The Institution of Civil Engineers
on behalf of Transport for London

Rotherhithe to Canary Wharf Crossing

Review of bridge opening mechanism options

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Rotherhithe to Canary Wharf Crossing - review of bridge opening mechanism options

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Executive Summary

Transport for London (TfL) have been developing proposals for an opening pedestrian and cycle bridge across the river Thames from Rotherhithe to Canary Wharf, and have approached the Institution of Civil Engineers (ICE) for independent advice regarding the opening mechanism for the bridge. This report presents that advice.

The busy marine traffic on the river includes occasional very large ocean-going ships as well as a plethora of smaller vessels, and acting on advice from the Port of London Authority (PLA) it has been decided that the bridge will need to provide a vertical navigation clearance of at least 12m when closed and at least 60m when open. Furthermore, there can be no physical obstruction in the river within the width of the authorised navigation channel.

A preferred alignment for the crossing has been selected which connects Durand's Wharf on the south side of the river to Westferry Circus in Canary Wharf on the north side. This alignment requires the main span to cross the navigation channel at a skewed angle, immediately south of the Jubilee Line tunnel, resulting in a clear span of approximately 180m. This places the bridge among the longest opening bridges in the world, and makes it by far the longest opening pedestrian / cycle bridge.

Three types of opening bridge mechanism have been considered: a double-leaf bascule bridge, a double-leaf swing bridge and a vertical lifting bridge. The various factors that influence the choice of bridge mechanism have been examined in relation to these three bridge types. These factors include the duration of the opening cycle which determines the delay to users of the bridge and passing vessels, the risks that the bridge may not be able to open in extreme circumstances causing unacceptable delay to large ships, the difficulties associated with construction and long term operation and maintenance, visual and environmental impacts, as well as other considerations.

It is clear that the double-leaf bascule bridge is the least preferred solution, and it presents several difficulties making it doubtful as a viable option for the bridge. It would be approximately twice the size of any double-bascule bridge built to date.

The swing bridge would be feasible but has a number of undesirable features such as the added risk of vessel impact on the open spans. In addition, the bridge needs a locking mechanism between the leaves at midspan and these can cause difficulties in operation leading to the risk of delays in opening the bridge with unacceptable consequences to navigation.

The preferred operating mechanism is the vertical lifting bridge. It has the simplest and most reliable operating system, presenting the fewest risks and the greatest opportunities. It would undoubtedly be a most impressive landmark, forming a new gateway to London, and it demands the highest quality in design and architecture to suit this unique location.

1 Introduction

By an agreement dated 30th January 2019, I have been appointed by the Institution of Civil Engineers (ICE), acting on behalf of Transport for London (TfL), to provide independent advice regarding the opening mechanism for the proposed Rotherhithe to Canary Wharf Bridge across the river Thames.

The bridge will cross a very busy navigation channel in the river which is used regularly by large ocean-going ships as well as smaller craft. A fixed high level bridge with sufficient headroom clearance to accommodate such ships would need very long approach ramps and/or elevators and be inappropriate at this site. It has consequently been dismissed as a non-viable solution, and TfL have been considering the various options for an opening bridge.

The bridge proposals have now advanced to the point at which TfL will shortly be seeking powers to construct the bridge through a Transport and Works Acts Order (TWAO). Having arrived at a preferred design solution they are seeking an independent opinion on the suitability of the opening mechanism which has been selected for the bridge. This report seeks to provide that independent opinion.

The documents which have been received from TfL, and which form the basis for this independent review of the proposed opening mechanism, are listed in the References section at the end of this document.

The brief for this review is attached in Appendix A. It contains the key specific question which this independent review is required to address, namely: "Has TfL appropriately considered different mechanism options and chosen the most appropriate for this scheme?" This report sets out my considerations and conclusions. The brief also invites observations on any other issues that I identify, and these are given in Appendix B.

Note: Throughout this report, reference to a bridge in the open condition or open position means that the bridge is open to allow large vessels to pass and is thus closed to pedestrians and cyclists. Conversely a bridge in the closed position is one in which pedestrians and cyclists can cross but large vessels may not pass.

2 Background

The need for a pedestrian crossing of the river Thames between Rotherhithe on the south side of the river and Canary Wharf in the Isle of Dogs on the north side of the river has been the subject of many studies. In recent years these have included the following:

- Sustrans Thames Pedestrian and Cycle Bridge - Feasibility Study. [Ref 1]
- Rotherhithe to Canary Wharf Crossing Bridge Options Study. [Ref 8]
- Rotherhithe to Canary Wharf Crossing Bridge Feasibility Study. [Ref 14]
- Rotherhithe to Canary Wharf Bridge Crossing Concept Design Study. [Ref 23]

Three principle bridge alignments have been the focus of these recent studies, referred to as the north, central and southern alignments. These are illustrated in Figure 1.

The river at this point actually runs north-south as it flows in a large meander around the Isle of Dogs, so the bridge is effectively aligned east-west. In the case of the central option, the available landing sites are not opposite each other across the river, so this results in a skewed alignment where the bridge crosses the navigation channel. This skewed alignment results in the main span being longer for the central option than for the other two cases, all other things being equal.

