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Title: **Managing designing for safety: A framework to support whole-team decision-making and risk control**

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Managing designing for safety: A framework to support whole-team decision-making and risk control

Abstract

Designing for Safety (DfS) aims to make designs inherently safer to build, operate and maintain, but any residual risk must be controlled, something essential to realising the benefits of inherently safer designs. Here, a conceptual decision-making framework to support DfS, developed in conjunction with industry, is introduced. It aims to assist designers in communicating risk, residual risk and actions needed to support DfS, in a way easily understood by non-specialists such as clients and business leaders. The framework proposes a qualitative categorisation for DfS linked to a clear numerical scale, which embraces the complexity of engineering assessment across the full asset lifecycle, while using a form of language (numbers) that can be readily understood by all. The framework was empirically explored through an operational design workshop with four engineers. It was found to bring a range of benefits for DfS at the design stage: it provided structure for the discussion of DfS, made the consideration of DfS objective, gave a new vernacular which improved the collective thought process, and made the debate and the resultant design decisions more accessible to non-specialists. The framework provides a tool to assist the implementation of DfS in practice.

Keywords: Designing for safety, risk management, risk control, safety

Introduction

Designing for Safety (DfS) is now a familiar concept within the global construction and civil engineering industries (Behm 2005; Gambatese et al 2005; Lingard et al 2014a; Goh and Chua 2016; Hardison and Hallowell 2019). It is an accepted understanding that the design of projects has significant implications for the safety of workers during construction, operation and all other asset lifecycle stages. It has been recognised across the design and construction supply chain to the extent that it can be found embedded in legislation across the world.

However, realisation of the benefits of DfS requires not only improved design, but also that any residual health and/or safety risk inherent in the design is communicated and controlled. While legislation, such as the UK's Construction (Design and Management) Regulations 2015 (UK Government 2015) and the Australian Work Health and Safety Regulations 2011 (Australian Government 2011a) are clear on the need for residual risk management, the academic literature arguably gives it less attention with only a few notable exceptions (see Iain et al 2008 for example). Communication of DfS can also be challenging if the requirements to assure safety cannot be readily and concisely shared with those making the business and commercial decisions for projects. Such decision-makers are often in client or business management roles and so often not also technical or design specialists. Even if they are familiar with the business-as-usual use of an asset, they may lack understanding of construction methods and the influence of DfS. When decisions are made to release a design for manufacture or construction, cost, schedule and procurement options are familiar and understood, but safety and DfS can struggle for inclusion at these critical decision-making points, due to a lack of comparable visibility and simplicity in their communication. The insights of designers and their professional judgement must not be lost in the decision-making process if decisions are to be both collective and fully informed. Communication of DfS must therefore be understandable and unambiguous for all.

Here, a new decision-making framework is introduced which aims to help improve communication of DfS. It is intended to be used as a tool to enable project managers, business managers and clients to effectively and efficiently make DfS decisions. It can also support designers to reflect on their designs as they are produced, enabling them to consider how the assets they are designing would manifest residual risk at each stage of their lifecycle. The framework was co-produced with industry as a practical aid to reinforce and support the practice of DfS and thus construction and engineering safety overall.

This paper adopts the following structure: the context of DfS is discussed before the framework is introduced and its components explained. The framework is then explored through an empirical case study in which it was applied to a real-life project scenario in a workshop environment held with members of the project's design team. Analysis of their interactions and use of the framework have been captured and reported, and are followed by reflection, limitations and proposals for future work.

Context

DfS is not a new concept within the construction and civil engineering industries. Although there has been variation in the terminology used, for example 'Design for Safety' (Behm 2005; Gambatese et al 2008), 'Safe By Design' (Hale et al 2007), and 'Designing for Safer Construction' and 'Prevention through Design' (Lingard and Wakefield 2013), the underlying premise remains the same: that design plays a key role in the resultant safety of a project throughout its lifecycle, and that the best way to prevent and control safety risks is to eliminate or mitigate them by design (Manuele 2008). Here, the term 'Design for Safety' (DfS) is used to reference the concept as applied to the full asset lifecycle, rather than specifically during a single phase, such as the site-based construction phase.

The extent of the influence of DfS as an ideology has long been the subject of debate, and Hardison and Hallowell (2019) have argued that there is actually a lack of objective evidence of its effectiveness in practice, specifically in terms of consequences for the construction phase. They suggest that research has focused on subjective rather than objective data, seeking opinions rather than testing hypotheses, and therefore DfS remains a '… theory based on prevailing opinion rather than fact' (Hardison and Hallowell 2019:521). However, within this body of subjective data, a range of between 20-60% of accidents are considered by experts to have at least one significant causal factor attributed to poor design (Hale et al 2007). Design in this space is not limited to the design of permanent works, but also includes the design of temporary works, construction materials and construction equipment (Health and Safety Executive 2003). It therefore remains a largely accepted premise that the design of projects does have some influence on the safety of the activities that follow, both in the construction and operation of the asset (Lingard and Wakefield 2013).

Notwithstanding these reservations, DfS has gained such traction in recent years that it has become enshrined in law in several countries. For example, in the UK, DfS has been recognised within construction-specific legislation in the form of the Construction (Design and Management) Regulations 2015 (UK Government 2015). These Regulations place legal duties on designers to consider the safety of their design for those constructing, operating and ultimately decommissioning the built environment asset, stating that they ‘must take into account the general principles of prevention and any pre-construction information to eliminate, so far as is reasonably practicable, foreseeable risks to the health or safety of any person’ (Clause 9.2). Singapore has also recently addressed this issue in their legislation, through the Design for Safety Regulations 2015 (Goh and Chua 2016), whilst Australia makes reference to DfS within a number of OSH Acts within the various states and territories (Lingard and Wakefield 2013), including the Work Health and Safety Act 2011 (Australian Government 2011b). In all cases, the legislation also seeks to ensure that any residual risk in the design is also communicated to those tasked with its implementation.

Design for Safety in Design Practice

Previous research has examined the ways in which designers are able to adopt and enact DfS principles in their work. For example, analysis of the processes of hazard identification by designers revealed that during the design process they are usually able to identify only around half of the safety hazards that would result on site (Hallowell et al 2016). The idea that systematic design management can lead to solutions that mitigate safety risks during construction has also been explored (Lingard and Wakefield 2013), as have designers’ attitudes and practices towards DfS, which found knowledge and practice to be limited in this area (Goh and Chua 2016). The increasing use of BIM and other technologies within DfS is also a growing area of research (Che Ibrahim et al 2022), yet such work remains largely in the potential and theoretical space. This body of work overall suggests that there are still improvements to be made in the *practical* inclusion of DfS within contemporary design practice. Given the professional training and skills held by designers in order for them to undertake design work, it can be expected, based on these findings, that knowledge and awareness of DfS will be even more limited among non-designers and those without practical construction experience, such as business leaders and clients.

