There is Strength in Numbers: Seven Principles to Contain and Reduce Error and Mitigate Rework in Transport Mega-projects

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Abstract – Errors cannot be always be prevented as they are a normal part of any work routine. Performing rework due to an error can significantly increase construction costs in transport mega projects. Moreover, rework results in productivity loss, schedule delays, injuries and accidents, pollution, and contamination in projects and tarnish an organization's reputation. Drawing on our empirical research examining error culture and rework, we suggest that developing an error mastery mindset based on seven fundamental principles provides the much-needed ingredients to contain (i.e., enhance detection and recovery from errors as well as minimize adverse consequences) and reduce (i.e., limit is occurrence) error and build resilience in mega-transport projects.

Keywords – Error, error management, error mastery, mega-project, rework, transport

INTRODUCTION

With our cities experiencing increasing levels of traffic congestion, ageing public transport networks, and airport facilities unable to cope with growing passenger and freight demands, the response of governments worldwide has been to significantly invest in upgrading and constructing new transport infrastructure assets. Such investment is none more so than in

Australia, where the Commonwealth Government is committing $110 billion over ten years from 2021-22 in transport infrastructure through its rolling infrastructure pipeline, of which a substantial component is under the Infrastructure Investment Program[1]. Examples of nation-building projects in Australia include Sydney's WestConnex ($16 billion), Sydney Metro ($12 billion), Melbourne Metro Tunnel ($11 billion), Melbourne to Brisbane Inland Rail ($9.3 billion), Melbourne's West Gate Tunnel ($6.8 billion), and Brisbane's Cross River Rail ($5.4 billion), to name a few.

Projects of this sheer magnitude and complexity are prone to mis-performing during construction [1]. It has been shown that rework can increase construction costs by as much as 12% [2]. Moreover, when rework is performed, there is a greater likelihood for safety and environmental incidents to occur [3], [4]. Despite the wealth of research that has sought to quantify the costs of rework and its causes[2] and develop solutions to mitigate its adverse consequences [5]-[9], construction organizations still struggle to minimize its occurrence [10]. Hence the motivation for our article.

In Australia, for example, organizations involved in delivering transport mega-projects, such as the Level Crossing Removal Project (LXRP), are aware that rework materializes from change and errors[3] and accordingly *only* exercises control through their quality management systems. Control-oriented principles used by organizations as part of their quality initiatives include [11]: increasing control and reliability (e.g., supervision, Value Stream Mapping and

[1] Details can be found at: https://investment.infrastructure.gov.au/

[2] Research in construction has focused on the 'proximal' cause of rework rather than the conditions (i.e., latent conditions such as culture, management and supervisory shortcomings) that result in its occurrence in projects. The *counterfactual fallacy* has always been ignored: that is, if things had been different then rework would not be needed; *thus*, the absence of such differences caused the rework. So, like accidents, rework happens due to the ever-present competing demands between production (schedule/cost) and quality "that create latent factors that collectively produce defensive weaknesses that permit the chance conjunctions of local triggers and active failures to breach all the barriers and safeguards" [p.138]

[3] A dedicated Rework Symposium, November 4th, 2018, Melbourne, Australia was organized with major Tier 1 contractors, design engineers and the like was organized. Details available at: https://vimeo.com/301757104/a32e3fdab0.

Last Planner®); (2) exploiting existing skills and resources; (3) first-order learning[4] (cybernetic feedback); and (4) monitoring and assessing known client (also stakeholder) needs. However, a singular emphasis on the control of quality is not "suited to conditions of high task uncertainty" [12: p.573]. To this end, the engagement of control-orientated principles (i.e., 'learning from errors' by having in place error correction mechanisms) hinders the ability of construction organizations to engage in the process of 'learning through' (i.e., how to handle errors) an event requiring rework [4].

The institutionalization and legitimization of control orientated work norms, and practices of construction organizations align with an error prevention (also known as aversion) culture, where a mindset that errors can and need to be averted exists [13]. Indeed, an organization's work culture sets the tone and influences its response to errors and how information is shared. Yet, errors are an inherent and recurring aspect of work and our daily lives. We cannot learn without committing an error, and "innovations are not possible without making errors" [13: p.663]. Every organization is confronted with errors, and thus it holds that they cannot be prevented. So, error-making has a critical role to play in the development and successful performance of construction organizations and their projects.