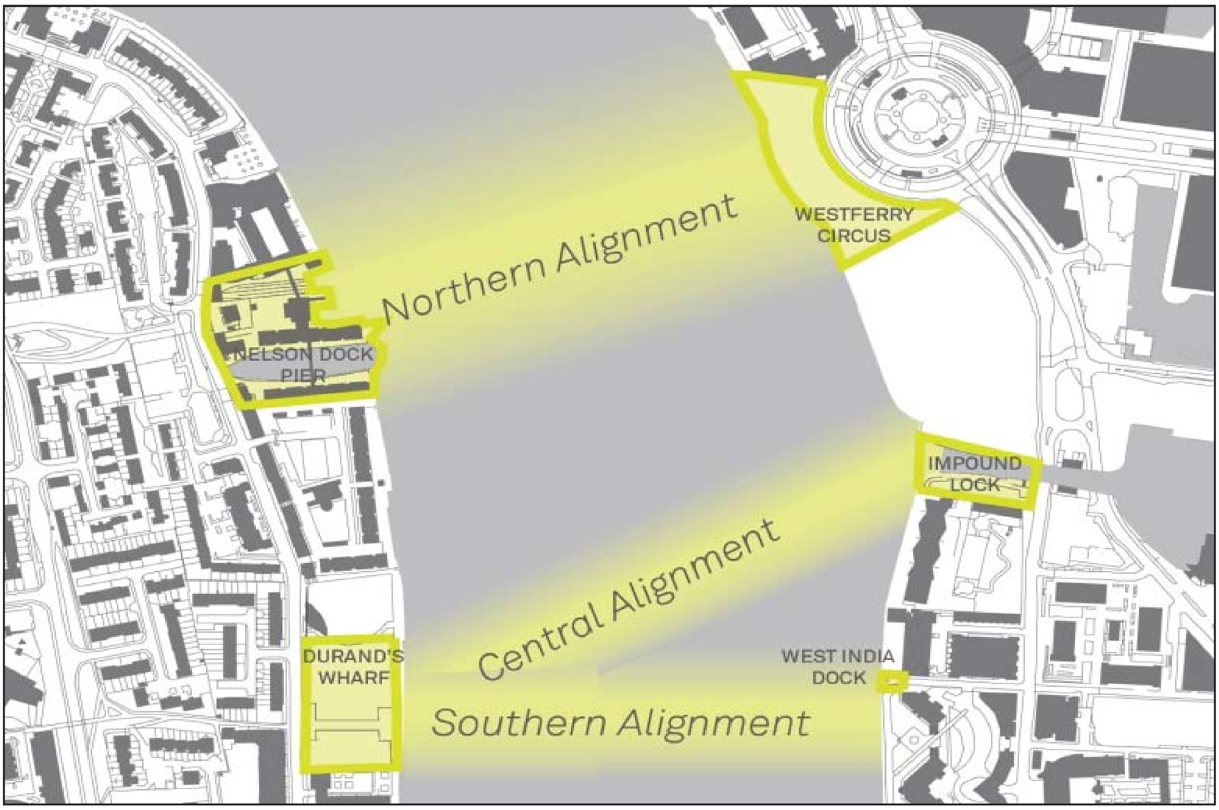

Figure 1 *Alignment options considered for the proposed crossing. (From Ref 21)*

Marine traffic on this stretch of the Thames is extremely busy, with large numbers of vessels passing along the river every day, including very large ocean-going cruise ships. The authorised navigation channel here varies in width between approximately 130m and 140m, and the Port of London Authority (PLA) has stipulated that the bridge span should be long enough to accommodate this channel plus an additional margin for safety on each side. There must be no supports in the river within this clear navigation zone.

TfL has carried out a thorough analysis to evaluate the alignment options, taking into account many factors including a variety of structural forms and opening mechanisms. As a result of these studies, the central alignment has emerged as the preferred location for the bridge. TfL has carried out public consultation exercises to elicit comments and preferences from those most directly affected by the bridge regarding the selection of preferred alignment.

Space restrictions on the Canary Wharf side of the river have resulted in the landing point on that side being moved northwards to Westferry Circus. This means that a long approach ramp is needed running northwards from the bridge, along the east edge of the river, between the navigation channel and the river bank. So the current proposal is for a bridge alignment connecting Durand's Wharf on the Rotherhithe (south) side of the river to Westferry Circus on the Canary Wharf (north) side. (Figure 2)

Figure 2 *Preferred alignment between Durand's Wharf and Westferry Circus. (From Ref 21)*

TfL's studies have explored many options with the PLA regarding the navigation clearances to be provided by the bridge, and by way of summary, the requirements currently defining the geometric constraints for the main span of the bridge are as follows:

- On the skewed central alignment, a minimum clear span of 180m.
- Bridge closed: minimum vertical clearance of 12m across the central 40m width of the channel and 9m elsewhere. Levels measured above Mean High Water Springs (MHWS).
- Bridge open: a minimum vertical clearance of 60m above MHWS across the full clear width of the main span opening, including the margins each side of the authorised navigation channel.

The current preferred alignment is shown in Figure 3.

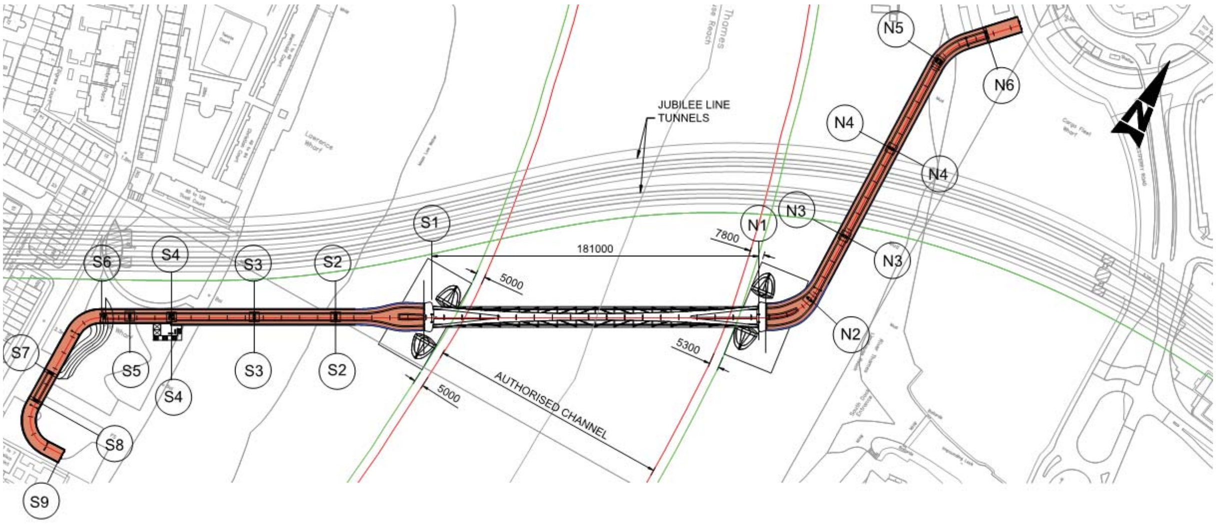

Figure 3 *Preferred alignment showing the 181m skewed main span. (From Ref 23)*

Note that the Jubilee Line tunnel also crosses the river at this location, just to the north of the proposed bridge alignment, and the approach ramp on the Canary Wharf side crosses over this at one point between piers N3 and N4.