Although ‘there is no consensus … on how [DfS] can be optimally implemented…’ there is agreement that some form of DfS should remain part of a project’s ‘… constructability review process’ (Hardison and Hallowell 2019:521). Consequently, in order to support designers in enacting DfS principles, various tools have been developed for practical use. An early example of this was Gambatese et al’s (1997) Design for Safety Toolbox, which contains design suggestions for different building elements to enhance their safety. This has since been supplemented by an additional tool developed by Dewlaney and Hallowell (2012) which focused on sustainable construction elements.

Another notable example is the Construction Hazard Assessment Implication Review (CHAIR) process developed in Australia by WorkCover (2001) which sets out a process to bring together key stakeholders including designers, constructors and clients at three key stages of the design process (conceptual design, construction and demolition phases, and maintenance). The aim is to support them in a review of information in a way that eliminates or reduces potential issues around DfS throughout the project’s life cycle, using ‘Guidewords’ to support the discussion. However, as Larsen and Whyte (2013) note ‘understanding the safety issues embedded within a design…is vital’, and so, although this process engages stakeholders, including business leaders, within the discussions, the process itself still requires a professional appreciation of complexity and consequences implicit within the design. Even a relatively simple construction project will likely require due evaluation of geotechnics, loads, forces, material compositions, construction technology, longevity and maintenance requirements among many others. The risk then emerges that a change to one element of the design to enhance safety during a particular project phase creates unintended consequences elsewhere, should decisions be made by those without such holistic design knowledge.

Such potential issues are also noted by Hardison and Hallowell (2019:522) who purport that there are three key challenges in relying on a safety perspective to drive DfS: '(1) safety experts may fail to recognise high risk areas in designs due to unfamiliarity of the design itself; (2) a design solution in one environment may not be an optimal solution in another; (3) a design change that may be optimal in one context may shuffle risks to other locations, phases, exposures, and tasks thereby inadvertently increasing lifecycle risk through sub-optimisation.' Indeed, Hardison and Hallowell (2019:523) highlight that such 'risk shuffling' as a consequence of DfS remains an unexplored aspect within the body of contemporary DfS research.

Introducing the Framework

The framework was first conceived in 2016 and was subsequently developed through a number of iterations, in co-production with over 200 practitioners through various forums, whose contributions are acknowledged at the end of this case study. As such, a methodological approach of reflective equilibrium (Daniels 2016) was adopted. Reflective equilibrium is a method more familiar to philosophers than engineers, which enables those engaged to discuss and develop their ideas over a period of time and ultimately produces an agreed and acceptable coherence around a phenomenon. As such the framework was industry-led, rather than academic-led, and to a large extent its development can only be retrospectively determined from diary notes and meeting minutes, although its fundamental premises are grounded in UK Legislation.

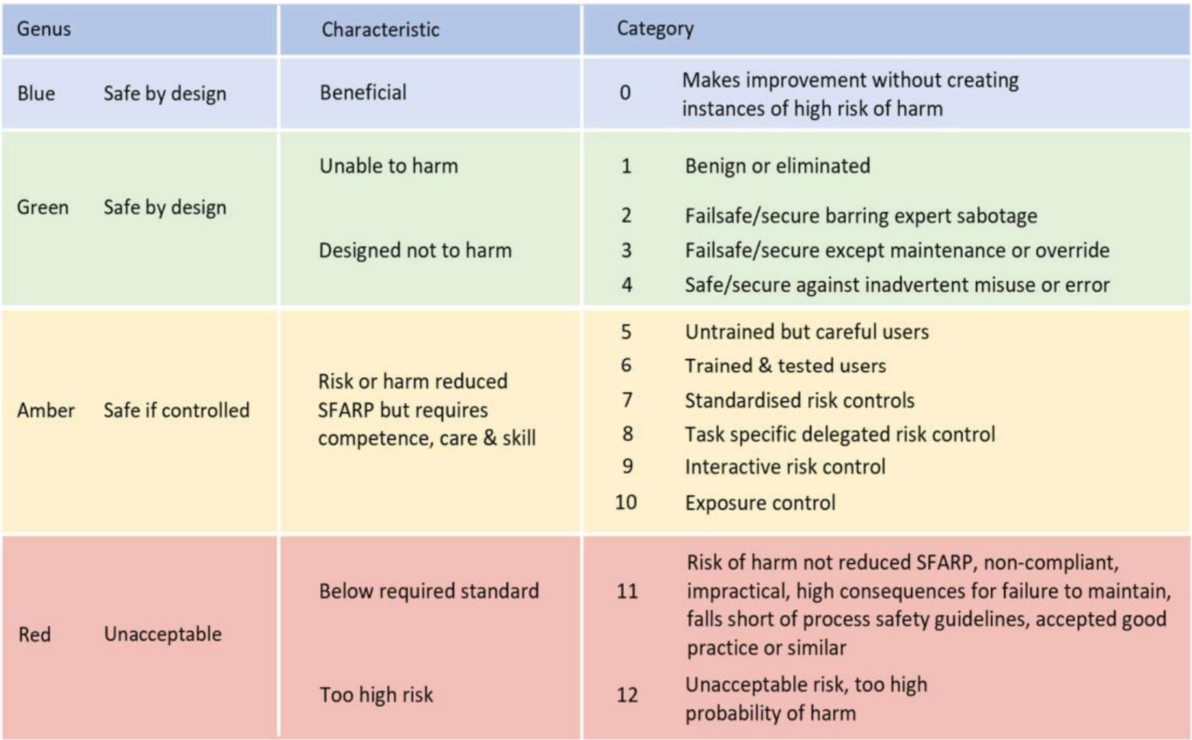
Structure of the Framework

The framework combines three operational aspects: The DfS categories, the guiding principles, and the life-cycle phases.

Design for Safety Categories

The DfS categories (see Figure 1) are defined in terms of the residual risk of the design, calibrated by the subsequent management required to control the risk. Figure 1 shows that inherently unacceptable or unsafe designs are identified clearly as such (categories 11 and 12), but a graded approach is taken to what is, or can be, 'safe', i.e. what can be reliably executed without causing harm, or, at any rate, unacceptable or lasting harm (categories 0 – 10). Therefore, to make a design acceptable it must be first 'not unacceptable' (i.e. not within categories 11 or 12); it must then meet any further requirements for safety, which is a relativistic point: for instance, categories 9 and 10 are not acceptable to all clients, and anything for use in the public realm is unlikely to be acceptable above category 5; safety critical features in high hazard assets will need category 0-4.

