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Fast-and-frugal heuristics: an exploration into building an adaptive toolbox to assess the uncertainty of rework

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ABSTRACT

Performing rework within the production system of construction is the most expensive waste that confronts organisations, with its causation yet to be fully understood in practice. Any effort to assess the risk of rework poses challenges due to limited information about its frequency and causes, rendering the use of statistical models immeasurable. Research has shown that fast-and-frugal heuristics enable epistemic success under conditions of uncertainty and cognitive complexity – they are accurate, fast, and rely on limited information. Thus, this paper proposes the following research question: *How can fast-and-frugal heuristics effectively assess the uncertainty of rework in construction?* The theoretical framing of ecological rationality provides an environmental structure for bounded rationality to explore this question, enabling a person's 'adaptive toolbox' of fast-and-frugal heuristics tailored for different epistemic and pragmatic decisions to be utilised. Situations during the construction of a transport infrastructure mega-project (>AU$18 billion) where there was profound uncertainty surrounding rework are presented. The heuristics, intuitively drawn from an individual's adaptive toolbox used to form judgments to assess the uncertainty of rework, are identified. The theoretical and practical implications of the paper are discussed before presenting suggestions for future research to help build a robust adaptive toolbox to be utilised for assessing the uncertainty of rework in construction.

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1. Introduction

How to make and do things better by reducing waste, money, materials, and energy through streamlining procedures and processes is a goal of industrial engineering. Having to perform rework is a significant waste that impacts the performance of a production system and supply chains (Biswas and Sarker 2008; Boudia, Louly, and Prins 2008; Doyle et al. 2021; Ullah and Kang 2014). In the case of construction – a production system and a form of engineer-to-order supply chain – rework is defined as 'the total direct cost of re-doing work in the field regardless of the initiating cause, which excludes explicitly change orders [variations and errors caused by off-site manufacture' (Gosling and Naim 2009; Robinson-Fayek, Dissanayake, and Campero 2004, 1078). Rework has been heralded as the 'most expensive problem' for organisations in construction (XYZ 2022). For example, construction organisations have been found to experience as much as a 27% reduction in annual profit due to rework (Love and Matthews 2020). Furthermore, rework adversely affects safety and environmental performance (Love, Matthews, Sing, et al. 2022).

The literature is replete with studies seeking to determine the costs and causes of rework in construction (Asadi, Wilkinson, and Rotimi 2021; Burati, Farrington, and Ledbetter 1992; CII 2001, 2005; Hwang et al. 2009; Matthews, Love, Ika, et al. 2022b; Matthews, Love, Porter, et al. 2022a; Taggart, Koskela, and Rooke 2014). However, these studies have had a limited impact on reducing the costs of rework and its occurrence in construction. This is not to say that studies have not provided the literature with new knowledge and insights about rework; quite the contrary. Instead, construction organisations have tended to view rework as 'uncomfortable knowledge' (i.e., denied, dismissed, displaced, or diverted) or explain its presence as a one-off event overlooking its role in contributing to a project's mis-performance (Love et al. 2019; Rayner 2012). Compounding these views has been the absence of systems to capture and record rework-related information beyond that contained in non-conformance reports (NCRs), which many teams on-site have been reluctant to document, as management often considers them a sign that a project is poorly performing (Love, Smith, et al. 2018).

With the increasing pressure from public and private sector clients to improve the productivity and performance of construction projects, organisations have recognised the need to mitigate non-value-adding activities, such as rework (Love and Matthews 2022a, 2022b, 2022c; XYZ 2022). Industry-based bodies such as the 'Get it Right Initiative' in the United Kingdom (UK) have been instrumental in calling

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for construction organisations to focus on eliminating errors, as they are a key contributor to rework.

While there is an increased awareness about the nature and impact of rework, many construction organisations do not formally consider it part of a project's 'risk register'. Even when it is included, the absence of information about definitive causes and effects makes risks indeterminate. Rework arises in an environment of volatility, uncertainty, complexity, and ambiguity (VUCA) where its risks are difficult to pin down (CII 2001; Love and Matthews 2020; Love and Matthews 2022b; Love and Sing 2013; Love, Matthews, and Fang 2021; Love, Matthews, Ika, et al. 2022). A cursory review of the literature reveals that studies have tended to overlook the context within which rework occurs and instead only focus on identifying its perceived root and proximate causes using a series of adjectives and nouns such as 'poor site management' (Love, Matthews, Sing, et al. 2022).

All the same, *bounded rationality* (i.e., the human decision-making process which attempts to satisfice rather than optimise) pervades practice in construction – perfect information and knowledge do not exist – so decision-makers (e.g., site supervisors and engineers) need to work within their temporal and cognitive limitations and make choices to the best of their understanding (Love and Matthews 2022a, 2022b, 2022c). In this instance, heuristics become the 'go-to' for decision-makers, albeit informally, but their precision 'may often look like curiosities in the absence of an overarching theory' (Gigerenzer and Gaissmaier 2011, 453). Accordingly, heuristics are not given the credence they deserve in decision-making.

In this paper, a heuristic[1], otherwise known as a fast-and-frugal heuristic, is defined as a 'conscious or unconscious strategy that ignores part of the information to make better judgments. It enables us to make a decision fast, with little search for information, but nevertheless with high accuracy' (Gigerenzer 2014, 269). Such heuristics are problem-dependent. Additionally, meta-heuristics, though not the focus of this paper – problem-independent techniques – are higher-level techniques that seek, generate, or select a heuristic that may provide a sufficiently good solution to an optimisation problem (Attea et al. 2021). Such techniques have been widely applied to solve various problems in the operations and production management literature (Faramarzi-Oghani et al. 2023; Shin, Kwon, and Ryu 2008; Sobreiro and Nagano 2012; Tonge 1961).

An extensive body of research has shown that heuristics designed to be fast and frugal are more accurate than standard statistical models that draw on the same or more information, particularly under conditions of uncertainty (Gigerenzer 2008; Gigerenzer and Gaissmaier 2011; Gigerenzer and Goldstein 1996; Goldstein and Rothschild 2014; Hoffrage et al. 2000; Wübben and Wangenheim 2008). Research notably suggests that decision-makers may use heuristics informally to confront the uncertainty of rework, but there has been little empirical investigation on the topic (Love and Matthews 2022a).

To fill this gap, this paper proposes the following research question: *How can fast-and-frugal heuristics effectively assess the uncertainty of rework in construction?* The paper espouses the theory of *ecological rationality* (Gigerenzer et al. 1999; Hertwig et al. 2022; Luan, Reb, and Gigerenzer 2019; Simon 1990) and conjectures that it provides an environmental structure for bounded rationality where heuristics, with the twin advantages of speed and accuracy, can provide a realistic determination of rework, so that it can be incorporated into a construction organisation's risk management strategy. Thus, the contributions of our paper are twofold as we: (1) identify the potential of using fast-and-frugal heuristics for accommodating uncertainty during construction; and (2) provide an avenue for developing a formalised adaptive toolbox that is drawn upon for effective decision-making about the uncertainties of rework under varying conditions, situations and concerning specific events.

The paper commences by briefly explaining why decisions under risk are not the same as those under uncertainty (Section 2). The theoretical setting for the research is next introduced (Section 3). Then, we present a collection of fast-and-frugal heuristics from the literature that form part of a decision maker's adaptive toolbox that can address the uncertainty and cognitive complexity associated with accommodating rework during the construction of projects (Section 4). The intuitive use of heuristics observed in various situations during the construction of a transport infrastructure mega-project and their informal application to accommodate the uncertainty of rework in practice are identified (Section 5). The theoretical and practical implications of the paper are discussed before presenting suggestions for future research (Section 6) and its conclusions (Section 7).