I do not propose to comment on the selected bridge alignment here as it is not strictly part of the specific brief for this review. But I have made a few general comments for consideration on the alignment and some other issues in Appendix B.

The latest predicted pedestrian and cycle traffic flow figures obtained by TfL are given in the Concept Design Study report [Ref 23] and reproduced in Table 1. This shows predicted peak flows projected forwards to 2031 and 2041 and indicates potentially busy usage at peak times. A large proportion of the users will be using the bridge to get to and from work, and they will be particularly keen to avoid long delays in the event that the bridge has to open during their journey. Marine vessels also desire a minimum of delay while they must wait for the bridge to open, so a minimum opening cycle time will be an important bridge design parameter for both these sets of users.

	Period	2031			2041		
		Low	Medium	High	Low	Medium	High
Pedestrians	AM Peak (1 hr)	939	1,083 to 1,506	1,739	1152	1,330 to 1,538	1,776
	Am Peak (3 hours)	1,704	1,950 to 2,722	3,119	2091	2,394 to 2,780	3,186
	Daily	5,714	6,621 to 9,194	10,657	7015	8,129 to 9,391	10,884
Cyclists	AM Peak (1 hr)	223	988	1,573	283	1,255	1,998
	Am Peak (3 hours)	N/A	N/A	N/A	N/A	N/A	N/A
	Daily	N/A	N/A	N/A	N/A	N/A	N/A

<u>Table 1</u> Predicted peak pedestrian and cycle traffic flows. (From Ref 23)

Environmental and archaeological issues are important here, as elsewhere on the river, and have been examined in detail in the Sustrans Thames Pedestrian and Cycle Bridge Feasibility Study [Ref 1] and in other studies. All agree that the number of piers in the water should be minimised, and particular care is required along the river margins to avoid disturbing natural habitats and important ecologies. But perhaps of greater significance to the selection of bridge opening mechanism are the aesthetic and urban design considerations. A bridge of this scale will make a large visual impact and will be seen from a distance along the river as well as close up by occupants of nearby buildings. Considerable thought has been given to all these issues in the TfL studies, and has informed the selection of the preferred option.

3 Bridge opening mechanisms considered

The extensive studies carried out to date have considered a range of different possible types of bridge opening mechanism. In particular, the Bridge Options Study by Arcadis and Knight Architects [Ref 8] includes an extensive list of different types. That study and all the studies to date have correctly concentrated on three main relevant options; a double-leaf bascule bridge, a double-leaf swing bridge and a vertical lifting bridge. All agree that these are the only options to be seriously considered for an opening bridge of the required scale on this site. The double-leaf bascule bridge is generally considered to be the least viable for reasons which will become apparent, and I agree entirely with that assessment.

Other types of opening mechanism do exist, but in view of the large number of bridge users, the large opening span and particularly the busy marine traffic in the river, they have all been rejected, correctly in my view. The principal options are described below.

3.1 Double-leaf bascule bridge

This is a bridge with two opening leaves, rotating about a transverse axis through the abutments. In the open position, the two leaves rotate upwards to allow vessels to pass. Generally speaking, they tend to contain a counterweight in the tail to partly balance the weight of the opening leaf and reduce the machinery power required to open the bridge. One of the most familiar of this type is the nearby Tower Bridge. (Figure 4)

Figure 4 *Tower Bridge, London, partially open to allow a medium-sized vessel to pass. A much larger vessel would require the leaves to rotate to almost the vertical position.*

Some smaller modern bascule bridges dispense with the counterweight and just provide sufficiently powerful hydraulic or mechanical systems to lift the spans.

Small and medium sized vessels may not require the leaves to open fully because the mast can fit between the tips of the partially-raised spans. But large ships which tend to be almost as wide at high level as they are at water level will require the bridge to open fully, with the leaves rotating to a nearly vertical position.

The clear distance between the bridge piers needs to be large enough to accommodate the navigation channel plus at least twice the depth of the bridge section, so as to make room for the leaves in the open position, one on each side.

3.2 Double-leaf swing bridge

This is a bridge with two opening leaves, rotating about a vertical axis. In most cases, the axis is close to one end, with a large counterweight contained in the tail to balance the weight of the forward-reaching cantilever. A modern large single-leaf version of this bridge is the cable stayed Samuel Becket Bridge in Dublin, designed by Santiago Calatrava. (Figure 5)

In the open position, the leaves sweep horizontally across an arc of the river, usually through about 90 degrees, to lie parallel with the navigation channel and alongside it. Thus, in the double-leaf swing bridge, the clear distance between the bridge piers needs to be larger than the width required to accommodate the navigation channel by at least the width of the bridge; ie. half the bridge width on each side of the channel.

Figure 5 *Samuel Becket Swing Bridge, Dublin, in the half-open position.*

The largest double-leaf swing bridge in the world, by a significant margin, is the El Ferdan Railway Bridge in Egypt. (Figure 6) Instead of using large counterweights in the tail, this bridge places the pivot near the middle of each moving section, creating in effect two large balanced cantilevers.