Figure 1 : 0 to 12 Scale of categories for Design for Safety (DfS)



Genus		Characteristic	Category	
Blue	Safe by design	Beneficial	0	Makes improvement without creating instances of high risk of harm
Green	Safe by design	Unable to harm	1	Benign or eliminated
		Designed not to harm	2	Failsafe/secure barring expert sabotage
			3	Failsafe/secure except maintenance or override
			4	Safe/secure against inadvertent misuse or error
Amber	Safe if controlled	Risk or harm reduced SFARP but requires competence, care & skill	5	Untrained but careful users
			6	Trained & tested users
			7	Standardised risk controls
			8	Task specific delegated risk control
			9	Interactive risk control
			10	Exposure control
Red	Unacceptable	Below required standard	11	Risk of harm not reduced SFARP, non-compliant, impractical, high consequences for failure to maintain, falls short of process safety guidelines, accepted good practice or similar
		Too high risk	12	Unacceptable risk, too high probability of harm

The category definitions in Figure 1 draw attention to the operational management actions needed to make the activity, or use of the asset, safe. These are explained in Table 1.

Table 1: Design for Safety Category Explanations

Category		Explanation
0	Makes improvement without creating instances of high risk of harm	A system or work routine is designed to be ergonomic so as to actively improve human health; materials are used which lead to a positive change in bio-diversity

1	Benign or eliminated	A ‘benign’ design for safety example would be vehicle detection systems using induction loops buried in the road, a solution that presents no physical risk to road users, there is nothing can be hit, tripped over etc. However, it should be noted that it is seldom possible to solve an engineering problem without creating some kind of risk at some stage in the solution’s lifecycle. When a solution is deemed ‘benign’ or ‘eliminated’ this is usually in reference to only a part of the lifecycle and a full lifecycle analysis would be needed. In the example given , the installation and maintenance of induction loops in the road would not itself be without risk to the workers. A ‘benign’ example in sustainability engineering would be one which maintains healthy biodiversity.
2	Failsafe/secure barring expert sabotage	Should failure occur, the asset will fail in a safe or benign condition or position generating no further harm, but sabotage may cause this design feature to be ineffective. Rail signally systems, which use interlocking, are examples of a correct application of this level of design safety.
3	Failsafe/secure except maintenance or override	Should failure occur, the asset will fail in a safe position generating no further harm, but maintenance staff are able to override the safety systems. An example of override actually causing a failure was the Smiler Ride incident at a UK Theme Park where human error caused a crash leading to serious injury (ROSPA 2016).
4	Safe/secure against inadvertent misuse or error	An example are the high voltage (400V) plugs and sockets used in industry: different sizes and pin arrangements are used for different ampere ratings (69mm for 63amp, 57mm for 32amp, 49mm for 16amp). Devices (which have the correct plugs fitted) cannot be inadvertently connected to the wrong power sources. An example of error actually leading to a failure was the Camelford water treatment works incident in 1988, where the same key fitted all the tanks and a mistake by a tanker driver meant poison was added to the water supply.
5	Untrained but careful users	Potential for the harm of users is reduced SFARP, but does rely on those using the asset to adopt normal behaviours that one experiences in public (not reckless). A flight of stairs would fall into this category. In a place where normal behaviours cannot be expected, for instance in a home for people with movement difficulties, the design may need to be different
6	Trained & tested users	Those using the asset are trained and tested to prescribed levels of competence, which might be in their specialist areas of work, or if they are a driver using the roads, the road design presumes that users have passed a driving test.

7	Standardised risk controls	Those doing the work need a level of assessed competence to ensure they know what risk controls are needed, and appropriate work methods and time must be allowed so that they can implement them. The majority of ‘risk assessed’ activity (for instance routine construction work, working in a hospital or school) falls into this category.
8	Task specific delegated risk control	Those doing the work need a level of assessed competence to ensure they know what the task-specific risk controls are, and appropriate work methods and time must be allowed so that they can implement them. In construction, something like a one-off crane lift would fall into this category. In healthcare, a first-of-a-kind and high risk operation would be in this category.
9	Interactive risk control	Those doing the work need a level of assessed competence to be able to operate under an interactive-risk control structure, and appropriate work methods and time must be allowed so that they can implement them. This comes into play where the risks and how various factors combine cannot be fully foreseen, nor every eventuality planned for in detail. An example from the authors’ experience concerns the maintenance procedures on the iconic Clifton Suspension Bridge in Bristol. Here the hanger connections corrode and the hanger fixings need to be replaced periodically. This activity is personally overseen by the Bridgemaster to ensure, for instance, that as work is revealed to sight, a hanger is not removed if the neighbouring hanger is already quite well corroded; in such an eventuality the sequence of work might be reversed, or a new method planned. Other examples are routine in heavy cranage and load sequence control in construction methodology.
10	Exposure control	Activities such as hyperbaric working (for instance in tunnels) and exposure to noise or vibration cause harm to persons, but the body will repair itself provided there is not over exposure. Ideally such activities would be eliminated, but this is not always possible.
11	Risk of harm not reduced SFARP, non-compliant, impractical, high consequences for failure to maintain, falls short of process safety guidelines, accepted good practice or similar	This category is in effect the area of ‘technical fouls’. In the UK’s CDM Reulations, for instance, there is a legal requirement to apply the hierarchy of control on risks, wherever the risk is significant. It is possible that this process may not have been conducted, even though the risk is not great. This failure to apply process is a failure to apply the law, notwithstanding the level of risk.
12	Unacceptable risk, too high probability of harm	Design proposals which are fundamentally dangerous, a structure which is too weak to stand would be in this category.

The categories within Table 1 can be determined either through the definitions provided, but also be considered from the converse perspective. For example, for category 7 if ‘standardised risk controls’ will not be sufficient to control the residual risk, the category cannot be ‘category 7’ and categorisation should be increased.

Guiding Principles

The use of the framework is governed by six overarching guiding principles; five of them relate to assessing categorisation, the sixth to adjacencies and context:

Principle 1: The categories of the framework (Table 1) are designed to be used at the granularity of work packages, or sub-elements of work packages. Where a collective view is required of an overall project, the highest individual score within the collective is taken as the score for the whole.