2. The meaning of risk and uncertainty

In the risk management literature, decision-making situations can be classified into three categories (Luan, Reb, and Gigerenzer 2019 1738; Mousavi and Gigerenzer 2014): (1) *certainty* – each action is known to result in a specific outcome; (2) *risk* – all outcomes and probabilities of each outcome can be known; and (3) *uncertainty* – outcomes may be known but not necessarily their probabilities. In situations of perfect knowledge, heuristics are generally second-best, but this is seldom the case within the context of decision-making in construction. In this instance, perfect foresight is, by and large, absent, and optimisation rather impossible. Thus, heuristics can 'outperform complex strategies that try to fine-tune past data' (Luan, Reb, and Gigerenzer 2019, 1738). What is more, even with large datasets, what may have been optimal in the past cannot be guaranteed to be the best in the future.

Human error is the primary factor that contributes to rework in construction (Love, Matthews, and Fang 2021). Errors are unintentional deviations from goals, rules, and standards and can arise from a person's actions (Frese and Keith 2015). They can also occur due to errors in judgement and decision-making (Weber and Johnson 2009). Although empirical research demonstrating a causal link between errors in judgement and decision-making and rework has not been forthcoming, anecdotal evidence indicates otherwise (Love and Matthews 2022a), especially as in general business, 50% of management decisions fail (Nutt 2002) and

50% of wrong decisions could have been avoided (Carroll and Mui 2008).

Indeed, human error can be predicted in high-risk environments (e.g., aviation and plant maintenance) using approaches such as THERP[2] and SHERPA[3], where tasks are routine (Read et al. 2021; Stanton and Stevenage 1998). But in VUCA environments, such as construction with varying workplace demands and constraints, and where decisions involve dependencies in time and interdependencies amongst multiple agents, predicting the likelihood of people making an error requiring rework is implausible. As uncertainty prevails, it is also unknown if rework will occur in projects.

Contrary to popular belief, it has been shown that only some projects are subject to rework. For example, Love, Teo, and Morrison (2018) examination of 569 construction projects found that *only* 218 experienced rework − 351 did not! Of the 218 projects studied, 7082 non-conformances requiring rework were issued, resulting in a mean cost of 0.18% of a project's contract value. Moreover, approximately 40% of rework costs were incurred in 45 major events across 42 projects. Approximately 5000 rework events cost less than AU$2000; the majority are relatively minor. Errors are a consequence rather than a cause, *per se*, having their origins not so much in the perversity of human nature. Instead, they are a product of a project's environment and workplace conditions (Love, Matthews, Sing, et al. 2022). Thus, when facing decisions about 'what might go wrong' due to the unknowns that can occur during construction, consideration must be given to people's experiences and the context within which they are made.

Hence, a decision-making strategy for accommodating the uncertainty of rework during construction should be established and enacted. A point that has been repeatedly reinforced in several studies of rework in construction (Love, Matthews, Sing, et al. 2022; Matthews et al. 2023). At this juncture, we would like to note that the literature is replete with reviews of rework in construction. Thus, we intend to refrain from reinforcing what is already known about rework and, therefore, direct readers to the work of Asadi, Wilkinson, and Rotimi (2021) and Love, Matthews, Sing, et al. (2022), as their treatment of the topic, while comprehensive, take different perspectives to explain its causation. Essentially, Asadi, Wilkinson, and Rotimi (2021) focus on the proximal and root causes of rework. Contrastingly, Love, Matthews, Sing, et al. (2022) take a broader and systemic view, considering the emergent and adaptive triggers (e.g., latent conditions) and social interactions between organisations in a project that manifest errors and the need for rework in construction.

To this end, the differences between risk and uncertainty have been summarised as follows by Gigerenzer (2014, 23–24): 'RISK: If risks are known, good decisions require logic and statistical thinking. UNCERTAINTY: If some risks are unknown, good decisions also require intuition and smart rules of thumb'.

3. Theoretical setting

The classical view of rationality, centring around theories such as 'Bayesian decision theory' and 'utility theory' and their underlying laws of probability theory and logic, assumes that a single universal decision determines the best course of action (i.e., people behave optimally) (Daston 1988; Laplace 1951; Tversky and Kahneman 1974; von Winterfeldt and Edwards 1986). Notwithstanding the conviction that people behave optimally in situations of risk, this assumption does not hold in conditions of uncertainty (Gigerenzer 2014; Knight 1921; Meder, Le Lec, and Osman 2013).

Thus, there are several problems with this classical view of rationality widely reported in the literature, with two standing out within the context of this paper, these being its (Anderson 1990; Birnbaum 1983; Chase, Hertwig, and Gigerenzer 1998; Gigerenzer and Gaissmaier 2011; Todd and Brighton 2016):

1. *Blindness to content and context*: When making inferences, the rules of probability are taken *a priori* as normative. Often, little attention is given to the content of the problem and people's underlying assumptions where a statistical model is applied. Thus, people's judgments cannot be interpreted without attention being given to their content and context.
2. *Unrealistic demands:* In many situations where rework manifests, a rational model cannot be used in the real world as the 'problem space is unbounded' (Chase, Hertwig, and Gigerenzer 1998, 207; Love and Matthews 2022a). When Bayes' theorem, for example, is applied to real-world problems, it can become mathematically and computationally intractable, rendering its use for making inferences futile. Moreover, it would appear that Bayesian models are applied to problems driven by convenience and less so by the argument that a decision-maker's cognition and the environment within which it is made are inseparable – a point examined below (Hertwig et al. 2022). What is more, as probability distributions are unable to comprehend 'real-world behaviour under uncertainty', and therefore assigning objective probabilities with future consequences, where a decision-maker 'hasn't got a clue' is 'highly questionable, if not invalid in principle' (Davidson 1991, 130). As Chase, Hertwig, and Gigerenzer (1998, 207) cogently point out, 'expecting people's inferences to conform to classical rational norms in [complex environments such as construction] requires believing that the human mind is a 'Laplacean demon'[4]: a super calculator with unlimited time, knowledge, and computational power'.

It is beyond the remit of this paper to examine the debate surrounding the varying visions of rationality and inference in decision-making. However, authors such as Vranas (2000), Smith (2008) and Kelman (2010) provide a robust and comprehensive account of the differing schools of thought that readers can refer to understand the intricacies of rationality and inference.

With limited in-depth information and knowledge about the causal nature of rework in construction projects being available for decision-making, bounded rationality is induced when making inferences about their occurrence when planning activities (Love and Matthews 2022b). Thus, a decision maker's experience and a project's culture and environment will be considered when required to make choices in planned actions.

Supporting this position, Chase, Hertwig, and Gigerenzer (1998, 207), drawing on the seminal work of Simon (1983,1990), point out that 'rationality cannot be defined except by reference to environmental and cognitive constraints'. Accordingly, Simon (1990, 7) uses the scissors analogy to set the scene for an alternative framing for making judgments, arguing that rational human rationality 'is shaped by scissors whose blades are the structure of tasks environments and the computational capabilities of the actor'.

3.1. Ecological rationality

The scissors analogy of Simon (1990) forms the basis of ecological rationality, which helps explain how people make decisions and achieve their goals under internal (cognitive) and external (environmental) constraints. Looking at a single blade (cognition or environment) of the scissors will not provide an understanding of its function – they need to be viewed simultaneously as people's reasoning results from adapting to the environment within which decisions will be made. Against this backdrop, Gigerenzer et al. (1999) refer to ecological rationality as the property of a heuristic that is rational to the degree that it adapts to the structure of the environment (e.g., a project). Thus, the key is understanding how cognitive and environmental structures fit together to produce a heuristic contributing to successful decision-making.

Fast-and-frugal heuristics are strategies generated by environmental situations and enabled by evolved or learned capacities. Selecting a heuristic strategy involves more than partial deliberation and can be instinctive. In the dynamic and complex environment of construction where timely decisions need to be made, a good decision is less about finding the best alternative than unearthing one that works.