Paradoxically, however, in the United Kingdom, the 'Getting it Right Initiative'(GIRI)[5] is striving to "eliminate error" and a "create an error-free culture" throughout its construction industry. While the GIRI's goals of elimination and error-free are at odds with the contemporary view of managing errors in the workplace [13], [15]-[20], it is heartening to see

[4] Learning within the context of a given problem definition and the analysis of the chosen solution for that problem, while retaining the underlying theoretical insights or deep convictions and values. The feedback loop is represented by using "standards of performance, measuring system performance, comparing that performance with standards, feeding back information about unwanted variances in the system, and modifying the system" [14: p.289].

[5] Details of the Getting it Right Initiative can be found at: https://getitright.uk.com/

that error is being recognized as an issue to be addressed in the practice of construction as it has received limited attention [3].

Transport mega-projects in Australia are typically delivered through Private Participation in Infrastructure (PPI) approaches such as Public-Private Partnerships (PPP) (e.g., Cross River Rail) or Alliancing (e.g., LXRP). Projects of this ilk are constructed over several years and aim to be collaborative. In the case of Alliancing, which is akin to the Integrated Project Delivery (IPD) strategy, collaboration is augmented as a no-blame environment is fostered. However, an error prevention culture tends to manifest and is often normalized in PPI projects and even to some extent in alliances.

Drawing on our empirical research examining error culture and rework [19], [20], we suggest that developing an error mastery mindset based on seven fundamental principles provides the much-needed ingredients to contain (i.e., enhance detection and recovery from errors as well as minimize adverse consequences) and reduce (i.e., limit is occurrence) rework and build error resilience in mega-transport projects. We commence this article by briefly examining the concept of error culture. Then we introduce and describe an error mastery mindset, which comprises seven principles that can engender and enact learning, encourage innovation, and improve the performance and productivity of organizations and teams participating in the construction of transport mega-projects.

ERROR CULTURE

Error definitions abound in the literature [13], [16]. Errors arise due to actions (e.g., slips and lapses), judgment and decision-making (e.g., cognitive biases or heuristics) or violations [21], [22]. In this article, we are only concerned with action errors, which are defined “as unintended

deviations from plans, goals, or adequate feedback processing as well as an incorrect action that result from lack of knowledge" [23: p.1229].

Errors are an effect or symptom of an organization and the project environment within which people work [23]-[25]. They are not random acts but are systematically connected to aspects of people's tools, tasks, and work environment [23]. The strategic decisions are taken by managers often provide the latent conditions for errors to materialize at the coalface of construction. While people make mistakes, organizations make it possible for them to be serious. Accordingly, Reason [22] aptly proffers, "we cannot change (the) human condition, but we can change the conditions under which people work" (p.768). It follows, therefore, that we can alter an organization's culture, which is shaped by both its "shared norms and practices", then we can change its approach to error-handling and rework [23: p.1229].