Principle 2: The principles of prevention must have been applied; if not, category 11 applies even if the proposed design would otherwise have an acceptable category.

Principle 3: The controls which are needed to make the design safe in practice must be communicated to all stakeholders and there must be a reasonable expectation that they will be applied.

Principle 4: If a design is improved in part, the potential effect of any change arising from the improvement must be checked on other parts of the asset and on other phases of the project lifecycle, to ensure none is rendered unacceptable by the change (i.e. there has been no ‘risk shuffling’).

Principle 5: Where a specific very low (‘very safe’) category is needed, to fail to provide this is unacceptable, notwithstanding the design might be ‘really quite safe’.

Principle 6: Consideration must be given to what is adjacent to the site or asset, and what other societal impacts the new asset may have; adjacencies may imply that especially low categories are required.

Life-Cycle Phases

The lifecycle phases used by the framework are those of the physical asset and the physical activities involved in its making, construction, operation, maintenance, re-purposing and eventual removal; design as an activity in and of itself is not included. Designs should be assessed for each phase of the asset's life-cycle, and the framework proposes 16 such phases as set out in Table 2:

Table 2: Life Cycle Phases

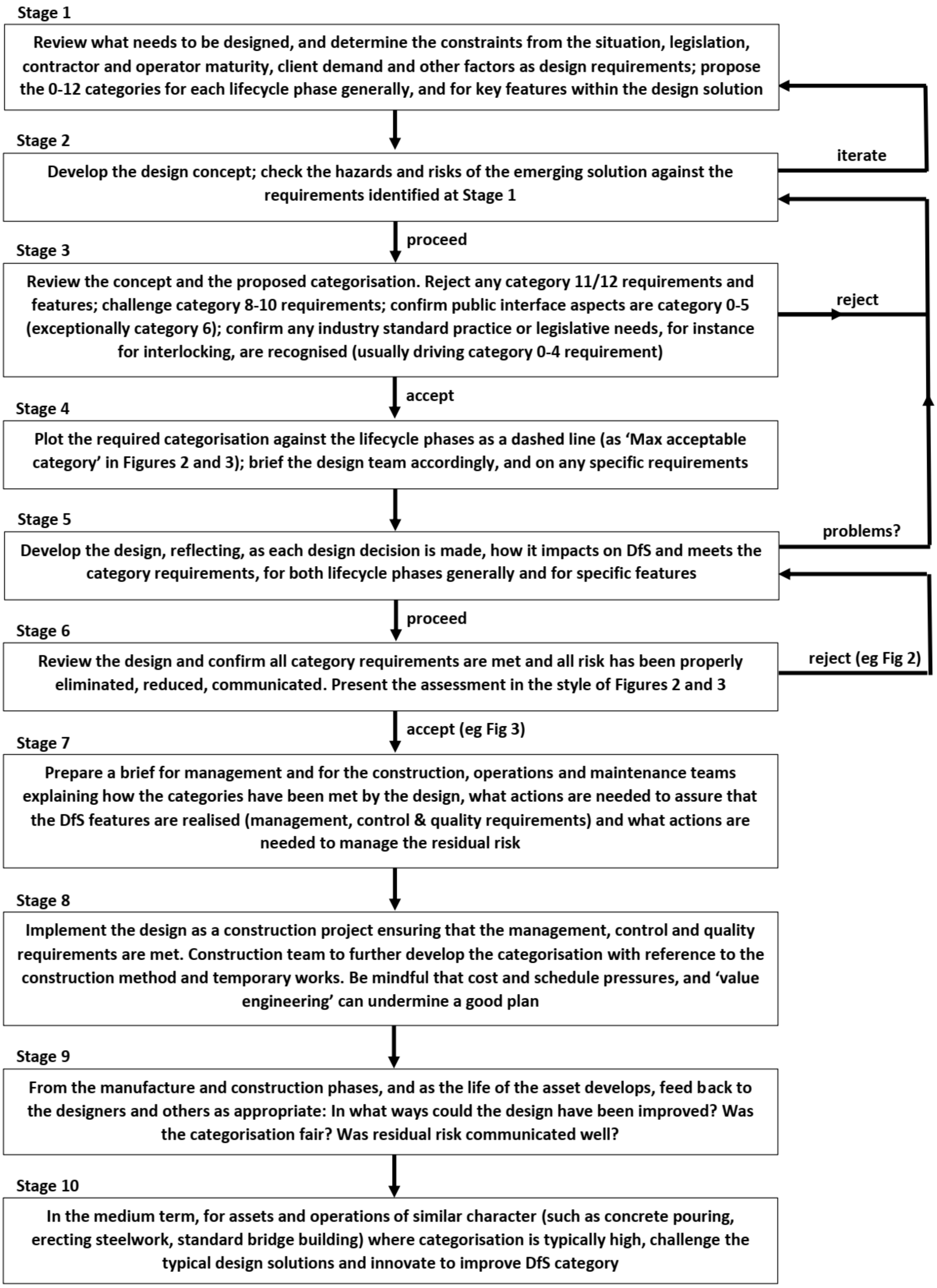
1.	Preliminary investigation, tests and prototypes	9.	Maintenance
2.	Materials sourcing	10.	High impact events
3.	Component manufacture	11.	Modification
4.	Storage, transport, logistics	12.	Ageing
5.	Install, construct	13.	Life extension
6.	Commission, site tests	14.	Demolition, removal
7.	Use	15.	Post processing
8.	Operation	16.	Materials disposal, reuse

One ambition of the framework is to help rebalance the weightings usually given to the different phases of the lifecycle. Traditionally, end of life (Stages 14, 15 and 16) has been given little attention, however the inclusion of maintenance and use within DfS-oriented legislation (such as the UK's CDM Regulations 2015), the increasing influence of Facilities Management professionals in design (Wang et al 2013), and increasing interest in a Circular Economy (Kirchher et al 2017) mean these later phases in an asset's life cycle are becoming far more prominent, and are therefore given equivalent priority to the construction stage in this framework.

Use of the Framework in Practice

The process for use of the framework in practice is set out in Figure 2. This approach is similar to a 'Gateway' model (see Hare and Cameron 2012 for a gateway model for health and safety for construction project planning), in which some stages enable progression through the 'Gateway' to subsequent action or a return to a previous stage for re-evaluation.

