend defect correction periods. With the major negative impacts that non-conformance and rework bring to the construction sector (e.g. cost and time overruns, reputational damage and loss of work) there is an endemic problem in understanding 'why' and 'how' rework occurs and how it can be extinguished [62]. There are scholars, for example Love and Matthews [65], who explored practitioner decision-making in the context of mitigate the risk and uncertainty of rework. They found that heuristics were being used informally due to the absence of information to make appropriate decisions [65]. Likewise, Love *et al.* [66] conclude that possessing the right knowledge and understanding of rework causations is pivotal to decision-making success of quality problems, and that supportive knowledge engineering systems are a must.

Aside from these types of works, there are few studies that delve into the accuracy of quality decision-making. It is clear that a better understanding of how project teams are executing quality problem solving is needed. Furthermore, whether cognitive decision-making tools can offer support and help practitioners navigate varying levels of uncertainty in quality problems.

This paper aims to investigate and analyse decision-making with respect to quality problems (i.e. NCRs) in a megaproject context, to better understand if and how projects are responding with appropriate action. To probe the decision-making assumptions, we apply the Cynefin framework to categorise the decision pathways and to deploy well-established quality management techniques to gather insights from the data. Specifically, Failure Mode and Effects Analysis (FMEA) and five whys root cause analysis (RCA) are used to map NCR pathways (i.e. how an NCR is resolved from identification through to close out), and the corresponding risk profiles, establishing rules to categorise projects as either simple, complicated, complex or chaotic.

Our primary research question is as follows:

RQ: How should project teams make decisions related to non-conformance and quality issues in megaprojects?

Given the recent recognition of the Cynefin framework as a contingency-based model for 'right-sizing' operations management interventions and decision-making [20], we exploit it to facilitate the identification of the causes of non-conformance uncertainties and remedial interventions. In our research, we take a systematic, analytical approach, using causal determination and Failure Mode and Effects Analysis (FMEA) to ascertain the scale of the uncertainties identified. It is the authors' understanding that the framework has not been used before to categorise decision-making pathways from non-conformance data, especially in a megaproject context. While other decision-making approaches were considered, the Cynefin framework, which has been applied in a wide range of industries and situations, e.g. [40], provides a concise way of interpreting decision-making in different environments, whilst providing tools to allow decision maker to act accordingly.

In meeting our aim and answering the research question, we contribute to the extant literature by determining managerial decision pathways to correct nonconformance to yield robust quality practices in construction operations, developing a novel approach to categorising such decision-making to mitigate quality issues and to suggest new practices for zero-defect industry culture.

II. LITERATURE REVIEW

A. Non-conformance and rework in construction megaprojects

Time and cost overruns have become a frequently occurring outcome for projects, seeing figures for rework of high as 16.5% of total project value [16]. Often, contracts are burdened by defect resolution periods that are not factored into the tender budget. This eats into project profit margins at the end of schemes, something that is not realised until it is too late. There has been extensive research into the challenges that the construction sector is having with regards to non-conformance and rework. Some of these studies include [14], [15], [16], [17], [18], [21], [22] and [24]. Many of these studies have expressed the ongoing struggles for the industry to reduce its number of errors and seek right-first-time outcomes.

Errors themselves are mistake that have occurred through performance, knowledge or violation that typically result in rework outcomes [25]. With regards to violation, Lopez and the research team define this as 'non-compliance' (i.e. non-conformance). Battikha defines non-conformance as a 'finished state of a project and/or its components deviating from established requirements' [24]. As rework is a biproduct of non-conformance, it is defined as 'the unnecessary efforts of re-doing a process or activity that was incorrectly implemented at the first time' [15]. Unsurprisingly, rework is one of the biggest dilemmas on construction projects. It inevitably leads to cost and time overrun which is usually realised during the handover into operational maintenance process as the product is vetted heavily prior to taking ownership by the relevant authority [17].

A significant part of dealing with non-conformance on projects is the way in which we make decisions to resolve them, i.e. 'the intervention'. Studies have concluded that the oversimplification of complexity domains is commonplace within cognitive decision-making [26]. In essence, oversimplification of decision-making is the excessive reduction of a problems context to a point whereby the proposed remediation does not completely address the issue. It is premature, incomplete, or an inappropriate solution, and largely ineffective in addressing a problem in full. As a result, there have been many instances of reoccurring NCRs on schemes because of poor decision-making through inaccurate RCA [18], thus the need for cognitive decision-making frameworks to assist. Smith and McCardle [27] note that a possible reason for poor problem solving could be the difficulty of evaluating decision problems which call for the consideration of complex conditional probability assessments, and their corresponding risk [16]. Furthermore, identifying the root cause of non-conformance on projects has also proved challenging owing to varying levels of complexity within quality problems [28], although methods of root cause analysis, such as the ‘five whys’, have proved highly effective in uncovering the underlying causes of problems [29]. With regards to problem solving and decision-making abilities of project teams, there are limited studies that assess the accuracy of quality problem solving done by practitioners. This is considered a missing link that needs targeting.