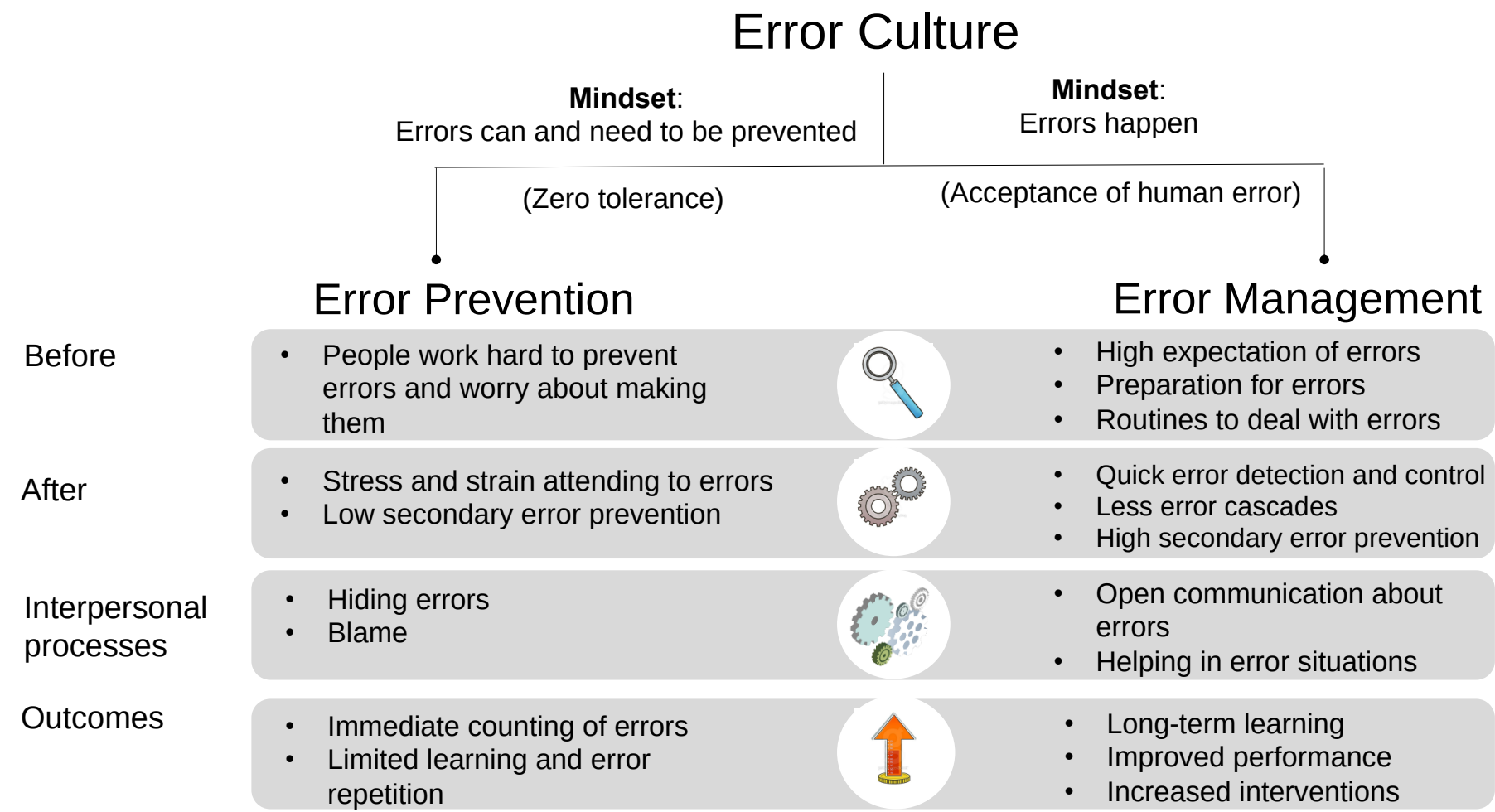
We define culture as "a pattern of shared basic assumptions learned by [an organisation] as it solved its problems of external adaptation and internal integration, which has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems" [26: p.18]. As we previously identified, two types of error culture exist [13], [23]: (1) error aversion; and (2) error management. Figure 1 compares these two approaches, and each will now be briefly discussed.

Error Prevention

By way of "design (of tools, systems, organizations) and through training (of individuals, and teams), error prevention" is operationalized "by blocking erroneous actions (meaning goal-directed behaviors, but also communication acts) [13: p.665]. An error prevention culture assumes errors are highly negative, with zero tolerance for their occurrence (Figure 1).

The upshot is that errors are associated with poor performance and negligence, and people are blamed for their existence [13]. Indeed, it is natural for construction organizations to prevent the errors that result in rework due to the ensuing adverse consequences. But when people live in fear of being reprimanded for error-making, they will habitually cover up and hide them. A case in point is the reluctance to report non-conformances during construction as management deemed them a product of a poorly managed project [27]. Under-reporting errors are common when incentives (e.g., financial bonuses) for exemplary performance exist and punishment happens for poor results [28].