Figure 2 : Flowchart for applying the framework in a construction context



Stage 1

Review what needs to be designed, and determine the constraints from the situation, legislation, contractor and operator maturity, client demand and other factors as design requirements; propose the 0-12 categories for each lifecycle phase generally, and for key features within the design solution

Stage 2

Develop the design concept; check the hazards and risks of the emerging solution against the requirements identified at Stage 1

Stage 3

Review the concept and the proposed categorisation. Reject any category 11/12 requirements and features; challenge category 8-10 requirements; confirm public interface aspects are category 0-5 (exceptionally category 6); confirm any industry standard practice or legislative needs, for instance for interlocking, are recognised (usually driving category 0-4 requirement)

Stage 4

Plot the required categorisation against the lifecycle phases as a dashed line (as 'Max acceptable category' in Figures 2 and 3); brief the design team accordingly, and on any specific requirements

Stage 5

Develop the design, reflecting, as each design decision is made, how it impacts on DfS and meets the category requirements, for both lifecycle phases generally and for specific features

Stage 6

Review the design and confirm all category requirements are met and all risk has been properly eliminated, reduced, communicated. Present the assessment in the style of Figures 2 and 3

Stage 7

Prepare a brief for management and for the construction, operations and maintenance teams explaining how the categories have been met by the design, what actions are needed to assure that the DfS features are realised (management, control & quality requirements) and what actions are needed to manage the residual risk

Stage 8

Implement the design as a construction project ensuring that the management, control and quality requirements are met. Construction team to further develop the categorisation with reference to the construction method and temporary works. Be mindful that cost and schedule pressures, and 'value engineering' can undermine a good plan

Stage 9

From the manufacture and construction phases, and as the life of the asset develops, feed back to the designers and others as appropriate: In what ways could the design have been improved? Was the categorisation fair? Was residual risk communicated well?

Stage 10

In the medium term, for assets and operations of similar character (such as concrete pouring, erecting steelwork, standard bridge building) where categorisation is typically high, challenge the typical design solutions and innovate to improve DfS category

Method

In order to empirically explore the use of the framework in practice, a case study design workshop was held in December 2019. A major rail re-development scheme, with elements at the Governance for Railway Investment Projects (GRIP) Stage 3 ‘Option selection’ (Network Rail 2017) provided access to the research team, who were invited to present and workshop the framework with the project design team. The element chosen for the workshop was the replacement of a road bridge over a railway interchange; the span of the existing bridge and its life-expectancy needed improving to meet scheme requirements. This element of the project had a value of around £40 million within a multi-billion pound budget overall, and allowed a local road and associated gas, electric and telecoms services to be diverted, which were essential preliminaries to improving the rail layout beneath.

Key characteristics of the project were:

- Existing hump-backed road bridge over an interchange of multiple fast and slow running railway tracks;
- Demolition of existing bridge and replacement with a new one; a slide-in bridge methodology preferred to minimise local road disruption;
- The site of the bridge close to houses and other buildings; therefore a sensitive site;
- Gas, electric and telecoms services cross the existing bridge, a major sewer was located under the approach ramp area;
- Existing bridge built in stages over past 100+ years; and as a consequence the full structural detail was not known;
- Rail line closures possible in phases, but costly.

The workshop was undertaken both as a practical, real-life design development discussion, and as an empirical research study. The research aim was to explore how the framework operated in practice, and the participants were asked to actively reflect on the workshop as it progressed. The workshop involved consideration of the bridge replacement as an ‘element’ within the overall scheme, and the framework was used to explore how design change impacted the risk profile of the replacement bridge asset, throughout its planned lifecycle.

The workshop was chaired by the lead author, with the other authors participating, and included two lead engineers from the main contractor and the two lead scheme design engineers for the replacement bridge element of the works, ensuring both design and practical considerations were considered. Between them, these four project engineers had considerable design, build, operate and maintenance experience. Each engineer has been allocated a letter (A, B, C or D) as an identifier and where their contributions are used in illustration in the findings, attribution is given either in the text or in brackets immediately after the quote used.

With full participant consent, the workshop was digitally recorded using an audio recorder and a 360-degree camera. The workshop lasted a total of 2 hours and 37 minutes. The resultant audio and visual qualitative data was analysed through the lens of the framework itself, with a focus on how the framework influenced and shaped discussions around DfS. Due to constraints of space, and the very early stage this empirical work presents in the evaluation and validation of the framework, only the most salient findings are presented below.

Findings

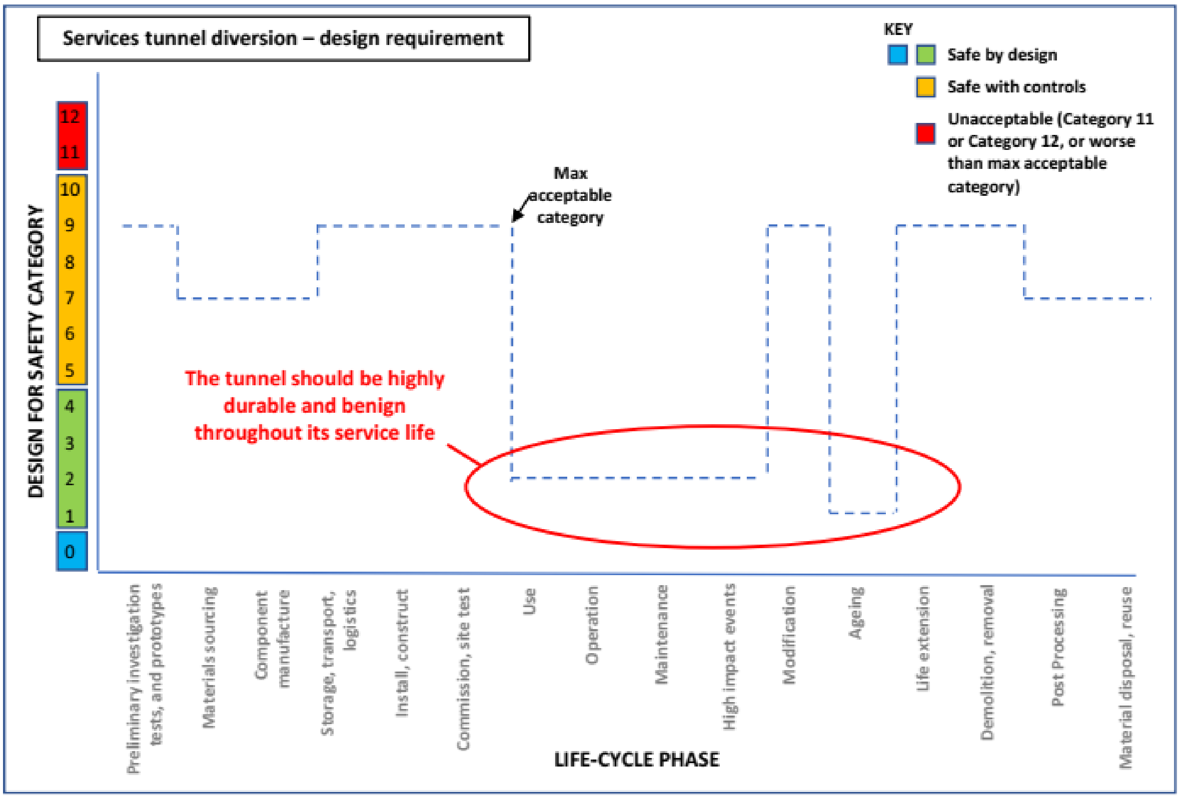
The workshop began with a period of team 'norming' and 'forming', including introductions and initial general conversation around subjects such as project value, the overall timeframe, the project's place in the local development plan and aspects of local infrastructure history. An overview of the framework was then presented by the lead author and the purpose of the workshop explained; then the project team explained the work scope for the new bridge and constraints upon it. All agreed that the bridge replacement was technically challenging work. Following these preliminaries the lifecycle phases created an 'agenda' for the workshop, and the 0 to 12 categorisation was used to assess potential design solutions.