B. Decision-making and the Cynefin framework

As indicated above, a significant part of managing project non-conformance failures is the decision-making involved in selecting appropriate interventions to resolve them. However, the inherent degree of uncertainty on infrastructure schemes can often result in many problematic issues, particularly when information is not ready or inaccurate. As a result, managers are often confronted with having to make decisions based on an imperfect and incomplete knowledge of future event [16]. Effective decision-making is a fundamental part of managing and delivering schemes successfully, particularly when it comes to non-conformance and rework [28]. It requires awareness of surroundings and the challenged faced to implement appropriate responses. According to Bakht and El-Diraby [30], complexity of engineering problems has resulted in a shift from judgemental to rational techniques to substantiate reasoning to respond and remove subjective behaviours. As construction projects are becoming increasingly complex to deliver greater value for less, precise decision-making using accurate information is top priority [31]. Furthermore, the need for organisations to process information correctly to enable managers to make more effective decisions has been crucial to future scheme success [4], [23], [65] and [66]. A vital step to addressing non-conformance on projects is the way in which we make decisions to detect, remediate and prevent future occurrence [24]. Decision-making tools have provided much benefit to construction problem solving including the topic of rework [67]. These benefits include promoting knowledge and learning which are critical to effective decision-making [65]. Researchers have requested projects embrace complexity and make sense of their environment through cognitive decision-making frameworks [16].

One particular conceptual tool that considers decision-making in the context of the degree of uncertainty and ambiguity encountered by managers is that originally proposed by Snowden [32], and latterly developed by Kurtz and Snowden [33] and Snowden and Boone [34], known as the Cynefin framework. The framework (Figure 1) is a decision-making schema that differentiates varying contextual domains wherein management knowledge is distinguished, in order to learn about how the selection of interventions is dependent on the degree of uncertainty encountered [35].

The framework consists of two ordered (Simple and Complicated) and two unordered domains (Complex and Chaotic). Each domain harbours different levels of uncertainty which increases from Simple through to Complicated and Complex through to Chaotic, rationalised by cause-and-effect relationships, along with prescribed management intervention pathways.

Figure 1 provides examples for each domain in the context of projects and interpreted in an operations management setting [36]. There is also a fifth domain (Disorder), for when there is ambiguity from decision maker(s) as to which of the other four domains their operational context resides within.

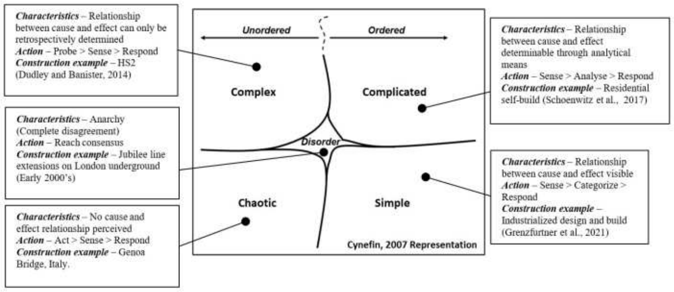


Fig. 1. Cynefin representation with key characteristics: adapted from [33]

From its origins in knowledge management [32]–[33], the Cynefin framework has been extended to management leadership [34], and more recently exploited in various operations management contexts, including healthcare [37] procurement [60], performance alignment [38], project management [39], supply chain design [36], and construction management [40]. Naim, Gosling and Hewlett undertook a comprehensive risk analysis of the failures in an infrastructure project. They determined that a contributing factor was the misperception of the degree of uncertainty encountered by managers and operatives. This is contrary to previous construction management research, where many have tended to impose solutions which have been shown to be effective in the Simple domain [41]–[42].

Other frameworks were considered, for example Mintzberg’s Model [63], but were not chosen over the Cynefin framework as they have limitations with regards to the realities of strategic decision-making and are considered worthless in ambiguous situations [64]. In addition, for project teams making using such tools, Mintzberg’s model for example is quite complicated and not so easy to understand, which is a necessity for those reacting to many problems at one time on construction projects. The Cynefin framework provides a concise way of interpreting decision-making in different environments whilst providing tools to allow decision maker to act accordingly. This is highly applicable to quality problem solving in construction projects where there are interlinks with cause-and-effect relationships, and varying levels of complexity to unearth root causes.

Noting the ongoing struggles with rework in the construction industry [18], and previous research through recent decades, there is a call to re-evaluate non-conformance in order to understand the fundamental areas of weakness that need improvement. This extends to how organisations address quality problems (i.e. non-conformance), particularly with the inclination to make decisions driven by assumptions of simplicity and lean practices.

Currently, literature does not explore how project teams are addressing quality problems. As such, we do not know whether problem solving is being executed appropriately, and whether cognitive frameworks are a possible solution. It is suspected that improving the problem-solving process for NCRs will lead to significant reductions of quality issues.

III. RESEARCH METHOD

A. Case study research: The research problem in context

Case research has been considered one of the most powerful research methods in operations management for interrogating current events and deploy new theories for discussion [43]. It allows the researcher to develop a deeper and novel understanding of specific phenomenon. As a result, continuous improvement and lean management techniques have been seen to emerge as critical success factors for implementing such methods within production planning and control [44]. Within case study research, a single case context was chosen in order to investigate deeply the decision-making processes within a megaproject environment. However, the case study has multiple embedded data collection protocols to help with reliability and validity, as per Yin, [45] and Roller and Lavrakas [46]. Highways projects in particular, typically have similar design parameters and repetitive components that can be seen to benefit from single-case research.