Heuristics practically represent how decisions are made and can thus be deemed a product of practical rationality[5]. However, heuristics are task-specific (i.e., problem-dependent). They are designed to solve a particular task (e.g., choice, numerical estimation, and categorisation). They thus cannot solve those they are not designed for – 'just as a hammer is ideal for hammering nails but useless for sawing a board' (Hoffrage and Reimer 2004, 441).

By exploiting the two blades of Simon's scissors, fast-and-frugal heuristics can be simultaneously simple and accurate. Fast-and-frugal heuristics possess four characteristics that enable them to be adapted to situations (Marewski and Gigerenzer 2012): (1) accessibility; (2) speed; (3) transparency; and (4) low costs. The importance of these characteristics varies with the goal and situation. For example, speed and frugality in decision-making are essential in projects subjected to production pressure, and accessibility allows choices to be executed without requiring extensive knowledge and training.

What makes a decision ecologically rational is how well its outcome matches the availability of information (i.e., economic and social) provided in a project's environment and becomes integrated into daily decision-making processes. Processing information in project environments will invariably include elements of both cognition and affect (i.e., feeling, emotion, and attachment). Accordingly, the brain can be conceptualised using the metaphor of the adaptive toolbox containing fast-and-frugal heuristics. These heuristics capture how actual minds make decisions under limited time and knowledge constraints, tailored for different epistemic and pragmatic decision tasks (Gigerenzer, Todd, and the ABC Research Group 1999). This conceptualisation typifies the environment of construction.

3.2. Adaptive toolbox

Fast-and-frugal heuristics are built on a robust theoretical and scientific underpinning and based on three common building blocks (Gigerenzer and Gaissmaier 2011): (1) search rules that specify *where* to look for information; (2) stopping rules that specify *when* to complete the search; and (3) decision rules that specify how the final decision is reached. The pool of fast-and-frugal heuristics, juxtaposed with the core mental capacities that the building blocks an individual has at hand provide, enable an adaptive toolbox to be established (Declerck and Boone 2015; Gigerenzer et al. 1999; Gigerenzer and Gaissmaier 2011). Such core mental capacities can be acquired through personal experience, expert training, or evolutionary learning (Gigerenzer 2008).

The assortment of fast-and-frugal heuristics in an adaptive toolbox involves using experience-based strategies for rapidly solving problems or making decisions under conditions of uncertainty that serve to 'satisfice' rather than optimise (Geary, Berch, and Koepke 2015). Thus, the conceptual lens underpinning fast-and-frugal heuristics commences with the premise that in situations of uncertainty, accurate decisions are not dependent on a high level of effort or complex strategies. Consequently, this differentiates fast-and-frugal from other approaches, such as the *heuristics-and-biases framework* of Kahneman, Slovic, and Tversky (1982) and the *adaptive decision-maker approach* (Payne, Bettman, and Johnson 1993), which rely on heuristics to solely reduce effort. Furthermore, as mentioned above, fast-and-frugal heuristics are simple without sacrificing accuracy as they utilise the intrinsic properties of Simon's scissors: 'the decision environment and the individual capabilities of the decision maker' (Hafenbradl et al. 2016, 217).

Equipped with several heuristics to draw upon, a decision-maker can arrive at a solution that is *good enough* rather than the best one. The assumption is that optimal choices are costly; thus, trade-offs enable good enough decisions to yield the best marginal returns. Heuristics can be categorised based on how much knowledge or information they require about the environment in which they can achieve epistemic success (Mousavi and Gigerenzer 2014). This success is possible by taking advantage of the environment through the naturalisation of rationality (Rich et al.

2021); people *can* and *ought to* apply intuitively simple heuristics to reach accuracy at little cost. Thus, the 'ought-can' principle is satisfied, and rationality is considered meaningfully normative. With this in mind, the toolbox adaptation can be explained *informally* by Rich et al. (2021, 5755):

> *Input*: The environment, which consists of (possible) situations and (available) actions for each situation, dictates which set of actions is satisfactory in that situation
>
> *Output*: An adaptive toolbox of heuristics that has minimal ecological rationality for the environment. The ecological rationality of the toolbox depends on its ability to select satisfactory actions.

This input-output mapping informally captures what toolbox adaptation aims to achieve. That said, an informal approach to toolbox adaptation needs to make explicit its specifics (Rich et al. 2021): (1) What precisely is an adaptive toolbox? (2) How can ecological rationality be determined in construction? (3) What is a situation? and (4) How are situations related to actions? Recognising the toolbox's adaptation lacks specificity, it can be formalised and expressed as (Rich et al. 2021, 5756):

> *Input*: An environment Γ which is defined by the triplet (S, A, D), consisting of a set S of situations, a set A of actions and a function D: $S \rightarrow 2^A$ that determines, for each situation, which set of actions is satisfactory and the minimal ecological rationality, $er_{min} \in [0, 1]$
>
> *Output*: An adaptive toolbox of heuristics T and its ecological rationality $er \geq er_{min}$ for environment Γ, if such a toolbox exists and a special symbol $\perp$ otherwise.

An adaptive toolbox comprises two components (Rich et al. 2021): (1) a set of heuristics; and (2) a selector heuristic, which selects the one to be used. Heuristics can be classified as (Gigerenzer and Gaissmaier 2011): (1) *recognition-based* basing judgments on recognition information only (e.g., recognition and fluency); (2) *one-reason decision-making* basing judgments on one good reason only, ignoring other cures (e.g., take-the -best and fast-and-frugal trees); (3) *trade-offs* where all cues receive weights or alternatives equally. As a result, trade-offs ensue (e.g., tallying and 1/N); (4) social heuristics, which are designed solely for social information (e.g., default, imitate and tit-for-tat). It has been suggested that the recognition-based and one-reason decision-making heuristics in Table 1 can be applied to make decisions under conditions of uncertainty in construction, particularly within the context of rework (Love and Matthews 2022a).

While there is an absence of empirical evidence examining the use of fast-and-frugal heuristics in construction, other disciplines have applied them successfully to solve many problems (Meder, Le Lec, and Osman 2013; Mousavi and Gigerenzer 2014; Raab and Gigerenzer 2015; Wübben and Wangenheim 2008). Other popular fast-and-frugal heuristics that have been studied extensively but are irrelevant to the context of this research are (Luan, Reb, and Gigerenzer 2019; Mousavi and Gigerenzer 2014; Raab and Gigerenzer 2015): (1) tallying; (2) one-bounce rule; (3) gaze heuristic; (4) 1/*N* rule; (5) default heuristic; (6) tit-for-tat; (7) imitate the majority; (8) imitate the successful; (9) Δ-inference; and (10) satisficing.

Two questions about heuristics repeatedly raised in the literature are related to: (1) What environments will a given heuristic succeed or fail in; and (2) How is a heuristic selected for a given problem? According to Todd et al. (2011), environmental structures where heuristics have been found to perform well are: (1) *uncertainty*: how well a criterion can be predicted; (2) *redundancy*: the correlation between cues[6]; (3) *sample size*: number of observations relative to the number of cues; and (4) *variability in weights*: the distribution of the cue weights.

Table 1. Adaptive toolbox: Examples of fast-and-frugal heuristics to assess the uncertainty of rework.