Establishing the Framework

The 0 to 12 DfS categories had entered the vernacular of the discussion by the 11th minute, and by the 18th minute, the life-cycle phases were also being explored concurrently and fluidly. Evidence for this could be seen in the prominence of their use, and it was clear that participants were finding the framework beneficial to both their understanding and expression. Interestingly, the discussion was one of balance and trade-offs, rather than progressive box-ticking. Holding all life-cycle stages simultaneously in the discussion facilitated the finding of optimised solutions, resolving potentially conflicting criteria. For example, maintenance was prominent throughout both design and construction discussions, as the framework demands, with Engineer A saying it should '…drive more intelligent design, for example the specification of paint on a wall could create the risk of needing to repaint the wall a number of times'. The inclusion of high impact events within the framework also generated considerable discussion, and ranged from over-weight road loads, to a de-railed train, to consequences of climate change, to terrorism. Engineer B said they need to consider '…what could occur…and what would be the cost of avoiding that potential…as compliance with standards could be OK from design perspectives, but the risk doesn't go away...'

When the discussion began to drift in focus (after around 30 minutes), the implied agenda of the life-cycle phases was effectively used to refocus the conversation and a detailed review of each life-cycle phase was then methodically undertaken. This review organically focussed on the idea of permanently diverting the gas, electrical and telecommunication services at the outset into a tunnel bored under the tracks, so that the existing bridge could be demolished and the new one built without concern for the services. A second option was to put the services on a temporary bridge, then, once the road bridge was re-built, divert the services back again. Within a further 30 minutes, a set of realistic 0 to 12 category scores for the service tunnel option (not the project as a whole) had been determined by consensus and can be seen in Figure 3. This in part suggested a natural boundary to the scope and scale of any asset under consideration for the framework in use, but the tunnel evaluation was still fully contextualised within the wider project throughout.

Figure 3 : Maximum acceptable categories for services tunnel diversions, developed at the workshop December 2019



Using the framework resulted in discussion which equitably incorporated both a review of what scores were readily achievable concurrently with discussion of what was needed. In practice, some aspects of risk were fixed, for example building a tunnel adjacent and under a live railway will always be a category 9 activity. Other categories could be more varied, for example storage would '…usually be an 8, but it's a 9 here as its by rail' (Engineer B).

The category scores were sketched out as a dashed line to set the maximum acceptable category for each life-cycle stage. In debating the scoring, each engineer contributed their own stories and vignettes, and a range of experiences and references to historic material were shared, enriching the risk conversation. The use of examples to support the allocation of scores was commonplace, and created a natural and collegiate discussion, which did not generate confrontation or argument, but instead opened up the conversation and inspired collective reflection.

The Framework in Action

In discussing the service tunnel design in detail, the conversation was helped by the guidance inherent in the framework and the fluidity across the life-cycle stages. With discussions focussing on residual risk, the consequences of design decisions were as prominent in the discussion as the technicalities of design itself. Certain aspects of the life-cycle had very specific requirements for low scores: for example, once the tunnel was built and the services installed, the tunnel structure needed to survive intact without intervention for the full 120 year design life, perhaps more. Inevitably maintenance was carefully considered, the discussion referencing inspection chambers, confined space work and working at height. As Engineer D said, whether the project was '…providing a pipe that doesn't need maintenance…whilst the services going through it may do…' meant the need to ensure the specification of long life within the services themselves, which, although more costly at the outset, was justified by the reduction of residual risk. Consideration of additional capacity in the tunnel was also discussed, as this could also increase the maintenance burden, but this necessitated 'another balance…[and it would be]…wise to put big enough service chambers to get new services easily into the ducts in the future, future proofing the project as well as helping the maintenance and enclosed space access' (Engineer B).

The service tunnel also needed to be highly robust to potential high impact events, such as a train derailment or some future need to demolish the bridge: in the event of a rail accident, no one wanted a damaged gas main adding to the catastrophe. This resulted in another category 2 being applied to ensure neither '…a train de-rail affected the service, or a service affecting the rail' (Engineer A). The discussion was therefore not so much about designing a tunnel, so much as what would make the tunnel fit for purpose. This consideration extended to the demolition/removal phase, in which a category 9 was applied as it would be very hard to 'remove' in practice, grout pumping being a likely solution, but '…making demolition easy is not a priority for this particular element' (Engineer B).

As the service tunnel had not yet been designed, it was not possible to review the design against the criteria, so no solid bars have been added to Figure 3, as that would be a matter for design review. There was, however, confidence that the maximum allowable scores were achievable using the permanent diversion tunnel option. A caveat needs to be made here: it was evident in the conversation that the low score for 'impact' (category 2) was to a degree driven by what was possible more than what was needed; the risk of setting maximum allowable scores on this basis would undermine proper choice of options and could stray into politicisation, a tendency that was agreed to be best avoided. Similarly, while the service tunnel structure needed to remain intact for 120 plus years without intervention (giving a maximum allowable 'aging' category score of 1), the same was not necessarily the case for the bridge solution, as maintenance, while difficult, would be achievable: to assess the 'bridge' option against the 'tunnel criteria' is not entirely fair. However, it was felt that the framework made the safety benefits of the tunnel option stand out and become self-evident. As Engineer C put it: 'it's always in conflict or balance, but we've set the acceptable line so now the design needs to get there'.