B. The project

The A14 Huntingdon Improvement highways scheme in Cambridge, United Kingdom (circa £1.5bn) involved the upgrading of 21 miles of existing A14 highway infrastructure to relieve congestion in the region. At its peak, there were 2,500 employees working daily on the scheme, and 14,000 people across its construction lifespan. The project was setup as a joint venture (JV) partnership, led by National Highways. The team was setup as an integrated, collaborative environment to remove any differentiation between parent companies. Collectively, the JV partners have over 62,500 employees worldwide, with a multitude of experts in various disciplines, including transportation, nuclear, water, oil and gas, technology and aviation. In recent years, all three companies have focused efforts on quality delivery to carry out operations without error. NCR project data is important information that should be analysed for the purposes of continuous improvement, such as understanding current avenues of failure, the decision pathways taken to resolve problems, and the necessary steps to prevent reoccurrence. Noting that non-conformance is still prevalent in schemes, a principal contractor's senior leadership team commissioned research to understand prevalent areas of failure through non-conformance data analysis, so that the most notable findings could be used for continuous improvement internally, and shared with JV partners, clients and the wider construction industry.

C. Research design

The research project has been set up in two parts (Figure 2).

Part 1 consists of the collection and analysis of non-conformance data, primarily to differentiate between real-time (i.e. what was actually done) and retrospective (i.e. what could have been done) decision-making pathways for each case. We refer to this as a 'complexity categorisation' exercise.

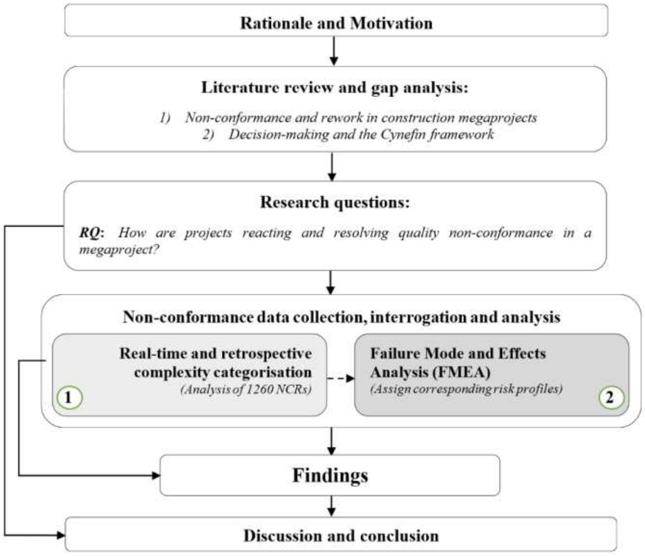


Fig. 2. Research process

Using the Cynefin framework, we map the intervention pathways undertaken 'real-time' by the project team at the time the NCR was discovered, and then in hindsight, or retrospectively, by the research team, using the information within the NCR dataset. Cross-examination of real-time and retrospective decision-making indicates whether appropriate decisions are being made to rectify non-compliant works and to diagnose whether problems are being under or over simplified. To do so, a categorisation ruling is devised that links the Cynefin framework domains [33] and the cause-and-effect relationships they each possess. By combining the 'five whys?' principal with the Cynefin framework, each domain is assigned a flow path that coincides with cause-and-effect relationships, as in Figure 3.

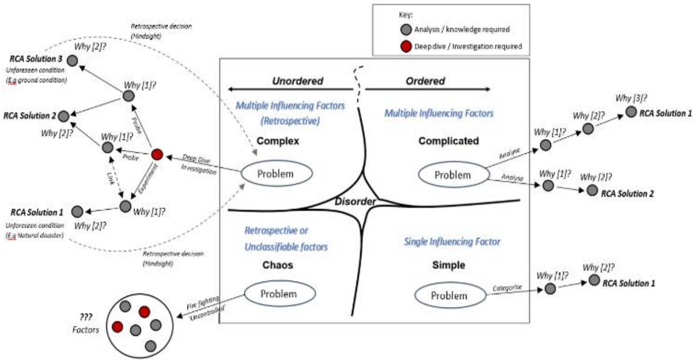


Fig. 3. Decision-making complexity ruling for NCR analysis

Beginning with the retrospective pathways, NCRs that warrant little analysis to identify their root causes are categorised as 'Simple'. Those with up to two attributable root causes are labelled as 'Complicated'. Non-conformances that exhibit many root causes, show signs of experimentation to achieve further understanding or yield retrospective conditions as a fundamental factor (e.g. unforeseen ground conditions or adverse weather) are classified as ‘Complex’. Finally, those showing signs of fire-fighting techniques without consideration of the underlying cause are classified as ‘Chaotic’.

With regards to the real-time mapping, as RCA pathways are non-determinable from the NCR dataset, real-time categorisation is based on the decision path made by the project team factoring in the problem; the perceived root cause, the remedial action to correct the defect, and the corrective action sequentially i.e. how the project team captured, gained understanding and responded to the problem. Considering the level of investigation conducted, the researchers were able to match each NCR to the appropriate Cynefin framework domain through the action pathways denoted by Kurtz and Snowden [33] in Figure 1. For example, if the project team ‘analysed’ the NCR prior to addressing it, this would be categorised as ‘complicated’ in line with the Cynefin frameworks action path. Likewise, if the project team undertook deep dives, investigations or experimentational measures, such as forensic materials analysis, to validate composition (i.e. ‘probe’), these are categorised as ‘Complex’. At the other end, those that displayed obvious root causes are categorised as ‘Simple’ (e.g. damage to permanent works caused by careless behaviour than in turn resulted in rework). Last, those exhibiting erratic, non-compliant behaviour, with team members acting on intuition rather than following due process (e.g. omission of detail without prior design approval), are tagged as ‘Chaotic’.

Following five whys root cause analysis and complexity categorisation of each NCR, the data is then interrogated using Failure Mode and Effects Analysis (FMEA) to assign corresponding risk profiles (part 2). FMEA is a structured analytical method of failure and risk interrogation that has provided benefits in addressing latent construction problems [47].