Heuristic	Definition	Ecologically Rational if:	Bold Predictions
Recognition	If one of two alternatives (i.e., a and b) is recognised, infer that it has a higher value on the criterion	Recognition validity >0.5	Contradicting information about a recognised object, less-is-more effect, if a > b, forgetting is beneficial
Fluency	If both alternatives are recognised, but one is recognised faster, infer that it has a higher value on the criterion	Fluency validity > 0.5	Can predict differences between two recognition latencies.
Take-the-best (See Figure 1)	Infer which of two alternatives has the higher values by; (a) assessing through cues in order of validity; (b)stopping the search as a cue discriminates; and (c) choosing the alternative this cue favours.	Cue validities vary; moderate to high redundancy, scarce information	Can predict as accurately as or more than multiple regression, neural networks, and classification and regression trees
Take-the-first	Choice from self-generated options by: (a) searching through options in order of validity; (b) stopping the search after two or three options; and (c) choosing the first option generated	Option validity varies highly; option validity is learned through feedback	Can predict limited research better than memory models
Fast-and-frugal tree (See Figures 2 to 5)	Classify an object into two categories by: (a) searching cues according to their order; (b) stopping the search as soon as a cue allows to do so, and (c) choosing the object specified	Refer to take-the-best heuristic	Can predict accurately as or better than logistic regression

Adapted from Gigerenzer (2008), Gigerenzer and Gaissmaier (2011), Raab and Gigerenzer (2015).

Heuristics can be applied *with* and *without* awareness (Gigerenzer 2008). They can be selected based on an individual's learning, discovered through social processes by imitation, or learned from being taught how to apply them. When a heuristic is used without awareness, it is chosen intuitively. In this instance, a heuristic is applied unconsciously without explaining why it was chosen. The instinct of intuitively using heuristics provides a segue to introduce examples from a transport infrastructure mega-project case study, where fast-and-frugal heuristics have been and can be applied to deal with the uncertainty surrounding errors and rework in construction.

This exploratory research focuses on *what* heuristics are utilised for decision-making rather than *how* they are selected. Thus, the research takes an informal perspective on toolbox adaptation to understand and make sense of *how* fast-and-frugal heuristics can achieve epistemic success within the context of assessing the uncertainty of rework. Against this contextual backdrop, the VUCA environment (Γ) is the construction project, the situation (S) is the rework event, and actions (A) are those activities to manage errors and rework.

4. Research approach

To recap, the paper's research question is: *How can fast-and-frugal heuristics effectively assess the uncertainty of rework in construction?* A case study is utilised as it is a fitting strategy to explain the 'how' of phenomena using a sensemaking lens (Stake 1995). Sensemaking is defined as 'how people make sense out of their experience in the world' (Klein, Moon, and Hoffman 2006, 70). The use of sensemaking is suitable when there is an explicit goal to improve the practices and processes that exist within the workplace, and there prevails an awareness and understanding of situations of high complexity or uncertainty to make decisions (Klein, Moon, and Hoffman 2006).

4.1. Case description

The case study is an Australian transport infrastructure mega-project (>AU$18 billion) aiming to remove 110-level crossings causing congestion and limiting the speed and frequency of rail services. The project was established in 2015 and uses a program alliance delivery strategy comprising five alliances. Four options exist for separating the rail line from the road and removing a level crossing:

1. *Rail over the road*: A rail bridge is constructed over the road, which remains at the current level. In this case, train stations may need to be modified to suit the new rail level. It can improve pedestrian access and create opportunities to use the area beneath the rail line.
2. *A rail tunnel is built beneath the existing road*: The road remains at the current level. Nearby train stations may need to be modified or rebuilt to suit the new rail level. Additional pedestrian or cycling bridges may be built to improve access across the lowered rail line.
3. *The rail line remains at the current level, but a road bridge is constructed over the rail line*: Service roads and alternate access options are built. Pedestrian access to train stations is maintained. Train station modifications are usually unnecessary as the rail level stays the same.
4. *The rail line remains at its current level, but an underpass is constructed beneath the rail line for the road*: Service roads and alternate access options need to be built. Pedestrian access to train stations needs to be maintained. Modifications to train stations are usually optional as the rail level stays the same.

By 2025, it is expected that 75 level crossings will have been removed and substituted with one of the above options.

4.2. Data sources

An alliance provided the authors unlimited access to their project documentation, which includes non-conformances, site diaries, internal/requests for information (i/RFIs), site instructions, safety reports, punch lists, lessons learned, and the schedule documented using Touchplan®. Additionally, the authors regularly attended fortnightly continuous improvement meetings over two years and conducted 19 semi-structured interviews with alliance members (e.g., engineering manager, site superintendents, and quality manager) and subcontractors to determine the causal nature of errors and rework.

Interviews ranged from 30 to 60 minutes and were digitally recorded. Interviewees involved in a rework event identified and described their experiences with errors and rework, enabling the authors to make sense of what had transpired. The authors stitch together various data sources to create a narrative for each example where heuristic decision-making occurs for situations where rework is uncertain.

4.3. Analysis

Interviewees provided us with their view of rework events, and those that were repeated and could be supported with documentation were examined. Data was inputted into NVivo version 12 and systemically categorised and coded using interview excerpts linked to referenced documents (e.g., NCRs) where events were identified. Thematic analysis was adopted, enabling us to actively engage in the process of reflexivity, derive meaning from the data and identify the appropriate heuristic (i.e., themes) that was being applied. We now present our analysis and interpretation of the data we obtained during the course of our exploratory study.

5. Fast-and-frugal heuristics in practice

Examples of how practitioners *intuitively* used heuristics in their decision-making are now examined, namely the; (1) recognition heuristic (RH); (2) fluency heuristic (FH), and (3) take-the-best (TTB). Then, the potential of fast-and-frugal trees (FFT) as a heuristic to accommodate the uncertainty of rework based on actual events that arose is explored.

The authors hasten to note that the examples presented are not exhaustive, as practitioners operating at the coalface of operations in construction will invariably rely on a variety of heuristics as part of their daily decision-making routines to deal with the potential presence of errors and the need for rework. Moreover, the examples presented occur in a specific project context where people possess agency and are empowered to make decisions without fear of reprimand. However, as noted in the rework situations in Table 2 in Section 5.4, newly appointed project engineers eschewed reporting a non-conformance as they wanted to avoid being singled out for their underperformance. To the best of the authors' knowledge, this situation was an aberration.

5.1. Recognition heuristic

The RH – the most frugal of all heuristics – makes inferences from patterns of missing knowledge – infers that if one of two objects is recognised and the other is not, then assume that the recognised object has the higher value concerning the criterion (Goldstein and Gigerenzer 2002). People 'go with what they know'. Individuals and groups relying on the RH in their decision-making ignore contradicting cues, enabling quick choices and improved accuracy (Katsikopoulos, Schooler, and Hertwig 2010; Reimer and Katsikopoulos 2004).

5.1.1. Commencing work before or after the 'Issue for construction' drawings

When undertaking look-ahead planning during the construction of an asset, for example, site superintendents are generally cognisant that people will commit errors and rework may be needed; these concerns are seldom made explicit, but buffer may be included in formulating a plan. Routinely, when making decisions, site superintendents rely on their experience to generate tacit rules of thumb applied to a given context (Love and Matthews 2022a). In the case of a project constructed by an alliance, the preparatory and temporary site works had been completed.

The much-needed 'Issue for Construction' (IFC) drawings for inground services had yet to be made available to the contractor, potentially delaying work and the project's completion date. A newly appointed site superintendent faced a binary decision: (a) proceed with works before producing the 'IFC drawings', ignoring the potential of errors or changes in the 'Issue for approval' (IFA) drawings and the potential for rework or (b) wait for their issue, possibly causing a delay. Technically, no work should commence before the IFC drawings as they form an integral part of a project's contract documents, but it had become common practice to do so to adhere to the schedule.

In a previously constructed project, for example, a site superintendent had decided to proceed with the works based on IFA drawings and not IFC drawings so as not to cause a delay – a judgement under uncertainty was made. Work commenced on preparing the trenches for the inground services based on the IFA drawings. Several days later, the IFC drawings were distributed to the contractor. The IFA drawings contained errors, and thus, the work undertaken needed to be rectified to correspond with those IFC. The decision to proceed based on the IFA drawings caused a delay of a week, and rework costs had to be borne by the contractor.