Figure 6 *El Ferdan Railway Bridge over the Suez Canal, Egypt, in the half-open position.*

A variant of the double-leaf swing bridge, using the model of the large balanced cantilever, is the centrally-pivoted swing bridge where the main pivot support is placed in the middle of the river and the navigation channel is split either side of it. In this arrangement, there are two main spans which pivot around a vertical axis through the central support. For this project, it is understood that the PLA have ruled out this option as there is no scope to split the navigation channel in this stretch of the river. For this and other reasons, this type of swing bridge has not been seriously considered for this crossing.

3.3 Vertical lift bridge

As the name implies, this is simply a bridge in which the span across the navigation channel is lifted vertically to a sufficient height to allow tall vessels to pass underneath. Such bridges require a tall tower on each side to accommodate the lifting mechanism, but the clear width of the navigation opening does not change, regardless of whether the bridge is raised or lowered.

A good example of this type of bridge is the Lowry Footbridge in Salford. (Figure 7)

Figure 7 *Millennium footbridge at the Lowry Centre, Salford Quays, in the partially lifted position.*

With a vertical lift bridge, the lifting section behaves as a simply supported span under all conditions, and is consequently often designed as either a tied arch or a large through-truss structure.

Unlike the other types, the length of the vertical lifting span is only a little longer than the navigation opening. There is no back span or extension to the moving structure to support the counterweight as the counterweight is not part of the moving span.

3.4 Other types of opening mechanism

Other types of opening mechanism have been considered by TfL, but all have been rejected because they do not suit the large span, the busy navigation traffic or for other reasons. Most of these other types tend to be suitable only for shorter spans where it is possible adopt unusual structural forms and opening mechanisms whose designs are not dominated by the very large forces experienced by larger spans and where vessel impact issues are less critical.

For example, one option which might suggest itself here because the opening span is less than half the river width, would be the retractable type of opening bridge. This type of bridge divides in the middle like the double-leaf swing or bascule bridge, but instead of rotating horizontally or vertically it slides back to open up the navigation channel. This is only possible where there is enough room each side of the navigation channel to accommodate the leaves in the open position. An example of this type of bridge in the Inner Harbour Bridge in Copenhagen. (Figure 8) In this case, the bridge rolls back into the space either side of the channel without having to lift or swing.

Figure 8 *Inner Harbour Bridge, Copenhagen, in the open position to allow a vessel to pass.*

The topography in the Thames at this location could accommodate this type of solution, but for reasons explained later it would not be seen as the preferred option.

4 Precedents for large span opening bridges

The Rotherhithe to Canary Wharf bridge will cross the river at a point where the authorised navigation channel is approximately 135m wide. However, the alignment requires it to cross at a skewed angle resulting in a required clear span of at least 180m making it the longest opening pedestrian and cycle bridge in the world by some margin. Although there are a few larger opening spans, such as the huge El Ferdan double swing bridge where the navigation channel is 320m (Figure 6), these are for road bridges and are of a much heavier and imposing design which would be entirely unsuitable for a lightweight pedestrian and cycle crossing.

The technical note from Arcadis dated 25th August 2017 [Ref 4] includes a useful list of long span opening bridges. There is some contradiction between some of the reports over exactly which bridge is the longest of each type, I suspect because of confusing span length and navigation channel width, but in general the consistency is good so I have not carried out a thorough independent investigation of current world span records in this regard.

In summary, the current maximum navigation channel widths in the world for the three main opening mechanism types under consideration are approximately as follows:

Double-leaf bascule:	92m.	Port of Europa Bridge, Barcelona.
Double-leaf swing:	320m.	El Ferdan Bridge, Egypt.
Vertical lift:	160m.	Arthur Kill Crossing, New York.

The Arthur Kill crossing in New York is the longest vertical lift bridge and has a span similar to that needed for the Rotherhithe to Canary Wharf crossing. It comprises a steel truss suspended between two steel lattice truss towers and has a rather bulky appearance. (Figure 9) However, this is because it carries a railway line for heavy freight trains, so the bridge needs to be very much heavier and stockier than would be the case for a lightweight pedestrian and cycle crossing. The heavy industrial character of the Arthur Kill bridge is arguably well suited to the railway infrastructure that it serves, but a rather different and much more elegant appearance would be more suitable for a pedestrian and cycle bridge of similar scale.

<u>Figure 9</u> The Arthur Kill lifting railway bridge, new York in the fully open position.

The Arthur Kill bridge, together with several other vertical lift bridges with spans around 140 to 160 metres, demonstrates that a vertical lifting bridge of this scale is feasible.

The El Ferdan bridge in Egypt clearly demonstrates the feasibility of a double-leaf swing bridge of the scale required for the proposed Rotherhithe to Canary Wharf crossing, although again it has an appearance and character which would be inappropriate in this case. Ignoring the El Ferdan bridge, the largest double-leaf swing bridges are the George P Colman Bridge in Virginia and the Harbour Island Bridge in Seattle, both of which provide a navigation channel width of about 140m when open, so are of a similar scale to that required for the Thames crossing. Again, these demonstrate the feasibility, in principle, of a double-leaf swing bridge for this project.

The Port of Europa Bridge in Barcelona is a double-leaf bascule bridge with a 109m span providing a 92m clear navigation channel when open. (Figure 10) The Market Street Bridge in Chattanooga, USA, is cited as the longest double-leaf bascule span in the November 2017 Bridge Options Study report by Arcadis [Ref 8]. However, although this has a similar main span length to the Barcelona bridge, the open channel width for large vessels is narrower owing to the fact that the leaves cannot rotate up to a near-vertical position because of the arrangement of the overhead counterweights. These record-breaking double-leaf bascule bridges provide only about half the clear navigation channel width required for the Rotherhithe to Canary Wharf bridge, and so this type demands extra scrutiny in the evaluation to determine its feasibility in this case.