Traditionally, non-conformances have been the *de facto* source of data to quantify rework, representing only a fraction of the total in projects [4]-[6]. Often rework is camouflaged as changes, back-charged to subcontractors or is simply not documented with its costs being part of routine work practices [27]. As such, construction organizations have to work with the data, they have, not what is missing. It is the missing data, which hinders the ability of organizations to garner an awareness and insights about the real impact of rework on the productivity and performance of projects. Putting aside this issue, projects with low non-conformance levels are typically considered exemplars of quality performance. However, relying solely on non-conformances to determine quality performance is misleading as it provides organizations with "ghost data artefacts" that cannot be used for effective risk management of rework [9], [29: p.2].



Adapted from Frese and Keith [13]

Figure 1. Error culture, processes and outcomes

We often see construction organizations shaping their ideological settings for quality by implementing a ‘zero-vision’ strategy (i.e., defects). In this instance, those working on-site are asked to follow a cliche predicated on “bureaucratic entrepreneurialism” [30: p.31]. In this instance, construction organisations can claim that significant accomplishments in their work have been attained. Still, more is required, as zero is not achieved, despite knowing subconsciously that it never will. To reiterate, the elimination of error is an unviable proposition. Under the circumstances, error prevention cannot deal with the ubiquity of errors that pervade practice in construction and therefore, an acceptance that errors happen needs to prevail.

Error Management

Error management was initially developed as an add-on approach to address the limitations of error prevention [31]. Error management commences after an error has occurred and aims to block or reduce its negative consequences through design or training. In sum, “error management involves coping with errors to avoid negative error consequences, controlling damage quickly (including reducing the chances of error cascades), and reducing the occurrence of similar errors in the future (secondary error prevention) as well as optimizing the positive consequences of errors, such as long-term learning, performance, and innovations” [31: p.665].

An error management culture comprises organizational practices related to communicating about errors, sharing error knowledge, helping in error situations, analyzing errors, quickly detecting and handling errors and coordinating error handling [23]. A high error management culture translates into improvements in containing (i.e., enhance detection and recovery from

errors as well as minimize adverse consequences) and reducing (i.e., limit is occurrence) rework in mega-transport projects [19], [20].

Communication about errors is the most important error management practice as it enables knowledge to be shared. For example, within an alliance and its project teams we have examined, people were encouraged to freely discuss errors and rework to learn and identify potential future risks [19], [20], [32]. For example, every day at pre-start meetings and 2.00 pm supervisor coordination meetings, likely areas prone to rework were discussed and risks identified. Additionally, sharing knowledge of different error and rework situations enables secondary error prevention. Such open communication stimulated learning from errors – "without communication, [people] are only able to benefit from their own errors" [23: p.1230]. The communication of errors also enables others to help resolve a problem quickly and effectively in similar situations. Indeed, the swiftness between the occurrence and detection of an error determines the effectiveness of error management. The longer an error remains undetected, the more severe its consequences are likely to be.

Construction is dynamic and subject to constant change as planned work progresses. Errors that result in rework constitute unplanned work interfering with workflow, which can cause delays, increased costs and posse safety hazards. It is thus critical to identify errors. Sometimes errors can go undetected, lying dormant for years, and then manifest as a failure resulting in disastrous consequences. Many structural engineering failures due to design errors have occurred over the last two hundred years. Examples include the Minneapolis Interstate 35W bridge collapse in 2007, killing 13 people and injuring 145, the Florida International University pedestrian bridge collapse in 2018, killing six people and injuring ten.

While underlying premises of error prevention and error management are antithetical, they can be used in concert to address rework in construction. Thus, an error prevention mindset can focus on *before* and error management *after* an error occurs [33]. As we suggest have indicated already, it is the inability of construction organizations to *understand*, *embrace* and *adapt* when an error has occurred which has stymied progress toward rework mitigation. While error prevention is maladaptive, the high-reliability organization literature suggests that its combination with error management can create a more adaptive culture as people need to balance both perspectives when performing activities [13], [33].

ERROR MASTERY MINDSET

Our proposed error mastery mindset for mitigating rework "entails a positive approach, optimally balancing the needs and possibilities for both error prevention and management (e.g., correction and learning) of errors" [34: p.429] and building resilience (i.e., transforming lessons from the past into future success). Figure 2 proposes seven principles, likely benefits, and process outcomes of enacting an error mastery mindset in a transport mega-project. Such principles, benefits and outcomes have emerged from observing best practices in alliancing projects which we have studied [18]-[20]. The principles we derive from our observations of alliances, identified in Figure 2 and described in Table 1, interact, operating in unison to enable the benefits of embracing an error mastery mindset to be realized.