The new site superintendent, unaware of what had transpired previously, needed to make a quick decision even though they were uncertain about its consequences (e.g., delay and rework). They had yet to be confronted with making a decision of this nature before but recognised (b) immediately as the most appropriate action based on their experience with proceeding with incomplete drawings.

Arguably, several factors could have influenced the new superintendent's decision, such as weather, safety, plant availability and contractual obligations. However, it was ultimately made using their intuition and not knowing its consequences. While the IFC drawings were issued two days after the work was supposed to commence, works could be completed on time. Notably, service pits had been relocated, and as a result, waiting for the IFC drawings, potential rework and a safety incident were averted. If experience and knowledge were considered *a priori* regarding possible consequences, then a trade-off heuristic may have been applied to weight cues such as tallying or the 1/N rule. Future research is required in this case to examine this situation and how trade-offs emerge and need to be enacted.

To this end, when presented with the above situation, the following simple rule of thumb should be followed to mitigate rework: *Only commence work when IFC drawings have been issued*. When subjected to production pressure, it is naturally tempting for construction organisations to jumpstart activities to keep abreast of their schedule and commence preliminary work before IFC drawings are issued. No matter how luring this may be, the decision will unequivocally be made in the realm of uncertainty.

5.2. Fluency heuristic

Heuristics are only applicable under limited circumstances. So, in the case of the RH, it cannot be applied when both objects (or instances) are either recognised or unrecognised. When both objects (or instances) are recognised, and no other knowledge (e.g., in terms of probabilistic cues), a suitable heuristic is the FH (Table 1). Akin to the RH, the FH is useful when there is a 'correlation – in either direction – between a criterion and recognition and/or retrieval fluency' (Hertwig et al. 2008, 1192). The FH relies on mnemonic information to make a swift inference using a person's automatic by-product of retrieval from memory.

When alliance members and subcontractors were invited to select whether alliances or conventional project delivery strategies induce higher rework costs, all, without hesitation, chose the latter (Love, Matthews, Ika, et al. 2022; Matthews et al. 2022b). Thus, the following rule of thumb emerges for the situation presented: *Alliance contracting results in less*

Table 2. Description of rework situations.

VUCA Project Environment (Γ)	Situation (S)	Cues for Actions (A)
• Rail line remains at its current level- Road bridge constructed (Figure 2)	Two project engineers were required to check the quantity of reinforcement installed. They paid limited attention to the nuances of the design and what had been installed. The engineers were inexperienced and solely focused on completing the pour as it was a critical activity. Seven pile caps needed to be checked, and six had been completed without an issue. So, it was assumed that the final pile cap would also conform, and a concrete pour was scheduled. However, before the concrete pour, the supervisor noticed a mistake in the reinforcement cog, requiring work to be halted, resulting in rework and delays to work incurred. The engineers checked the quantity but did not check the actual cog (i.e., the bar bend). It was the wrong length. The cage had to be amended, requiring rework, and the concrete pour was delayed.	• Is the activity on the critical path? • Has a concrete pour for pile caps been scheduled? • Is there an error in the reinforcement installation? *Actions*: Proceed with the planned work schedule OR perform rework
• Rail line remains at its current level- Underpass is constructed (Figure 3)	A subcontractor initially forgot to install five starter bars in the slab for an underpass ramp's retention wall. Then, after realising this oversight, the subcontractor drilled and grouted the bars into the slab (i.e., mistake). This perceived remedial action was non-compliant with the IFC drawings. In this instance, an error resulted in another error occurring. An internal Request for Information (i-RFI) was raised and followed up with an NCR issue. The estimated cost of rectification was AU$ 500.	• Starter bar installation on a slab for RC retaining walls? • Have the starter bars been cast in situ? • Does the starter bar installation adhere to IFC drawings? *Actions*: Approve the work after checking OR issue a non-conformance requiring rework
• Rail over the road (Figure 4)	Overhead pile footings identified on the IFC drawing indicated that they should be circular. However, the footings resembled an oval shape. The project engineers, new to the project, knew the footings were non-compliant but were reluctant to report it as a non-conformance. The engineering manager suggested they first thought the project's engineers did not want the spotlight on them, as they had not adequately supervised the works and undertaken the required engineering checks. While inspecting the site, the quality manager noticed the problem – the formwork had been installed incorrectly.	• Did the project engineers perform engineering checks on the footings? • Were any errors identified during the pre-pour check? • Was the formwork incorrectly set out? *Actions*: Issue a non-conformance OR proceed with work
• Rail line remains at its current level- Road bridge constructed (Figure 5)	The architectural screens for a bridge over rail had been designed, manufactured and installed as per the IFC drawings. After their installation, they began to deflect during high winds, raising concerns about their structural integrity. The steel fabricator produced the shop drawings based on the IFC drawings. The shop drawings had not been checked and approved by the structural engineer but instead by the architect/ should have been checked and approved by the structural engineer. However, instead, the architect approved them. The bolt and rivet and the welding detail were inadequate to support the aluminium and steel frame of the screen.	• Have the IFCs been issued for the architectural screens? • Have the shop drawings been produced and approved by a structural engineer? • Have errors been rectified and drawings approved? *Actions*: Proceed with work OR issue an RFI

rework in construction than projects delivered using conventional procurement strategies.

There may be occasions when two choices (or more) are unavailable to decide. So, memory is relied upon to generate the first alternative that comes to mind. This heuristic is the 'take-the-first' heuristic – a variant of the fluency heuristic – but was not identified to have been utilised in the rework situations derived from the case. However, this is not to say it is not used in daily decision-making in construction; quite the contrary, it is required for a wide range of performance-related tasks, such as navigating complex and dynamic spatial environments of construction sites (Colin 2009; Raab and Gigerenzer 2015).

Retrieval fluency is also associated with Tversky and Kahneman (1973) availability heuristic[7], but the FH has distinct differences. The availability heuristic assesses the target event's frequency (i.e., probability) based on prior instances. The FH bases its inferences on the speed within which an event is recognised, where its availability is interpreted as an 'ecologically rational strategy by rooting fluency in the informational structure of the environment' (Schooler and Hertwig 2005, 626).

5.2.1. Choosing between reinforcement design in the IFCs and Australian standards

At daily toolbox safety meetings, issues associated with quality were also identified insofar as it presented an avenue to convey issues previously in similar projects constructed by the alliance and raise awareness about the problems related to performing rework. Besides discussing safety measures and risks at the daily meeting, the site superintendent would discuss the quality-related requirements and expectations of the works and seek feedback and suggestions from subcontractors. In one case, the site superintendent, referring to the IFC and contract documents, explained how the reinforcement for a concrete structure was to be laid and identified potential risks that would confront the subcontractor.

Splices/cogs were placed alternatively between reinforcement bars. Splicing is a method to join reinforcement bars and ensure forces are transferred effectively from one bar to another. A cog is a wheel or bar with projections on its edges that transfer motion by engaging with projections on another wheel or bar. The subcontractor's supervisor recognised that placing the splices/cogs alternative could result in them having to perform rework as it did not adhere to Australian standards. However, the IFC and contract documents specified otherwise, as did the rail operator's standards.

A request for information was sent to the engineer by the site superintendent in the morning, seeking clarification about the design of the reinforcements. A response was not forthcoming, and a concrete pour was due at the end of the day. Faced with making a snap decision, the subcontractor's supervisor considered the two options, recognising that the Australian standards would have to be met, therefore choosing to ignore the IFCs and advising their workforce to place splices and cogs between all reinforcement bars.