The process of computing the Risk Priority Number (RPN) using likelihood, severity and detection values is calculated using the same method proposed by Carbone and Tippett [48]. In doing so, three exercises are carried out. First, we organise the NCR results from most to least frequent (i.e. Pareto) in line with the Specification for Highway Works series (SHW). The specification governs each project activity against an industry standard, and is split into series activities such as drainage, earthworks and pavements [49]. The non-conformance series are then allocated a rating of occurrence (i.e. likelihood of reoccurring) as per the Kmenta and Ishii [50], table 4 and Liu *et al.* [51], Table 1. Each SHW series frequency is calculated against the overall NCR total to determine its probability failure rate and to allocate an appropriate rank. For example, if the frequency of NCRs in a particular SHW series was 250 and the total number of NCRs within the dataset was 1000, this would equate to 25% of the overall total, giving a probability rank of 8 as it’s greater than 1 in 8 but less than 1 in 3. A similar exercise is formed on the costs of each SHW series to assign severity ratings, and to understand the severity profiling of NCRs against costs to the scheme [51]. The greater the costs the greater the impact it will have on the scheme (i.e. severity of the situation). Series that had either zero likelihood or severity ratings would yield a zero RPN number and were discounted accordingly.

Second, to determine the detectability index (D) for each series, we link to cause-and-effect relationships by categorising the Cynefin framework domains within a detectability matrix [52]. Cause-and-effect relationships, risk profiles, and uncertainty levels are linked to the likelihood of detection, with 1 being almost certain to be detected, with direct links to cause and effect, and 10 being absolutely uncertain, with no links whatsoever. For example, the ‘Simple’ domain is categorised as being between 1 and 3, ‘Complicated’ as being between 4 and 5, ‘Complex’ as being between 6 and 7, ‘Chaotic’ as being between 8 and 9, leaving ‘Disorder’ as 10 (Figure 4).

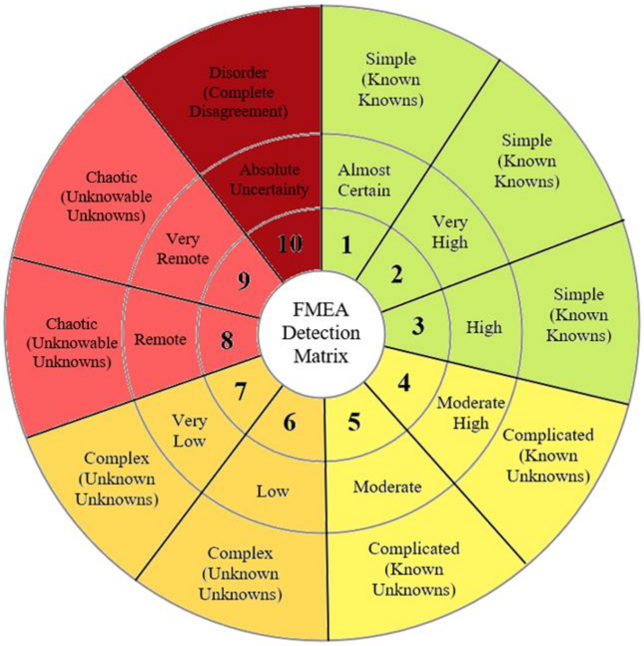


Fig. 4. FMEA detectability wheel against the Cynefin Framework domains

Third, we identify the detectability score for each series in order to calculate the RPN value. To do so, the real-time and retrospective decision-making pathway data obtained in part 1 is aggregated by multiplying the total number of cases within each domain against the corresponding likelihood score. All domain scores are then totalled to provide an overall detectability score per series. With the exception of ‘Disorder’, each domain spans more than one likelihood score within Figure 4. As such, an average is taken. For example, the ‘Simple’ domain would use a value of 2, the ‘Complicated’ domain a value of 4.5, the ‘Complex’ domain a value of 6.5, and so on, to compute a median value. Lastly, the RPN for each SHW series is calculated by multiplying the likelihood, severity and detectability values [48]. This is calculated for the real-time and retrospective cases, where the difference between RPN values presents the differing risk profile of decision-making.

D. Quantitative data collection: ‘The dataset’

Gaining access to NCR data is often challenging, as it represents poor quality performance, which many project teams are often unwilling to share [19]. Furthermore, they often hold commercially sensitive information, such as estimated costs of correction, which further inhibits information sharing. Instead, this information gets archived, and is never analysed or used to make future improvements [53]. This is unfortunate from a learning viewpoint, as to improve, develop and innovate, we must learn from our mistakes, rather than not acknowledging they exist. Similar concerns are discussed by Abdul-Rahman *et al.* [14] where they conclude that 'by learning from the results, those involved in the industry can reduce the impact of non-conformance'.

We utilise a unique dataset consisting of detailed non-conformance report information from a highways megaproject. Specifically, 1260 non-conformance reports over a period of 60 months (from 21/12/2016 to 20/01/2021) were supplied by the case highways scheme.