The designers found it reassuring to demonstrate benefits in a numerical way, which although not truly independently objective, does enable a fair evaluation between options. Drawing attention to the vulnerability of the services on the bridge (the alternative option) if a high impact event occurred was a key argument, which would create a 'red bar' if the temporary diversion option was scored against the maximum allowable category score of 2 for a high impact event.

Suggestions for Improvement

As the workshop progressed and the conversation matured, the designers became more familiar with the framework, and even suggested some potential improvements. These included that the number of people or 'person-hours' at risk should figure within the histograms, the '…number of people potentially exposed' (Engineer C), represented by the fattening or slimming of the bars in the bar chart. In this case, there are orders of magnitude to consider: more rail users at risk from some kind of catastrophic failure than workers at risk during site investigation, so the 'use' and 'high impact event' bars merit a great deal more width than the 'preliminary investigation, tests and prototypes' bar. Another suggestion was to calculate 'gross risk' by multiplying the risk scores on the 0 to 12 scale by the number of persons or person-hours, then adding them all up across the life-cycle phases; by assessing various design changes, a minimum value of this 'gross risk' would justify a design as being as safe as possible.

Another potential improvement would be to adapt the principles to design for health and for sustainability. Table 1 does hint at this possibility.

Summary of the Workshop

The workshop participants felt that the framework worked well for a specific, if complex, element of construction. The services tunnel was deemed appropriate in terms of scope for the application of the framework. However, the bridge as a whole, with its set of stages of construction and multi-disciplinary content, was simply too large. Yet it could be beneficially treated in parts, of which the diversion tunnel was one, and the temporary bridge another. With regards to the entire multi-billion pound programme, the framework enables a platform for strategic intent, even though the overall programme was, as a unity, far too complex for analysis using the design decision-making framework.

The participants felt the workshop was beneficial, and commented that the time spent had been very worthwhile. Engineer A said 'The benefit was that the session was focussed on outcomes, envisaging the asset at all stages of its life, and how it would fare, and how people would work with it. It was a creative session, helping us to share our expertise to find the right design solution.' Asked what was normally done to assess life-cycle risk, the response was 'We are asked for our top 10 risks over the lifecycle' (Engineer A) with the comment that this amounted to little more than a box-ticking exercise by individual designers who lacked actual operational experience: 'The creativity and teamwork are lacking' (Engineer A).

The route to consensus involved the exploration and explication of knowledge, skills and experience, mobilising peer learning. Those involved felt they better understood the risks they were designing for and had more clarity on what needed to be done to manage them once the work scope developed on site. They also had more confidence in their decisions, although in some aspects they felt less secure, for example as Engineer B noted it was '…hard to cost maintenance, we need a more nuanced understanding of all elements of the life cycle'. This suggests supplemental expertise could be needed to support optimum use of the framework in practice.

The output, in the form of a simple chart, was seen as a straight-forward starting point for a more engaged discussion with non-expert third parties, drawing clear attention to where risks are high and need especial attention to management and detail. As Engineer D said, '…you can show the original or improved version to project management and cost it, this is much more simple, and is able to be understood readily'. The framework gave a vernacular to abstract technical ideas in the DfS space, as well as a means to contrast options numerically, greatly facilitating communication on why the chosen design option was selected. The designers saw power in this, the numeric presentation, supported by a (potentially) industry-standard phraseology, was seen to give DfS the same profile in project management meetings as cost and time, which would normally be the only characteristics to receive numerical treatment. The shift from nominal assessment of compliance (a binary 'complies' vs. 'does not comply', or 'tick box'), to an ordinal scale (giving the possibility 'both of these solutions comply but this one is measurably better in terms of safety (not just cost) than that one') was seen as a game-changer in DfS discourse, which had the potential to drive excellence, not mere compliance.

Reflection

The framework presented in this case study offers a numerically based tool to assist DfS. The design engineers who participated in the workshop felt enabled by the framework as, notwithstanding its numerical basis, it broadened and diversified their narrative, deepening their understanding of the safety issues surrounding the assets that they were either designing or building. They considered that the numerical outputs from the framework would raise the status of their opinion in project management circles, as it gives DfS the 'support' of a numerical value and fixed vernacular, as already enjoyed by time and cost. The framework presents design decisions in a way which emphasises objectivity in their comparison, and indeed could be used to allow totally different schemes to be contrasted at the highest level. There is the potential for the framework to achieve clear and unambiguous communication to all stakeholders involved in a project, including non-cognates, to support their engagement and understanding of DfS, and to do so for all stages of the project's lifecycle.

More work is needed if the framework is to become a standard engineering design tool. While the characteristics and use of the framework gained traction quickly (by the 11th minute in the workshop), there is a degree of complication in having 13 categories, 16 lifecycle phases, 10 stages of application in the design process (Figure 2) and 6 principles, which require a level of explanation and support. In the workshop, the lead author undertook the facilitator role which was critical in guiding people through the process of using the framework, but also in providing forensic engineering expertise to support and inform discussions and decision making. Such expertise is not commonplace, and how best to embed such knowledge within the framework is a necessary further consideration. Enhanced guidance is also needed with regards to the aspects that should be included in each of the identified life-cycle phases and how to categorise designs against the 0 to 12 category scale. This will apply especially to categories 10, 11 and 12, which are likely to prove contentious, as they imply the design is either unacceptable or will put people in harm's way; a good knowledge of both legislation (category 10 and 11) and forensic engineering (category 12) is therefore required to ensure accurate evaluations.

The evaluation work presented here is inherently and inevitably limited, and thus no claim to validation of this framework is made; that is the next stage in this research. However, these initial findings strongly suggest that such efforts would be beneficial and worthwhile. Close monitoring and testing of the framework in practice, from the design stage and then throughout the construction, operation and maintenance of the resultant asset in the real world is needed to achieve validation in practice. This would require a much more extensive longitudinal study, running in tandem with a real construction project. Such a study should also include the introduction and use of the framework with non-cognates, the business leaders and managers who make significant project decisions but are not experts in design or DfS. The ability of the framework to communicate engineering design decisions at this level, to the understanding of all, is a key ambition for the framework that has not been explored here, which is noted as a further limitation.