Benefits

Naturally, within a project adopting an error mastery mindset, errors will be contained and reduced, enabling clear quality and safety improvements to materialize as they have a symbiotic relationship. Other immediate benefits will be project cost and time savings, improved risk and uncertainty management, and a realization of environmental benefits and

value (Figure 2). Such benefits will materialize as a project makes progress during its design and construction, and error management organizational practices are instigated. Moreover, besides improving project performance, the outcomes of taking a positive view of errors will be learning, innovation and resilience [23].

Relational Project Delivery

For all intents and purposes, alliancing is a relationship-based delivery strategy that is characterized by a culture of collaboration and cooperation between the parties working together to deliver a project. Indeed, it is the collaboration and cooperative qualities of an alliance that engender dialogue to take place, which triggers trust to be established between parties.

The participants of an alliance are usually the purchaser of services (the owner), the service provider(s), and non-owner participants such as head contractor(s) and operator(s). As previously mentioned, in an alliance, contract risks are shared with incentives offered by the owner for how well the project is delivered as measured against agreed objectives. Three basic principles underpin the mechanics of alliancing: (1) a project is delivered by a single integrated team; (2) a joint governance framework is established; and (3) decisions are made on a 'best-for-project' basis within a no-blame environment. Alliances are traditionally used to deliver complex projects, which require flexibility (e.g., scope) and innovation. Besides the LXRP, other large-scale transports procured using an alliance in Australia include the AU$5.3 billion Metronet (Perth, Western Australia) and the $196 million Ovingham Level Crossing Removal Project (Adelaide, South Australia).

Management Commitment to Learn Through Errors

An error management culture can begin to evolve in transport mega-projects where the values associated with alliancing (also IPD) such as collaboration, sharing of risk, no-blame, best-for-project and 'gain-share/pain-share' regimes reside. Still, management must be committed to ensuring its practices are assiduously executed and providing workplace support to enable people to 'learn through errors'. Our previous research suggests that error management organizational practices such as communicating and sharing errors unconsciously occur in alliances as a result of their no-blame focus, but an explicit effort is required to analyze errors, help in error situations, quickly detect and handle them as they are atypical routines in construction projects [18]-[20].

Alliances provide a mechanism to foster partnerships in projects genuinely. However, they are only appropriate for procuring transport assets funded by taxes (i.e., the government pays) rather than user charges (e.g., light transit rail, LRT). We have seen many PPPs being used to deliver user-charge assets such as the Canberra and Gold Coast LRT systems. In such projects, the public sector disproportionately offloads risks onto the private sector even though the term partnership has become almost meaningless [35]. Affirming this view, the Productivity Commission [36], referring to a submission to its inquiry by the University of New South Wales, states, "PPPs are partnerships in name only and that a risk-transfer culture often results in the inappropriate transfer of risk. This results in higher costs and increased likelihood of project failure as risks are passed down the contract chain to subcontractors that cannot manage them" (p.133).