A response from the engineer was received after work had commenced, stating that the requirement in the Australian standards took precedence over the documented design in the IFCs. As a result of this issue, the reinforcement design and specification were amended for future projects. Thus, the following rule of thumb should be followed when confronted with this situation: *Always check that reinforcement design conforms to Australian Standards – they take precedence above what is specified.*

5.2.2. Machinery selection

A piling rig was required to insert a series of bore-drilled piles for a bridge over a railway line. In this case, large holes are drilled into the ground and filled with concrete. Bored piles transfer the load above ground to the deep rock and soil layers below with minimal settlement. The piling subcontractor provided the construction manager with a choice of machinery to be used for the job: (1) a 20-tonne excavator pendulum drill rig; and (2) a purpose-built rig (e.g., rotary bored machine). The construction manager immediately selected the purpose-built rig.

While both pieces of machinery could have been used, the construction manager was cognisant of the uneven ground, which could have impacted the rotation allowance of the pendulum to remain in position while drilling, though it was cheaper to use. Moreover, anecdotal evidence in NCRs from previous projects indicated that pendulum attachments increased the propensity for pile intolerances.

There was a four-day window to install the piles, and a quick decision about the machinery selection was required as IFCs had been issued. The ease of retrieval fluency formed a proximal cue across several criteria (e.g., uneven ground and a pendulum attachment, which could have resulted in intolerances in piling and requiring their replacement). To this end, the rule of thumb that should be followed to confront the uncertainty of rework in situations of this ilk is: *Use purpose-built rigs for piling on uneven ground*. However, in the case of confined sites, there may be situations when an excavator pendulum drill rig, or equivalent, is required.

5.3. Take-the-best (ignore the rest)

While both the RH and FH base decisions on recognition information, the take-the-best relies on recall inferring which of two alternatives has a higher value on a criterion based on binary cue values. This heuristic, a lexicographic model, assumes a subjective rank order of cues according to their validities (Figure 1a). As mentioned in Section 3.2, a fast-and-frugal heuristic is underpinned by three building blocks. In the case of take-the-best, decision-making is simplified by stopping after the first cue and ordering cues unconditionally according to their validity, *v*, expressed as (Gigerenzer and Gaissmaier 2011, 464):

$$v = C/(C + W)$$

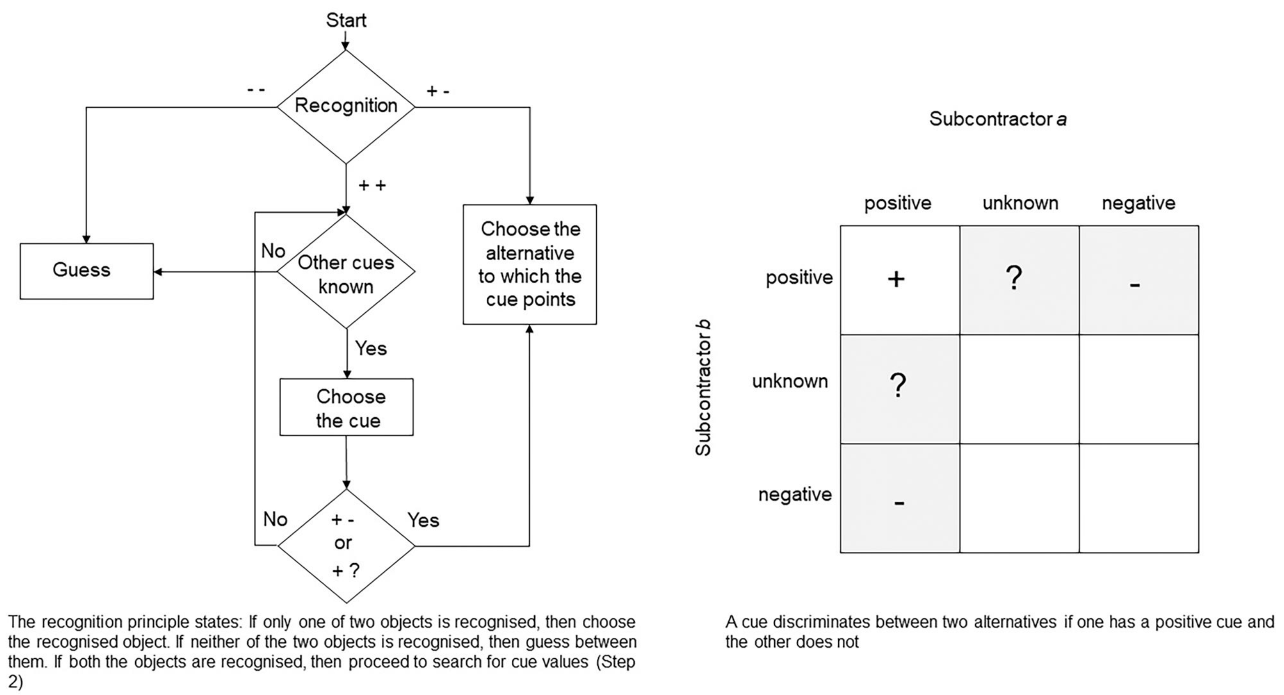
where *C* is the number of correct inferences when a cue discriminates, and *W* is the wrong number of inferences.

Research has demonstrated that the take-the-best heuristic provides better prediction accuracy than linear regression and other complex non-linear strategies under uncertainty (Czerlinski et al. 1999; Brighton & Gigerenzer 2011). Equally, the ecological rationality of the take-the-best heuristic has been extensively examined, and the best environments it exploits are those where there is (Gigerenzer and Gaissmaier 2011): (1) moderate to high cue information redundancy; and (2) moderate to high variability in cue weights. A simple example from our case study project where take-the-best was observed to occur is now examined using Gigerenzer and Goldstein (1996) method.

5.1.2. Subcontractor selection based on quality performance

Two civil engineering subcontractors, *a* and *b*, tendered for works on a rail over-the-road project. The tender price of $a > b$, and they had both worked previously completed works for the alliance. In this case, either *a* or *b* must be selected to construct the civil works. The process of enacting the take-the-first heuristic for this example goes through the following steps (Figure 1):

1. *Recognition*: A site superintendent with knowledge (i.e., recognised) of both *a* and *b* was asked to infer which had been issued more non-conformances. As the construction manager was new to the alliance, this was their first time working with these subcontractors. They thus relied on the site superintendent to decide who should be awarded the contract.
2. *Search for cue values*: For *a* and *b,* the cue for the site superintendent are the costs of rework (+) incurred as a consequence of non-conformance; that is, $b > a$. Other cues may include safety record, environmental performance and previous tendered prices, but these were not considered here, albeit made explicit.
3. *Discriminate rule*: A cue is identified to discriminate between *a* and *b* if one has a positive cue (+) value and the other does not (? or -). In Figure 1b, a cue



(a) A flow diagram of the take-the-best heuristic

(b) Discrimination rule

Figure 1. Take-the-best heuristic. Source: Gigerenzer and Goldstein (1996, 653).

discriminates between *a* and *b,* as a positive cue value exists. While *b* has a lower tender price, it had been issued with more non-conformances, resulting in higher rework costs incurred from other projects the alliance had delivered. Thus, *b* is negative (-).

4. *Cue-substitution principle*: If the cue discriminates, as it did in this case, the search for cue values stops. However, if the cue does not discriminate, Step 2 is enacted again, continuing with the next cue until one that discriminates is found.
5. *Maximising rule for choice:* The civil engineering subcontractor, *a*, with the positive cue, was selected. Without discriminating cues, the site superintendent would have had to guess whom to choose (i.e., cues are unknown?).

The site superintendent only based their decision on one cue as they had missing knowledge about the subcontractor's (*a*) safety and environmental performance and none about their previous tender performance.