Figure 10 The Port of Europa double-leaf bascule bridge, Barcelona. (Image: Arenas & Associados)

All of these record breakers are road or rail bridges. The record opening spans for pedestrian and cycle bridges are somewhat shorter. The vertical lifting Lowry Bridge in Salford (Figure 7) is one of the longest, providing a clear navigation channel width of about 90m.

The purpose of reviewing these existing large opening bridges is to set the scale of the proposed Rotherhithe to Canary Wharf bridge in context. There is no doubt that this bridge will be the longest of its kind in the world by a considerable margin, and the choice of opening mechanism is critically dependent on the risks associated with the construction and operation of such a large structure.

5 Primary considerations in the selection of opening mechanism

There are many factors influencing the choice of opening mechanism. In this section I have described what I consider to be the principal ones relevant to this project. There are others too, and the Opening Mechanism Option Selection Report [Ref. 18] includes a useful table summarising many of these. I have not included such an extensive list (although I generally agree with the conclusions of that report) but have concentrated on a few of the main aspects affecting the choice.

5.1 Opening cycle time

Minimising the opening cycle time is always of utmost importance for any opening bridge. This is particularly true wherever the numbers of bridge users and vessels requiring the bridge to open are high, as in this case. Bridge users (particularly commuters) do not want to be delayed on their journey longer than necessary when the bridge has to open to allow the passage of large river vessels. Conversely, vessels do not want to be delayed waiting for the bridge to be opened to allow them to pass.

However, the actual time it takes to open and close the bridge tends not to be the main issue; it usually only takes a few minutes. What takes the longest is firstly clearing the bridge of pedestrians and cyclists before the bridge can be allowed to open, and then the time taken for the vessel(s) to pass through before it can be closed again.

5.1.1 Clearing the opening section

The problem of clearing the bridge of users is worse for a pedestrian/cycle bridge than it is for any other type of bridge. This is because pedestrians tend to behave differently to car and van drivers, for example. With a road bridge, turning a traffic signal to "stop" at each end and closing the entry barriers will generally have the effect of immediately stopping new vehicles from entering the bridge. Then it is only a matter of a few seconds before the vehicles already on the bridge will clear off the far end and the exit barriers can be closed so the bridge opening sequence can start.

With pedestrians it is different. They tend to ignore signals, or at least to wait as long as possible before obeying them, and no partial barrier will prevent them walking round it and still getting onto the bridge. The only way to prevent pedestrians from coming onto the bridge while still allowing those already on the bridge to exit, is to have two fully segregated lanes, one for each direction, with no possibility of jumping between the two. Then you could close the entry barriers while still keeping the exist barriers open, but such segregation, which would need to be over a long length of the approaches to the bridge, would not be desirable. Entry/exit turnstiles can be used on smaller bridges but are inappropriate in this case.

Pedestrians already on the bridge tend to be very slow in getting off the bridge, even if there is an audible alarm sounding with announcements telling them to exit. In my experience, the only sure way to hurry them up is to have at least one bridge operator or bridge marshal, usually wearing a high visibility jacket, walk across the bridge instructing people to exit. They would walk across the bridge effectively pushing those walking in the same direction ahead of them. On reaching the far side they would close and lock the barriers and then turn and walk back doing the same with the remaining pedestrians until the bridge is clear and they can lock the other barriers. This may be necessary in this case if it is found that pedestrians do not reliably comply with audible instructions delivered remotely via a PA system.

The longer the opening section, or the longer the distance between the barriers at each end, the longer it takes to clear the bridge. Equally, if the bridge deck is very wide such that large numbers of pedestrians could gather there, and potentially pause to admire the view or watch events in the river below, the longer it would take to clear them off. These are among the most problematic issues for the operators of opening pedestrian bridges.

Typical adult walking speeds vary depending on a number of factors, with an average of about 1.4m/s. Thus, an average adult pedestrian, walking purposefully and not pausing to admire the view, would take a little over 2 minutes to walk the 180m length of the opening section. Allowing for slower walkers, the possibility of crowds, and the problem that people don't necessarily respond quickly to an instruction to clear the bridge, suggests that the time to clear the bridge of pedestrians may be typically about 4 or 5 minutes. This is a little longer than, but in broad agreement with, the assessment by Arcadis. [Ref. 11]

For most types of opening bridge, it is only safe to open it when all the pedestrians have cleared the opening span and are in a place of safety. Clearly this has to be the case for bascule bridges, but for some swing bridges and lifting bridges it may be possible for pedestrians to remain on the moving span while the bridge opens. Although this is technically possible, it would call into question a whole series of issues regarding safety, and it may be that the bridge would then fall under the very stringent safety rules governing the design and operation of fairground rides, for example. In any case, since the group of people stuck on the opening section would sometimes include some who would be very uncomfortable in such a scenario, I have assumed that this option is not being seriously considered.

5.1.2 Opening the bridge

The time it takes to clear the bridge of pedestrians is, of course, independent of the type of opening mechanism, but the time taken to open the bridge does depend on the type of opening mechanism as well as the length of the opening span. Rotational movements (for swing and bascule bridges) tend to be slower than linear movements (lifting bridges), and the greater the distance travelled by the moving section the longer it takes to open and close. This duration can be reduced by moving the span at a greater average speed, but this demands more power and also introduces greater inertia forces and other safety and structural concerns. There is thus a balance to be achieved between acceptable opening times and speeds.

In this case, the width of the opening span and the height of the navigation clearance are such that a vertical lifting span would take less time to clear the navigation envelope than a swing bridge or bascule which has further to travel. These are generalisations, but they arise from simply considering the distance travelled by the tip of the swing bridge or the bascule as against the deck of the lifting span. Given a 12m navigation clearance when closed and a 60m clearance when open, the maximum distance travelled by a vertical lifting bridge is about 48m. But given the required clear width of 180m, if the pivot for a swing bridge is set 5m back from the edge of the channel, the tip of the opening section has to travel through an arc length of about 150m and the mid point about 75m. Clearly the swing bridge would take longer to open unless it travels at a much faster speed. For comparison, in the case of a bascule bridge, with the fulcrum set back from the channel edge by about 3m and the span raising to about 5 degrees from the vertical position, the tip would travel through an arc of about 138m.