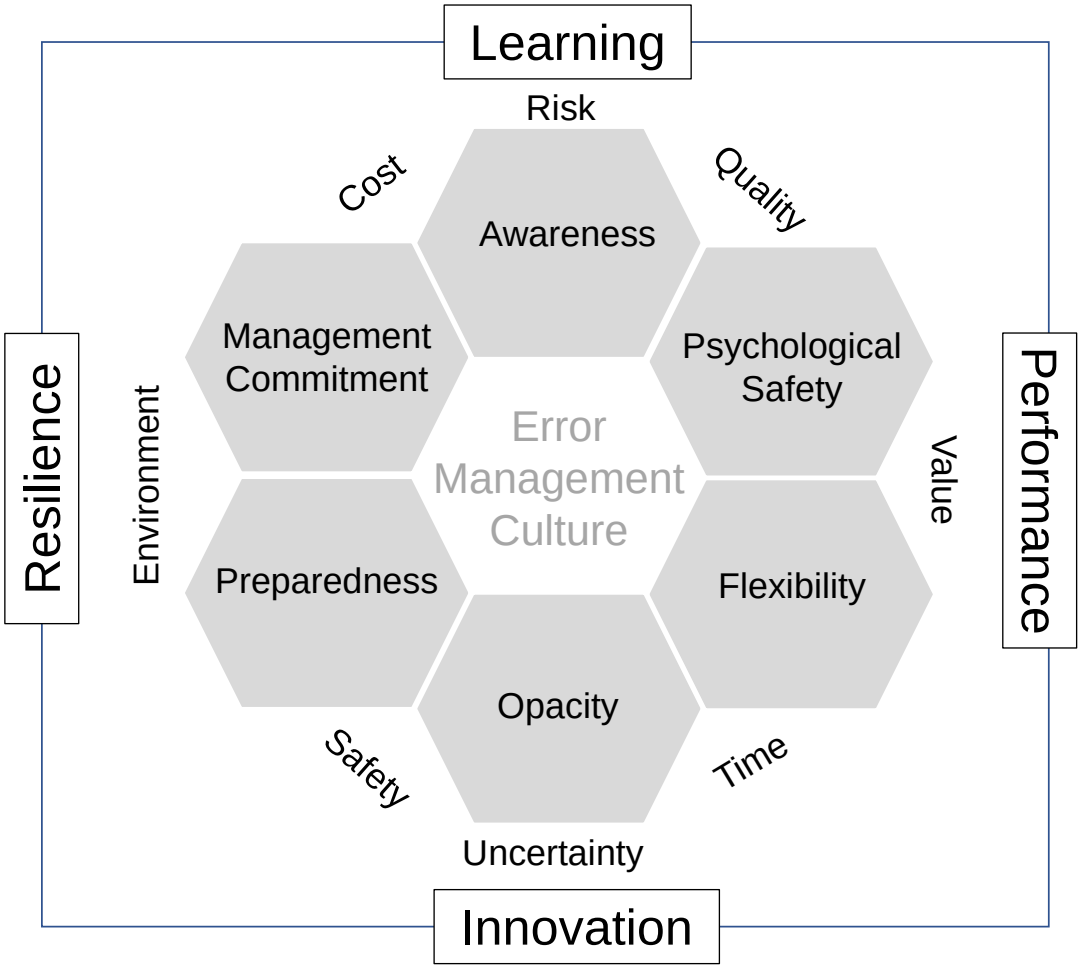


Figure 2. Principles, benefits and outcomes of an error mastery mindset

With such a risk-transfer culture in place, construction organizations tend to become control and prevention-focused to assure quality in their projects [10]. However, this is not to say error management cannot be adopted in a PPP project; quite the contrary. Alliance principles can be incorporated into PPPs, enabling flexible structure structures for the management of change, collaboration and long-term learning to flourish [35], [37], [38].

Cultivating an Error Management Culture

Cultivating an error management culture and implementing its organizational practices form the heart of our proposed error mastery mindset, which we believe can contain and reduce errors that result in rework in projects (Figure 2). What is more, an error mastery mindset will also significantly contribute to engendering innovation, improving learning, and the performance of projects [35].

Constructions organizations operating under the auspices of a relational project delivery method such as an alliance (or IPD) must consciously enact the *all*-error management organizational practices to establish the shared norms and values to reduce the negative and promote the positive consequences of error. Table 1 identifies seven principles to nurture an error mastery mindset. The principle of error management forms the core of an error mastery mindset providing the bedrock to address rework (Figure 2).