Due to the scheme's integrated nature, a highly collaborative atmosphere was formed to reward quality performance. As a result, a stringent NCR process was devised and signed up to by all parties at the very start of the scheme, to identify any non-conformance using a digital-based system. The NCR process consisted of a seven-stage gate process with a multi-level signoff that involved the supply chain, principal contractor, client, and in many cases, the designer. Figure 5 details the seven stages, from the start to the close out. Parts 1, 2, 3a, 4 and 5 were completed primarily by the Integrated Delivery Team (IDT) with input from suppliers as required, part 6 was completed by the independent quality assurance team, and parts 3 and 7 were completed by the client, to achieve a consensus for each NCR remedial action, corrective action, responsible party, and associated cost. Furthermore, costs were calculated by the IDT, factoring in administrative time, RCA time, and time for implementing the remedial works and corrective action necessary to prevent reoccurrence. These were then validated by the quality team and the client sequentially. Last, to ensure the validity and consistency of each input, the digital database was regulated independently by the Integrated Quality & Verification Team (IQVT), and used to log various meetings, investigations (deep dives) and RCA conclusions.

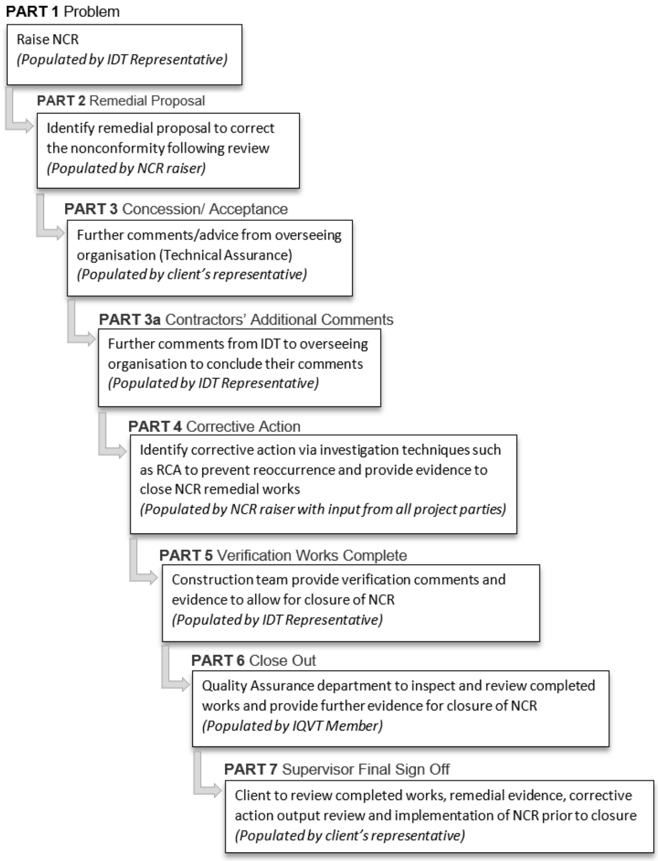


Fig. 5. NCR process used on highways megaproject

Potential for bias was considered and acknowledged upon receipt of the data. First, although the research team had a deep contextual knowledge of where the information had come from and how it was collected, the NCR process was established for the purpose of project improvement and early identification of noncompliant works, therefore the creation of the dataset was entirely independent of any research consideration [53]. This enhances the credibility of the data received, on the basis that the researchers could not have influenced data entries. Second, each NCR had to undergo a collective agreement via a rigorous seven-stage gate signoff process, thus removing opportunity for bias and ensuring only factual information was included. For example, if the client differed in opinion on a remedial solution or an underlying cause, they could challenge the contractor with a question or request for further information using part 3 of Figure 5. Third, the project benefited from a strong leadership team who advocated for continuous improvement and stressed the benefits of raising NCRs.

E. Non-conformance data analysis

A cleansing exercise was undertaken to remove notable human errors, such as typographical mistakes, along with a numerical validation check to identify duplications or missing NCR entries prior to analysis. During the initial screening process, 12 cases were discovered whereby no root cause was determined by the project, and where the dataset did not display enough information to provide a conclusion retrospectively. As such, these were labelled as ‘Unclassified’. Furthermore, the research team encountered 24 non-conformance cases that were raised for training purposes or duplicated with other NCRs. Last, there were 31 cases where the information was missing from the dataset altogether. All three observations were discounted from the analysis.

A sampling method was considered, however the researchers decided to analyse the full dataset, increasing the significance of data outcomes [54]. Furthermore, to avoid sequencing bias, we selected NCRs at random.

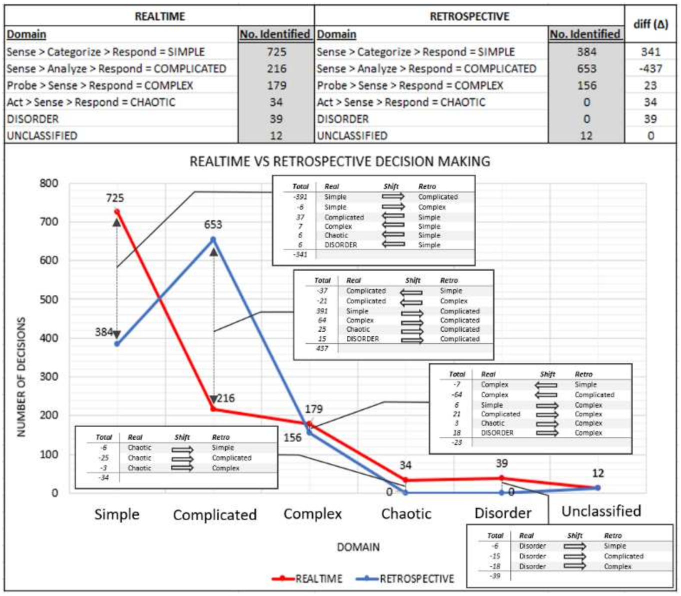
In order to provide validity and reliability of the retrospective root cause analysis, the primary researcher (a chartered quality professional with over 13 years engineering experience in the construction sector, trained in root cause analysis techniques) undertook five whys analysis on each NCR to validate the primary root causes and corrective actions to address the quality issue [55]. To enhance the retrospective interpretation, NCRs that yielded a different root cause to the real-time root cause were discussed and validated by existing senior members of the project team who had a comprehensive, detailed understanding of the non-conformity in question, but were not involved specifically in the NCR. Specifically, those with extensive experience and appreciated the necessity of honest feedback for the purposes of continuous improvement were selected. In total, there were five volunteers consisting of an engineering manager, quality manager and three engineers to help as to why the project concluded the NCR as they did. For these cases, emails were exchanged with the appropriate engineering professional to provide rationale or agree with the revised (retrospective) conclusion. This was followed up with a phone call to agree the most appropriate outcome to be inserted into the retrospective root cause field. With more freely available information to assess each NCR, it was unsurprising that the project had obtained different outcomes for several NCRs.