The assessments carried out by TfL suggest an opening time of between about 2.5 minutes in the case of a vertical lifting bridge and about 4 minutes for a swing bridge. Bascule bridges have not been considered to the same depth, but their opening time would be expected to be similar to the swing bridge. These durations include the time for closing the gates. The times for closing the bridge and opening the gates after the vessel(s) have passed are similar. These durations are in keeping with other large opening bridge times in my experience.

Of course an advantage of the vertical lift bridge, and to a certain extent the bascule bridge, is that it doesn't need to be opened fully to allow intermediate sized vessels to pass, and this would shorten the opening cycle time in those cases.

5.1.3 Passage of vessels

Finally, the time taken for the vessels to pass through the open bridge can also be relatively long, compared to the time taken to actually open it. Vessels, particularly large ones, tend to wait some distance away from the bridge and will only start to approach once the bridge is fully open and the navigation signals have changed to indicate that it is safe to proceed. Only relatively small or light vessels will wait close to the bridge. In the case of a swing bridge even these will have to wait far enough back to avoid the moving spans as they swing towards them.

Theoretically, vessels take longer to traverse through an open swing bridge than any other type, particularly if the leaves open in opposite directions as proposed by Arcadis, since they have to pass by the open bridge sections. But in practice most vessels will wait further back than this anyway and will travel well clear of the bridge before it starts to close.

The total time the bridge is open will also depend on the number of vessels wishing to pass, as they tend to do so one at a time. With such a wide opening, vessels passing in opposite directions may do so at the same time, except in the case of the very large ships.

Thus, it is not possible to quote a particular time delay to allow for the passage of vessels, as it depends on the number and size of vessels passing, but it could in some circumstances be anything up to about 10 minutes, and even longer for very large ships.

5.1.4 Total delay time for bridge users

So in summary, the total delay for a pedestrian or cyclist waiting to cross may be summarised as follows:

- Clearing the bridge: 4 to 5 minutes
- Opening the bridge: 2.5 to 4 minutes, depending on opening mechanism type.
- Passage of vessel(s): Assume 4 minutes, but could be much longer.
- Closing the bridge: 2.5 to 4 minutes, depending on opening mechanism type.
- Total delay to bridge users: 13 to 17 minutes depending on opening mechanism type.

A vertical lift bridge tends to enable a shorter opening cycle time than any other type, and the swing bridge tends to result in the longest. A vertical lift bridge also presents the opportunity to only lift it partially to allow intermediate height vessels to pass, thus further reducing the delay time.

5.2 Navigation issues

The Thames is a very busy navigable river, and this stretch witnesses the passage of large ocean-going ships which will need to pass through the bridge. In addition to the very large ships, there is a plethora of smaller craft, including large numbers of heavy barges and commercial vessels. It is of paramount importance to the PLA, and of course to the river users themselves, that not only should interruptions to vessel traffic be minimised but also that the risks of collision with the bridge or other vessels are acceptably low.

These factors tend to dictate the following all-important design parameters for the bridge:

- The width and headroom clearance of the navigation channel when the bridge is closed.
- The width and headroom clearance of the navigation channel when the bridge is open.
- The frequency of opening. (ie, how often it has to open to allow vessels to pass.)
- The opening sequence duration. (ie how long vessels have to wait before they can pass.)
- The clearance widths and heights in the approach spans.
- Any other features affecting safe passage of vessels, such as impact protection measures.

- Reliability in operation. ie. very low risk that the bridge will not open.

The currently stipulated clear height for the navigation channel in the bridge-open condition is 60m above MHWS. This corresponds to the clearance under the Emirates Cable Car downstream, although the QE II bridge at Dartford represents a lower constraint of 53.9m for any large vessel entering the Thames from the east. For comparison, the clearance at Tower Bridge just upstream is only 42.5m.

The PLA has stipulated that the clear width of the navigation channel through the bridge must be the width of the marked authorised channel plus a margin on each side. This margin is typically 15m, and the width of the authorised channel here is approximately 135m, meaning that a bridge crossing the channel at right angles should provide a clear width of about 165m. Figure 3, which is taken from the Atkins Concept Design Summary Report [Ref. 23], shows narrower margins of only about 5m suggesting that the PLA may have accepted a reduction in the margin they usually require resulting in an overall navigation clearance width of about 145m. Nevertheless, as already noted, the bridge crosses on a skewed alignment meaning the span will be longer in any case.

5.2.1 Opening frequency

The Arcadis Bridge Options Study [Ref. 8] contains a useful summary of the size and frequency of vessels predicted to be using this stretch of the Thames. This data shows that about 95% of them are low enough to be able to pass under the bridge without requiring it to open, assuming a vertical clear height of about 10m in the closed position. At the other end of the scale, the very large ships which will require the bridge to open fully, represent only about 0.05% of the total. In between are intermediate sized vessels, including several up to about 20m tall, which will require the bridge to open but not necessarily fully.

TfL's studies have evaluated the implications of different heights for the fixed bridge, which influences not only the bridge opening frequency but also the length of the approach ramps, among other things. The current recommendation which is summarised in the Atkins Concept Design Summary report [Ref. 23] is for a clear navigation envelope height of 12m above Mean High Water Springs (MHWS) over the central 40m width, and 9m each side for the remainder of the clear navigation channel width. With these fixed bridge height clearances, the bridge is expected to open on average about 5 or 6 times a day. This compares with about 4 times per day for Tower Bridge.

5.2.2 Split navigation channel option

The option of having a smaller secondary navigation channel alongside the main channel has been considered. This would allow a much smaller opening span to be used for the majority of vessels, involving shorter delays and lower operating costs, with the main opening span only being used for the largest vessels. Such as arrangement with a split navigation channel as been used successfully elsewhere, but the PLA have ruled it out for this location.