Contractors often prefer the lowest tender prices from subcontractors to maximise their margins. In this case, quality was a factor the alliance considered as rework adversely impacts costs, productivity, and safety. As a matter of fact, safety was a key result area forming part of the alliance's contractual financial compensation model – it was a priority. So, selecting a subcontractor with better quality performance would result in fewer non-conformances requiring rework and safety improvements.

Accordingly, the following rule of thumb should be followed in situations of subcontractor selection to alleviate the uncertainty of rework while simultaneously improving safety performance: *Only select subcontractors that can demonstrate their ability to provide superior quality performance.* This rule aligns with the National Highways Agency (UK), which proposed a new 10-year Integrated Delivery Framework (IDF) program estimated to be worth £20-30 billion. It is anticipated that the IDF will require poorly performing suppliers (e.g., contractors and subcontractors who are unproductive due to rework) to be barred from bidding for work within its program (Weinfass 2023).

5.4. Fast-and-frugal trees

An FFT is a class of heuristics for binary decisions and classifications and is used to decide between two categories to where an object belongs or what course of action to take. Given m cues, an FFT is a decision tree with $m + 1$ exits, with each of the first m cues having one and the last having two (Wang, Luan, and Gigerenzer 2022). Each time a cue is used, a question is asked concerning its value. Each answer to a question instantaneously leads to an exit, or a further question and eventually to an exit. A fundamental property of an FFT is that, for each question, at least one of the two possible answers leads to an exit. Like the take-the-best heuristic, the FFT is a lexicographic model that aims to make a decision as soon as information is available. The FFT can be *prescriptive* or *descriptive* (Katsikopoulos et al. 2021). Due to the nature of the data that has been obtained, descriptive FFTs are developed in this paper.

Figures 2 to 5 denote descriptive three-cue FFTs based on rework situations identified by interviews (Table 2). These figures are retrospectively developed to demonstrate that FFTs can be used to construct a repertoire of problems that can be drawn upon to anticipate what might go wrong in a similar environment. Table 2 presents context-specific situations of

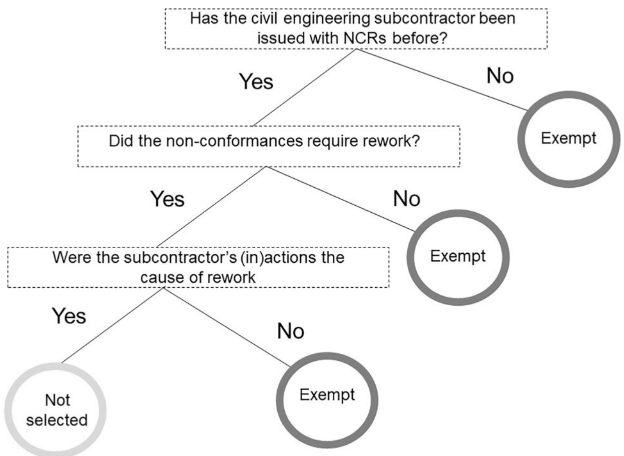


Figure 2. Fast-and-frugal trees: Reinforcement installation for piles.

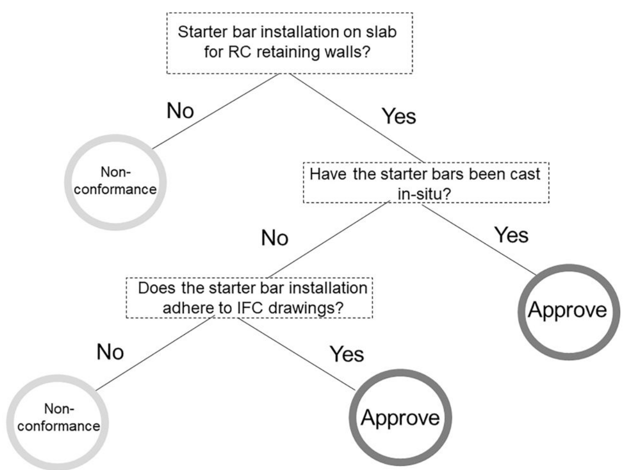


Figure 3. Fast-and-frugal tree: Starter bar installation.

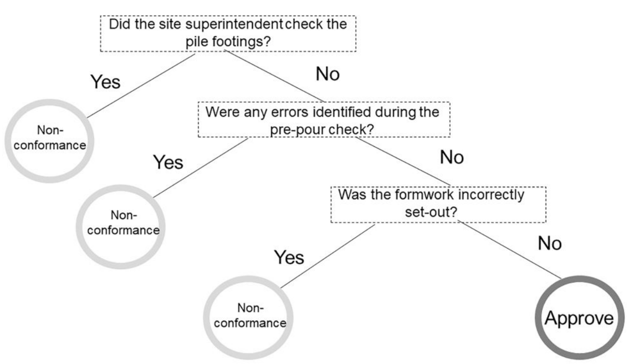


Figure 4. Fast-and-frugal tree: Pile footings.

rework where production pressure was profound, and decisions and actions were undertaken in response to the environment.

A detailed examination of the conditions that resulted in the architectural screens requiring rework, identified in Table 2, can be found in Love and Matthews (2022c). Figure 5 sketches a snapshot of cue ordering for this situation since it shows that if there were errors, they should have been rectified and approved by the structural engineer. Still, the RFI was sent to the architect, who approved it. The welding detail was incorrect; the screen failed and needed to be replaced.

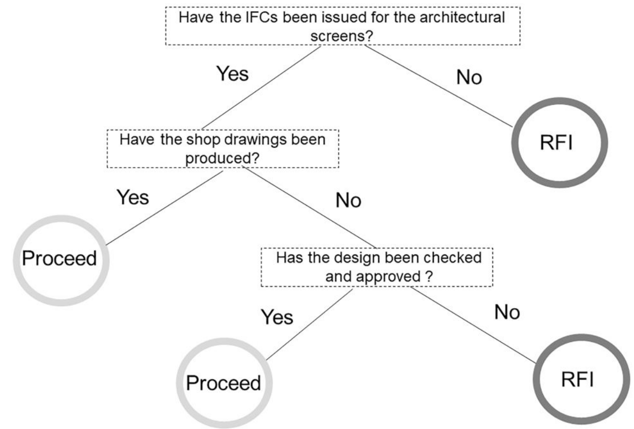


Figure 5. Fast-and-frugal tree: Architectural screens.

It should be acknowledged that the cues, their order, and decision cut-offs identified in Figures 2 to 5 may not fully reflect what actually transpired when decisions were made in the situations identified. However, it is proffered that the FFTs can be used to help understand how decisions in given situations can influence actions resulting in errors and rework.

6. Discussion

With limited available information about the environments and situations within which rework manifests, the ability to perform rigorous risk analysis and predict its probability of occurrence becomes a challenge. As a result, blind to the uncertainties ahead, construction organisations have been unable to implement formal strategies to accommodate rework during construction effectively. However, in the alliance examined in this paper, there was a heightened awareness of errors and rework as the unthinkable was made cognisable and visible by practitioners through dialogue, especially during toolbox talks. Moreover, sharing experiences with errors and rework created mindfulness to 'anticipate what might go wrong'. Armed with their intuition and experiences, practitioners possessed the agency to make decisions on the fly when confronted with difficult decisions needing to be made quickly.

Unconsciously simple fast-and-frugal heuristics have played a role in dealing with situations that mitigated rework, resulting in basic rules of thumb to follow going forward in the project. Indeed, the rules identified are straightforward and can be considered common sense, but when faced with production pressure, people are often prone to breaking rules, as, at the time, there is a perception that this will make their work more efficient. A case in point, identified in this paper, is commencing work without IFC drawings. Knowing that fast-and-frugal heuristics are drawn upon for decision-making and can be effective in situations of uncertainty, the exploratory research presented has several theoretical and practical implications.