IV RESULTS

A. Non-conformance decision complexity categorisation: ‘The intervention’

Using the Cynefin framework as a tool for identifying various complexity levels, the authors have mapped each non-conformance against the framework both in real-time (i.e. the NCR owner) and retrospectively (i.e. the researcher) to determine whether oversimplification is occurring.

Figure 6 presents the real-time and retrospective complexity classification of the NCRs by the project team (red) and by the research team (blue). Differences between the two have been calculated and presented at each domain to understand the shift in decision-making, as not all decisions move linearly to the next domain. For example, there were six cases where a ‘Simple’ real-time decision was actually ‘Complex’ owing to many attributing causes, such as political pressures, adverse weather conditions etc.



REALTIME		RETROSPECTIVE		diff (Δ)
Domain	No. Identified	Domain	No. Identified	
Sense > Categorize > Respond = SIMPLE	725	Sense > Categorize > Respond = SIMPLE	384	341
Sense > Analyze > Respond = COMPLICATED	216	Sense > Analyze > Respond = COMPLICATED	653	-437
Probe > Sense > Respond = COMPLEX	179	Probe > Sense > Respond = COMPLEX	156	23
Act > Sense > Respond = CHAOTIC	34	Act > Sense > Respond = CHAOTIC	0	34
DISORDER	39	DISORDER	0	39
UNCLASSIFIED	12	UNCLASSIFIED	12	0

Total	Real	Shift	Retro
-391	Simple	⇒	Complicated
-6	Simple	⇒	Complex
37	Complicated	⇐	Simple
7	Complex	⇐	Simple
6	Chaotic	⇐	Simple
6	DISORDER	⇐	Simple
-341			

Total	Real	Shift	Retro
-37	Complicated	⇐	Simple
-21	Complicated	⇐	Complex
391	Simple	⇒	Complicated
64	Complex	⇒	Complicated
25	Chaotic	⇒	Complicated
15	DISORDER	⇒	Complicated
437			

Total	Real	Shift	Retro
-7	Complex	⇐	Simple
-64	Complex	⇐	Complicated
6	Simple	⇒	Complex
21	Complicated	⇒	Complex
3	Chaotic	⇒	Complex
18	DISORDER	⇒	Complex
-23			

Total	Real	Shift	Retro
-6	Chaotic	⇒	Simple
-25	Chaotic	⇒	Complicated
-3	Chaotic	⇒	Complex
-34			

Total	Real	Shift	Retro
-6	Disorder	⇒	Simple
-15	Disorder	⇒	Complicated
-18	Disorder	⇒	Complex
-39			

Fig. 6. Real-time vs retrospective decision-making categorisation

First, in the Simple and Complicated domains, there was an obvious shift between levels of complexity and uncertainty. Specifically, there were differences of 341 cases for Simple, 437 cases for Complicated, 23 cases for Complex, 34 cases for Chaotic and 39 cases for Disorder. It is important to note that during the retrospective decision-making analysis, no Chaotic or Disorder cases were logged. However, in a world of hindsight and retrospective thinking, why would there be any? At worst, the situation would be Complex, with many perceivable root causes to a problem.

To be specific as to which work activities experienced the greatest difference between decision-making pathways (i.e. under/oversimplification difference), the results were further categorised against the project’s Specification for Highway Works (SHW) (Appendix I). There were five series that featured zero non-conformities (Series 1300 – Cantilever Masts, Series 1600 – Embedded Retaining Walls, Series 1900 – Steelwork Protection, Series 2400 – Brickwork, Blockwork and Stonework, and Series 2500 – Special Structures). As such, these were discounted to further consolidate the appendix.

By comparing the two decision-making categories it becomes clear that there are significant differences between the real-time and retrospective categorisations. For example, we note that the Series 1700 – Concrete (Bridges) category has many Simple categorisations within the real-time data where the project team has not taken appropriate action to uncover the underlying causes of non-conformance but instead only scratched the surface. Many of those cases in the ‘Simple’ category were far more complicated than what they were initially perceived to be. As such, the interventions made were premature. In many of these non-conformities there was more than one root cause of the problem and more than one solution required to address it (i.e. a lack of supervision and leadership mandate). The data provides a perspective on the levels of uncertainty projects face but also flag the capabilities of those in problem solving roles. Project teams should re-evaluate the way they perceive complexity when dealing with problems, particularly the mindset of oversimplifying. Rather, it is best to think of the worst then work backwards from there, turning over every stone until a clear picture is reached, similar to forensic investigative techniques used in safety [56].