5.2.3 Vessel impact risk

Avoiding vessel impacts of any sort is of course of paramount importance. The size of the main navigation channel in both the closed and open condition is dictated by such considerations, as is the size of the smaller openings in the approach spans. Most vessel impacts with bridges occur if the vessel loses control, for whatever reason, or the pilot misjudges the channel width, the strength of the current, the crosswind or other factors. Such impacts tend to occur at the edges of the navigation channel, and it is rare for a vessel to veer a long way off line and hit one of the approach spans. A risk analysis is needed (and may already have been carried out) to examine the possible vessel trajectories and associated probabilities to determine what type of impact scenarios may be expected so as to design accordingly.

Vessel impact protection measures are being provided to protect the main bridge piers alongside the main channel, and it may be necessary to consider additional protection outside of these if the impact risk analysis shows there to be an unacceptably high risk of impact in the event of a vessel trajectory missing the main channel.

In the case of an opening bridge, the risk of a vessel impacting with the open section(s) needs to be considered as well as when the bridge is closed. A swing bridge or retractable bridge is more vulnerable to impact in the open condition than the other types, and this might demand additional impact protection measures for the open spans.

5.2.4 Reliability in operation

For a vessel waiting to pass through the bridge, it is vital that the bridge will in fact open upon demand. Any risk that some mechanism or power supply should fail and prevent the bridge from opening is considered entirely unacceptable to vessel operators, and therefore such risks must be minimised. The financial and other consequences of a large vessel being stuck the wrong side of the bridge can be unthinkable!

Conversely, if the bridge fails to close after the vessel has passed, there will be several angry pedestrians who will have to find a different way to cross the river, but the consequences and costs are not anything like so severe.

So, reliability in operation is a key factor. Features such as a back-up power supply tend to be essential, and all mechanical and electrical features of the operating system need to be carefully designed to minimise the risks that the bridge will not be able to open when needed. One particular feature which often gives trouble to operators of swing and bascule bridges is the locking pin or span lock at midspan. This is needed to join the two halves of the bridge together in the closed position and allow the transfer of shear across the joint so as to avoid a step at this point. Such pins or span locks have a habit of getting stuck and being difficult to withdraw to allow the bridge to open. Differential temperature, wind, fabrication tolerances and other factors can cause a misalignment of the two sides across the joint, leading to difficulties in operation. Such difficulties are not present in the case of the vertical lifting bridge which simply rests on its bearings and does not need a locking pin to hold it down because the counterweight is lighter than the span.

5.3 Construction method

It is probable that the construction method will involve lifting in large pre-fabricated sections which have been assembled elsewhere and brought to site by barge. This is certainly the case for the opening span sections which will need to be delivered as a single large piece and placed using a large floating crane or jack-up facilities on a large floating barge. Clearly, the weight of such sections needs to be minimised, which would tend to favour the swing or bascule options since they are shorter than the full main span length, but there are other considerations too. Most critical is the need to allow the normal passage of vessels in the navigation channel to resume as soon as possible after bridge installation.

For the vertical lifting bridge, the lifting span may be longer than the clear distance between the supporting towers, and much will depend upon the arrangement of the bearing supports at each end. If the fixed bearing plinths between the tower legs extend slightly beyond the face of the towers, then the span could potentially be lifted higher than the plinths and simply placed down on its bearings, whereupon the floating crane could be dismissed, allowing the channel to open again, at least for low headroom vessels. Then it is a relatively simple matter to attach the lifting gear so that the span could be lifted up to allow taller vessels to pass. In fact, because of the frequency of such taller vessels, it is probable that the contractor would elect to raise the bridge to an elevated position while the works are completed on the lifting span, its supports and operating equipment, so that progress is not regularly disrupted by having to stop while such vessels pass. With suitable detailing of the ends of the span and the bearing plinths, it would be possible to quickly hook up the winch gear and raise the span clear of the navigation clearance envelope and minimise disruption to river traffic.

For the swing bridge option, there are at least two periods of disruption to river traffic since there are two sections to install. However, they would almost certainly be installed in the open position using temporary or permanent piers to support the nose. This means that the floating crane could be released relatively quickly, as for the vertical lift option, and disruption to river traffic could be kept to a sensible minimum. The fitting of the slewing ring and the installation and commissioning of bearings, counterweights and other equipment requires careful precision and adjustment before the span can be operable. This all takes time, which is why the work would be carried out in the open position using the nose support.

For the bascule bridge option, there are also at least two sections to install requiring two periods of disruption to river traffic, and in this case the overall disruption would be greater. It is probable that the contractor would need to place a temporary support at midspan and seek permission to close one half of the channel for an extended period followed by the other half. In fact, considering the scale of the bridge, it is quite hard to envisage how this can be done safely as a single piece without an additional temporary support in the middle of the river. The trunnions need to be aligned, fitted and adjusted while the span is temporarily supported, and as with the swing bridge this is precision work. The span could not be held up in the vertical position for an extended period while this work is carried out. Smaller bascule spans are sometimes installed complete with the trunnions and counterweights already fitted, but it is hard to imagine how this could be possible in this case.

5.4 Environmental and social impacts

In all cases, the environmental and social impacts of the bridge need to be carefully considered. These include the visual impact of the bridge in the context of the wide river and city landscape, considering views from the river bank and adjacent buildings in particular, as well as more distant views. Those views need to consider both the closed and open positions of the bridge.

The most obvious visual features are the two 90m tall towers of the vertical lifting bridge. These need very careful treatment to achieve an acceptable aesthetic outcome, and it is good to see the quality of the preliminary designs already prepared by TfL's consultants in this respect. These are relatively slender and elegant in an environment where much bulkier tall buildings already dominate the skyline. When the main span lifts up it will be visible from some distance, and it too demands care to produce an elegant design, but at least when lifted up it does not tend to obstruct views across the river because most views will be below it.