6.1. Theoretical implications

A theoretical vacuum exists for making judgments to accommodate rework in construction. However, as suggested in this paper, the theory of ecological rationality can fill this space, as it can show how heuristics match the structure of their environment and get their way into the decision-making process (Gigerenzer et al. 1999; Hertwig et al. 2022; Luan, Reb, and Gigerenzer 2019; Simon 1990). The situations that have been shown to occur in various project environments of the alliance suggest that recognition-based (e.g., recognition and fluency) and one-reason decision-making (e.g., take-the-best and fast-and-frugal trees) heuristics played an important role in selecting actions that prevented the need for rework (Rich et al. 2021). Notably, the retrospective creation of descriptive fast-and-frugal trees from rework events illustrates their potential role for decision-making in varying situations.

While fast-and-frugal heuristics were relied upon for making choices, Ika, Love, and Pinto (2022, 3320) suggest they can also be used to help 'learn and draw from experience to navigate complexity and the uncertainty'. Consequently, fast-and-frugal heuristics can contribute to establishing a much-needed theoretical underpinning to explain *why* and *how* rework occurs and to garner an 'understanding of the circumstances in which projects fail or not' (Ika, Love, and Pinto 2022, 3322). All in all, the paper extends the theory of ecological rationality in the uncertainty-prone situations of rework within the VUCA setting of construction projects.

6.2. Practical implications

The absence of information about the causal nature of rework and its frequency of occurrence in construction means that organisations need help to get to grips with its considerable heterogeneity across their portfolio of projects. Without any doubt whatsoever, construction organisations are aware of the negative impact that rework can have on their productivity and performance but, without information, cannot deal with its uncertainty.

Organisations often treat rework as a zemblanity (i.e., an unpleasant yet unsurprising discovery), resulting in reactive strategies to manage its occurrence instead of a proactive nature focusing on its mitigation (Love, Matthews, Sing, et al. 2022a, 248). Nevertheless, the heuristics unearthed in the situations presented can act as a frame of reference for making decisions in similar situations and provide knowledge about the tensions and dynamics that arise to arrive at a satisfactory action. To this end, the research provides construction organisations and their people with an initial set of ecologically rational heuristics to help build an adaptive toolbox for assessing the uncertainty of rework, albeit informally.

6.3. Implications for future research

The presented research is exploratory, framed around an informal view of toolbox adaptation. Only four heuristics were identified from the various rework situations that interviewees provided. Unquestionably, other heuristics were used in rework situations but could not be determined. Therefore, future research needs to focus on identifying different heuristic types and uncovering new ones that may exist so that a robust adaptive toolbox can be constructed and drawn upon to assess the uncertainty of rework.

It suggested that an informal adaptive toolbox, while informative, will only be accepted as a legitimate strategy in practice if its scientific underpinning is subjected to further rigour to ensure its relevance for decision-making. The fast-and-frugal heuristics in an informal toolbox will likely be intractable due to the prevailing heterogeneity of rework situations. Thus, future research needs to ensure that a formalised adaptive toolbox is built so that an understanding of the conditions under which its heuristics are tractably produced by adaptation can be established to ensure their epistemic success in practice.

There also is a need to acknowledge that situations within which rework occurs do not occur in isolation and, more often than not, are the product of a set of events (Love, Edwards, and Smith 2016). The formalisation of the adaptive toolbox defined above as (S, A, D) can be extended into a quadruple by adding a set of events E that may occur in a project environment Γ (E, S, A, D) and by associating to each situation $s_i \in S = \{s_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots s_n\}$ a function $s_{i:}$ E $\rightarrow \{true, false$, which specifies for each situation events that are present or not (Rich et al. 2021). Additionally, attention will need to be given to identifying the selector heuristic used to determine the heuristic to apply to a given situation.

As the fast-and-frugal heuristics presented in Table 1 and identified in this research have been considered ecologically rational, it was assumed they would be for the context in which they were used. Whether this is the case for decision-making in situations of rework will need to be explored, especially if new heuristics are identified. Guidance in defining ecological rationality has been provided by Rich et al. (2021), where *er* specifies the fit between an adaptive toolbox T and project environment Γ (E, S, A, D) as the satisfactory action selections:

$$er = \frac{situations\ where\ where\ satisfactory\ action\ is\ selected}{total\ number\ of\ situations} = \frac{|\{s|s\ \in\ S\ and\ T\ (s)\ \in\ D\ (s)\}|}{|S|}$$

Several adaptive toolboxes may simultaneously exist and be drawn upon within a project environment and used for various decision-making and problem-solving purposes. However, a formalised adaptive toolbox for assessing rework uncertainty would be a unifier as the events and situations contributing to its manifestation also influence a project's cost, schedule, safety performance, and productivity.

7. Conclusion

Rework is a problem that pervades practice in construction. Its risks are unknown and thus cannot be predicted. Construction organisations are, therefore, left with having to deal with rework, albeit reactively, as they cannot effectively assess its uncertainty in given situations. As this problem is widespread amongst organisations within the construction industry, this paper has set out to address the following research question: *How can fast-and-frugal heuristics effectively assess the uncertainty of rework in* *construction?* An ecological rationality lens, which views human rationality as a result of an adaptive fit between the human mind and the environment within which decisions are made, is used as the theoretical framing to address this question.

The methodological framing of the research is a case study, and sensemaking is utilised to understand 'how' fast-and-frugal heuristics are intuitively applied when making decisions in practice. The case examined is an AU$18 billion transport infrastructure mega-project procured using a program alliance. Several fast-and-frugal heuristics (e.g., recognition, take-the-best, and fluency) were unearthed based on several situations and the decision-making that resulted in rework being averted. Then, to demonstrate 'how' descriptive fast-and frugal trees could be used for decision-making, actual rework situations that arose during construction were retrospectively constructed.

The evidence presented indicates that an adaptive toolbox of fast-and-frugal heuristics has a role play in combating the uncertainty surrounding rework. It also suggests that the theoretical lens of ecological rationality provides the basis for ensuring decision strategies epistemically and pragmatically adapt to the VUCA environment of construction. However, an informal view of toolbox adaptation was examined in this paper, which has limitations. Accordingly, it proffered that future research should focus on formalising an adaptive toolbox to ensure it is tractable, ensuring flexibility in decision-making. Developing a formalised adaptive toolbox will be challenging. Once constructed, it will help people answer the descriptive question of what heuristic to use for a particular situation to enable epistemic success under conditions of uncertainty and cognitive complexity.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes

1. The term heuristic has many meanings in the philosophy and cognitive science literature to guide inference and/or judgment in problem-solving and decision-making. A detailed review and classification of heuristics and their importance about theorising about cognition and decision-making can be found in Chow (2015).
2. The Technique for Human Error-rate Prediction (THERP) is a technique used in human reliability assessment to evaluate the probability of a human error occurring throughout the completion of a specific task.
3. The Systematic Human Error Reduction and Prediction Approach (SHERPA) is a qualitative method for analysing human reliability in a system. SHERPA can be used to analyze the potential for human error associated with the ability or behaviour of the operator.
4. Laplace's Demon refers to an imagined all-knowing and all-powerful being who has complete knowledge of every detail of the universe, including the positions and velocities of all particles, and who is able to use this knowledge to predict the future with absolute certainty.
5. Practical rationality is the capacity to make decisions and take appropriate actions based on reason, evidence, and consideration of one's goals and values. It is the ability to evaluate different options and choose the best course of actions based on the available information (Verbeek and Southwood 2009).
6. A cue is anything an individual encounters in the environment that leads to using a mental shortcut when making a judgment or decision.
7. Fast-and-frugal heuristics are based on three building blocks, as noted in this paper. Such heuristics are in stark contrast to Tversky and Kahneman (1974) 'availability heuristic' as it does not specify building blocks and consists of an ambiguous 'one-word' label (Wang, Luan, and Gigerenzer 2022).

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