To add further justification, of the five most frequently raised NCR SHW categories listed within Appendix I, we categorised the decision-making interventions. Figures 7 and 8 present the domain allocation for real-time and retrospective decision-making pathways, which are colour coded to depict the change between levels of complexity.

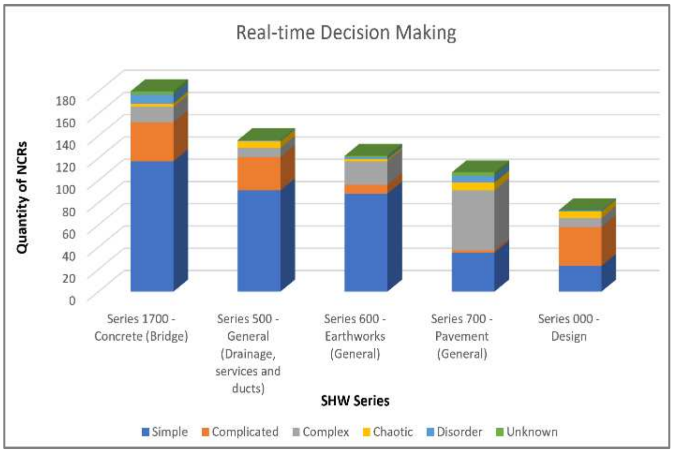


Fig. 7. Real-time decision-making of non-conformance

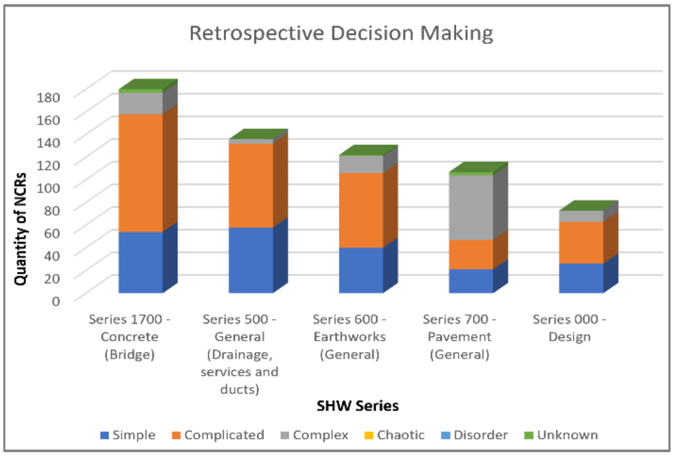


Fig. 8. Retrospective decision-making of non-conformance

There are clear patterns within Figures 7 and 8 that warrant further discussion.

First - Many of the oversimplified cases that were categorised as 'Simple' were in fact far more complicated than first envisaged (397 cases). Detailed root cause analysis indicates that in the majority of these cases, more than one kind of corrective action was necessary to address and mitigate the problem.

Second - There were 34 cases of 'Chaotic' behaviours whereby no thought or judgement had gone into resolving the problem. Process was not followed, and a quick fix attitude was adopted. In these cases, the retrospective decision-making suggests a far less complex solution could have resolved each problem.

Third - There were 39 cases of 'Disorder', due to a lack of consensus achieved over how to resolve the issue, or the issue was left stagnant with no resolution proposed/concluded. For these cases, the researchers were unable to conclude RCA and categorise them appropriately.

Fourth - The root cause analysis undertaken suggests that RCA is not being used efficiently or effectively by those problem solving. This may be down to a lack of training and a lack of competence in using such techniques [57] resulting in poorly executed, premature decisions.

B. Failure Mode and Effects Analysis (FMEA)

To support the notion that problems are often oversimplified, FMEA was exploited to identify the risk proportions for each SHW series activity. Real-time and retrospective NCR decision-making pathways were compared to build a clearer picture of the inherent risks associated with under/oversimplification (Appendix II). Those with zero NCRs raised were of nil risk.

On reviewing the findings and paying particular attention to the RPN difference number (Appendix II, Column 11), it is clear that those yielding a high negative value have been underestimated as activities. In reality, they pose greater levels of uncertainty and risk that should be managed far more carefully. For example, with activities such as bridge concrete piling and bitumen bound pavement operations, we saw significant oversimplification from this research that yielded a high negative value. At the other end of the scale, those that displayed high positive figures (e.g. sheet piling retraining walls and plant management) showed signs of over complicating matters rather than addressing underlying causes to provide simple, concise solutions. As the detectability scoring is a pivotal value that influences the RPN number, the complexity categorisation is important. In the positive examples mentioned above, each showed a higher detectability score for the real-time category than the retrospective. This indicates that there were more Complicated and Complex cases within the real-time space than the retrospective, and that the project struggled to deal with the complex/uncertain situations. With hindsight, the root causes of these cases were more determinable.

Finally, there were five SHW series (materials management, ecology, electrical works and steel culverts) that obtained the same real-time and retrospective scoring, meaning the projects decision-making assumptions were correct. This was the case for 15 NCRs within the dataset.

V DISCUSSION

In this section, we link back to the literature to reflect on the theory and practice of 'How project teams should make decisions related to non-conformance and quality issues in megaprojects'.

A. *Theoretical Implications*

Using the Cynefin framework and a categorisation rule against real-time and retrospective decision-making on non-conformance, we were able to conclude that the framework provides support in addressing problem solving in construction and in understanding the complexity of the problems projects encounter. Furthermore, we were able to determine that many NCR problems are oversimplified, along with the action pathways required to provide remedial and corrective actions. Alexander *et al.* [38] conclude there are similar benefits in elaborating on conceptualisations of unpredictability, complexity and the subsequent problems of misalignment, in Performance Measurement and Management (PMM). Rather than simplifying problems using lean practices, the most appropriate course of action would be to embrace uncertainty, understand the context of the situation, uncover the root cause through appropriate investigative techniques, and assign an appropriate course of action.