Conclusions

The proposed industry-led framework offers a novel and beneficial way to support DfS. It is able to aggregate residual risk and justify numerically that risk by design has been reduced to the lowest level (such that any change to the design increases the risk). Limited empirical work suggest that the framework brings a number of benefit to designers and designing engineers undertaking DfS, as they are better able to share their knowledge and expertise with each other, to consider all aspects of design decision making as it is undertaken and with due cognisance of the full life-cycle of the project, and to prioritise excellence over compliance. The framework creates an agenda and structure for this process, creating a new visualisation of DfS which was felt would help enhance and augment their decision making when communication with non-cognates, such as business leaders, is required. The framework therefore is complementary to DfS tools aimed at supporting designers as they design, such as the Design for Safety Toolbox, as it enables enhanced communication of those decisions to a non-cognate audience. It is also able to supplement existing shared DfS communication tools such as CHAIR, as it provides a holistic overview of a project that develops concurrently with decision making discussions, minimising risk shuffling and highlighting any unintended consequences to other project life cycle phases.

Further work is needed to fully validate the framework in practice, which it is hoped will also enrich the evidence base for DfS application to real-life project situations and thus optimise DfS in architectural, construction and engineering practice to create an inherently safer built environment for the future.

Acknowledgements

The framework presented in this case study was first mooted at a meeting of the UK's Temporary Works Forum's Client Group (TWF: www.twforum.org.uk). In reviewing the UK's arrangements for the management of construction risk from temporary works failures, a lack of guidance for non-specialists was identified. Clients expressed a particular concern that, while they held responsibilities for appointments of competent designers and contractors, there was little to help them assess risk and respond accordingly; while it was self-evident that risks were not equal, the guidance seemed to be 'one size fits all'. This challenge was taken forward by the authors, using the TWf, Standing Committee on Structural Safety (SCOSS: www.structural-safety.org) and a range of commercial engineering enterprises as sounding boards, as the framework was developed and evolved. The assistance of TWf, SCOSS, Expedition Engineering Ltd, Costain Ltd and Southern Water PLC is gratefully acknowledged. In particular, the authors recognise the contribution of Richard Snell (1940-2019), a longstanding member of SCOSS, whose insight and guidance was instrumental in the initial stages of the work.

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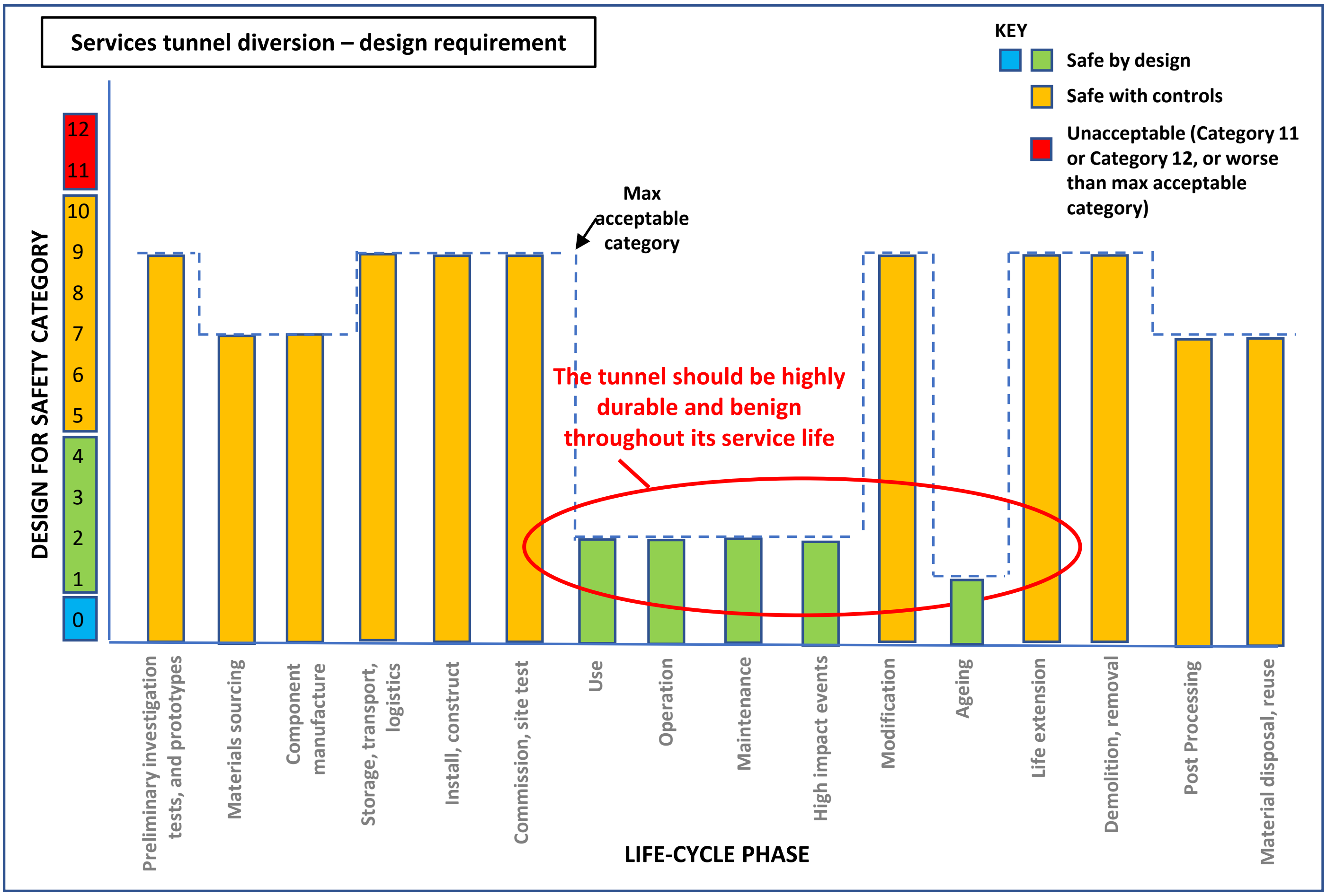
Services tunnel diversion – design requirement
KEY
Safe by design
Safe with controls
Unacceptable (Category 11 or Category 12, or worse than max acceptable category)
DESIGN FOR SAFETY CATEGORY
12
11
10
9
8
7
6
5
4
3
2
1
0
Max acceptable category
The tunnel should be highly durable and benign throughout its service life
Preliminary investigation tests, and prototypes
Materials sourcing
Component manufacture
Storage, transport, logistics
Install, construct
Commission, site test
Use
Operation
Maintenance
High impact events
Modification
Ageing
Life extension
Demolition, removal
Post Processing
Material disposal, reuse
LIFE-CYCLE PHASE