Table 1. Seven error mastery principles

Error Mastery Principles	Explanation	Strategy
Management Commitment	Management demonstrate commitment towards people's well-being and performance	Management regularly visits and walk-around project site(s) and establish a working committee to look at risks of error/rework and anticipate unexpected events.
Error Management Culture	A belief that errors are inevitable, potentially damaging, and can be turned into something positive. Involves coping with errors to avoid their negative consequences. Violations (e.g., culpable acts) are not tolerated and are dealt with separately (e.g., violation management)	Establish a clear mission/vision regarding errors. Implementation of organizational practices such as communicating about errors, sharing error knowledge, helping in error situations, and quickly detecting and handling errors.
Psychological Safety	Supports team members to report and speak up about issues without feeling embarrassed, their voice rejected, and they will be punished.	Support and encourage people to speak up during meetings and lessons learned workshops. Establish communities of practice to identify problems and propose solutions/innovations
Awareness	Data gathering and providing management with insights about the performance of people and project(s) to determine the extent of problems (e.g., rework) and the current state of defences	Routinely monitoring people's well-being. Also, issues such as rework and its consequences (e.g., associated wastes, costs, delays, environmental and safety, incidents)
Preparedness	Actively anticipate the impact the workplace demands and constraints can have on people's performance and prepares for them to *understand*, *embrace* and *adapt*	Foresight (i.e., predicting risks), coping (i.e., preventing risks) and recovering (i.e., recover from an issue if it happens) strategies are identified and integrated, and work practices amended accordingly
Flexibility	Adapt to new or complex problems in ways that maximize their ability to solve problems without disrupting work	Allowing specialist subcontractors to have' skin in the game' through early contractor involvement. Their involvement can help improve constructability, quality, safety, productivity and reduce costs.
Opacity	Awareness of the financial, workload, production, quality, safety and environmental pressures and where effort needs to be invested in ensuring defences are not degraded	Monitoring workplace pressures (e.g., programme) so that strategies can be developed to ensure standards and project deliverables are met

Adapted from Jeffcott *et al*. [39: p.258]

Facilitating Psychological Safety

With transport mega-projects being subjected to production pressure, management must commit to supporting people's well-being (i.e., physical and psychological) and performance. People's ability to cope and recover from errors depends on their personality traits [40]. As noted in Table 1 and Figure 2, we suggest it is necessary to provide a psychologically safe workplace where people feel comfortable speaking up about errors without feeling embarrassed, judged and blamed when they happen [41]. With an error management culture and psychological safety in place, construction organizations will be able "to prepare themselves to notice the unexpected and its development" [39: p.257]. Being mindful is an essential feature of resilience, where an organization anticipates failure, learns to adapt to circumstances where failure is indicated, and restore conditions after an event [39].

Enacting Resilience

The resilience principles of *awareness*, *preparedness*, *flexibility* and *opacity* complement [39] and reinforce error management organizational practices [23]. Developing awareness and insights about error and rework is needed to leverage the benefits of a construction organization's continuous improvement strategy. Thus, there is a need to establish a measurement system to capture the data required for decision-making about errors and rework [9]. By routinely monitoring errors and people's well-being, the functioning and effectiveness of organizational practices deployed during the construction process can be checked and amended accordingly to safeguard opacity within the project (Table 1).

While measurement supports the principle of awareness, improvement is enacted through preparedness. Here an emphasis is placed on building an "ability to anticipate and gauge potential future difficulties" and assist with the development of structured plans to optimize

workflows in construction [4], [39: p.258]. The accumulation of error and rework data enables a process of analysis to unfold, allowing the risks to be modeled and their prediction to help decision-makers examine a range of scenarios and "how to make trade-offs in the face of performance pressures" [39: p.259].

Adapting and responding to trade-offs without disrupting work requires managers to be flexible and open to embracing new ways of doing things. For example, early contractor involvement of specialist subcontractors in the design process would help improve constructability, stimulate innovation, and reduce costs. Seldom do construction organizations invite specialist subcontractors to be involved in the design process and provide them with financial incentives. However, in the case of the $705 million New Perth-Bunbury Highway, a specialist material supplier became a member of the alliance to provide cost certainty and ensure the supply of rock for the project's road base [10].

CONCLUSIONS

The seven key principles we lay out in this paper provide a set of defined practices that can be applied to contain and reduce error and mitigate rework in transport mega-projects procured within a collaborative delivery framework. We suggest that organizations involved with the delivery of transport mega-projects will need to shift their traditional mindset where errors can and need to be prevented to one where error happens. In doing so, organizations focus on coping with errors to optimize learning about successful behaviors and practices and simultaneously build resilience. Our intention has not been to provide a panacea for mitigating rework but to provide practitioners with a roadmap that can be drawn upon to make some headway in addressing a problem that pervades practice.

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