Our findings from the NCR analysis show that many NCR decisions were oversimplified and not responded to adequately. Cases that were categorised as 'Simple' were in fact far more complicated than first envisaged (397 cases). In addition, there were 34 cases of 'Chaotic' behaviours whereby no thought or judgement had gone into resolving issues. Decades later, oversimplification of complexity is still commonplace [26]. Such premature decision-making is having a lasting impact on project quality and impeding continuous improvement. The findings suggest that to avoid oversimplification, more nuanced decision-making models are needed. We conclude that a cognitive decision-making tool, the Cynefin framework, can be very useful in analysing decision-making of quality problems by determining when to switch intervention pathways to ensure the correct outcomes. Oversimplification of decision-making often results in incomplete corrective actions being taken to prevent future reoccurrence. With the coupling of RCA techniques (Figure 3), projects can assess their situation more carefully through cause-and-effect relationships that each NCR has, and apply more appropriate remedial and corrective action [24]. Lastly, the findings reveal that quality problems are not the same, i.e. have varying levels of complexity and uncertainty, and may require different decision-making pathways for different situations. The theoretical implications are that the Cynefin framework can be insightful to support decision-making in the context of infrastructure megaprojects. The theoretical contribution of this study provides a new concept of coupling RCA and decision-making tools to understand quality problem-solving accuracy.

B. *Practical Implications*

With any problem-solving challenge, to seek the underlying cause, specific skill sets and tools are needed to analyse uncertainty (e.g. deep dives, forensic techniques or root cause analysis). The data suggest that many people are not sufficiently trained to perform such techniques and/or pick the appropriate techniques. Rather, learning 'on the go' in a new role, with little support or coaching, is typical. Ma *et al.* [58] suggest a tangential but attributable factor is that, too often, projects are hindered by large numbers of quality problems that cause heavy workloads on experts and prevent them from spending sufficient time on individual problems. The application of RCA machine learning to interrogate quality problem solving has been suggested to support schemes, but may introduce new uncertainties, e.g. understanding data outputs from such machine learning [59].

As there are inherent uncertainties in projects, project leaders must learn from previous project data to eradicate the reoccurrence of non-conformance and rework. This will in turn increase the 'known unknowns' envelope for their project and reduce unwelcome surprises along the way, dealt with under a risk management portfolio [6]. Moreover, managers will be less surprised when similar situations arise, allowing them to make more appropriate decisions.

Our findings suggest that project actors need to be more challenging in their assessment of quality problem intervention to ensure root causes are not being overlooked. Furthermore, organisations must take note to capture, process and analyse information that is accurate (e.g. NCRs, observations, risk alerts etc.) to make more precise, effective decisions [23], [31]. The approach adopted in this paper can help those involved in the theory and practice of quality problems and provide a guiding light on how to effectively resolve through more self-reflective practices.

VI. CONCLUSION

Of specific interest in this paper was the very human tendency to oversimplify, particularly with regard to decision-making in relation to NCR problems, which we investigated via quantitative data. A large and unique rich dataset of NCRs from a megaproject is analysed to identify patterns and types of non-conformance and rework. Real-time vs retrospective decision-making assumptions were analysed using the Cynefin framework to determine appropriate root causes, remedial interventions and outcomes. This allowed the researchers to uncover the many instances of oversimplification (397 cases) through quality problem solving of NCRs, create a categorisation ruling for NCR analysis to understand assumptions of simplicity through cause-and-effect relationships, and presents the requirement for supportive decision-making tools such as the Cynefin framework to address quality problems. To conclude, there is an endemic issue of quality problem solving in construction. It is highly likely that many project members do not appreciate or understand the nuanced challenges to address quality problems in full, and fixate heavily on the remedial solutions, rather than preventative measures.

The contributions of this study are threefold: 1) using a unique and rich empirical dataset, we mapped NCR decision pathways and identified the issues of oversimplification in construction projects, with a view to stimulate more robust quality practices in construction operations. 2) improve the clarity of potential risks sources through FMEA and provide an improved understanding of quality problem complexity levels. 3) we create a novel approach to understanding project problem solving accuracy by categorising real-time and retrospective decision-making pathways through varying degree of uncertainty, applying the Cynefin framework in a new way and context. 4) more broadly, the work contributes to the non-conformance and rework body of knowledge to help drive towards an error free industry through NCR problem solving.

The practical implications of this study draw attention to the convoluted nature of quality problem solving and how the Cynefin framework, coupled with RCA techniques, can positively influence decision-making in problems. At a broader level, the industry and its operational leaders must be more spatially aware of quality problems and their inherent risks to project completion, improving training and self-reflective practice. Leaders must acknowledge and identify where complexity exists, and work through the challenges in an appropriate way to make effective decisions.

The quantitative findings are drawn from one dataset supplied by a highways megaproject. As such, the generalizability can be seen as a limitation of the work. However, all quality problems, regardless of sector, have cause-and-effect relationships that require interrogation through RCA techniques to solve. As such, the method may be transferrable. Further research could consider cross-sector analysis of quality problems to understand whether other divisions experience similar trends of oversimplification. Greater research on the effectiveness of decision-making frameworks in the construction problem-solving is called for to improve the cognitive awareness of complexity levels.

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