A swing bridge remains at the same low level throughout, but when open it does create a temporary visual obstruction to views across the river.

By contrast, when the bascule bridge lifts up, the two open span sections create a significant blockage to the views, and they would be more than 100m high. This is always the problem with bascule bridges; when open they display their underbelly to the world, and they do not tend to look very beautiful. For those in the buildings alongside the river, the views across the river would be significantly impaired by such large bascule spans lifting up in front of them.

The environmental and ecological impact in the river is mainly a function of the number of piers and foundations in the water, including the vessel impact protection measures. There is no difference between the three types of operating system for the main supporting piers and vessel impact protection, but in the case of the swing bridge there will be two additional piers to support the tips of the spans in the open position, potentially together with additional vessel impact measures. In the case of the bascule bridge there may have to be one or more additional temporary supports during construction.

During operation, the main considerations concern avoiding any contamination of the watercourse with hydraulic oil or other contaminants. Thus the type of operating mechanism is important, and where hydraulic systems are used under high pressure they must be designed to contain any leaks that could arise.

One particular type of potential contamination risk affects only the bascule bridge option. This is the risk that debris and/or other contaminants on the bridge deck end up in the river when the bridge lifts up. Any loose objects or materials on the bridge deck will roll down into the water unless they are some how captured first.

5.5 Structural and mechanical considerations

In addition to the reliability of operation already mentioned, which places significant demands on the engineering design, the following factors also inform the selection of mechanism type.

5.5.1 Wind loading

Wind loading on the open bridge can be a very significant design parameter for the structure and the operating mechanism. For example, the wind on the open bascule spans would create very large forces on the structure and supporting equipment. The bridge will no doubt be designed to be relatively streamlined when in the closed position so that the effects of wind are minimised, but when lifted up as a vertical cantilever with the wind blowing onto the underside or topside of the span, the forces created can be very difficult to sustain. The main lifting mechanism is designed to lift the span against gravity, and wind on the topside of the span substantially increases this effect. But often more problematic is wind on the underside which tries to push the span right over past the vertical, and this creates very difficult challenges for the operating mechanism. This is quite possibly one of the main reasons why large bascule bridges of this scale have not been seen before.

Opening the swing bridge in a strong wind places extra demand on the operating system which has to either work harder to move the span through the wind or hold the span back, depending on the wind direction.

When the main span of the vertical lifting bridge is lifted up to its full clearance height of 60m, the wind forces on the towers can be considerable. But here at least the span is in its relatively streamlined position to keep wind drag to a minimum, and the wind forces are resisted by structure of the two tower legs and not by the mechanical operating system which is much less able to sustain them.

5.5.2 Locking pins and span locks

These have already been mentioned as a potential source of problems in the context of the unacceptable risk to vessels that the bridge may not be able open to let them pass. Most operators prefer to avoid such features because of the risks of malfunction, but on a bridge of this scale that would impossible in the case of the swing or bascule bridge options. Their design is complex, often involving high power hydraulic or electrical rams to drive home the locking device to connect the two halves of the bridge together in service.

For the vertical lifting bridge, however, the issue is a different one. There is no need for a locking device to hold the span down, assuming the counterweight is a little lighter then the span, which is what is currently proposed; the bridge simply lifts up off its bearings. However, with the bridge raised up, there is a need for some safety mechanism to prevent it from falling in the event of a mechanical or power failure. This can be done is a number of ways, such as by inserting supporting pins under the span at each end. These do not have to carry load, except in the event of a lifting gear failure, as they are merely there as a precaution, so they can easily be withdrawn when the time comes for the span to be lowered back down to the service position.

5.5.3 Tolerances

The operating systems in the swing and bascule bridge options are much more sensitive to problems of misalignment and require much tighter tolerances in the fabrication of the structural and mechanical components than the vertical lift option. This all tends to add complexity and cost to the bridge, as well as further risks to reliable operation. The simplicity of the vertical lifting mechanism is one of its great advantages.

5.5.4 Power requirements

The different operating mechanisms have different power requirements depending on the amount of counterweight provided and other factors. With the vertical lifting mechanism, the power requirement is effectively constant, and relatively modest if the counterweights at each end are approximately 95% of the weight of each half span. Similarly, with suitable sizing of the slewing mechanism, the power requirements for a reasonably balanced swing bridge are relatively modest, as there is no requirement to lift the mass of the bridge through a significant distance. However, the mechanism will have to deal with the inertia and braking forces and the effects of wind on the span, and these can lead to significantly higher power demands.

In the bascule bridge, the power demand can be governed by the effects of wind on the open span. The difficulty of accommodating a significant counterweight has already been mentioned because of the long span relative to the height above water, but even if such a counterweight could be provided the mechanical system and associated hydraulics will still need to handle large wind forces which can be additive to the forces generated by the weight and geometry of the system.

5.5.5 Future maintenance

The bridge will require regular routine maintenance, and periodically more significant interventions. Easy access to inspect and service the machinery will be important, and all mechanical components would be expected to require replacement at least once during the life of the bridge.

In both the swing bridge and bascule bridges, the machinery would be housed in a large chamber within the main supporting pier on each side of the channel. Some of this would be expected to be low down close to river level. For the vertical lifting bridge, there will be a similar but rather smaller chamber required in the base of the towers or just below deck level, but in addition, it will be necessary to have access up the towers to the sheaves and other equipment housed at the top.

Replacing the slewing system on the swing bridge or the trunnions on the bascule, for example would be extremely significant operations, and may require lifting the entire span out in the reverse of its installation procedure. This would inevitably result in significant loss of service and disruption to river traffic.

On the other hand, the winch gear and ropes on the vertical lifting bridge could be designed to be replaced one by one without significant loss of service either using temporary additional winch gear or by designing sufficient redundancy into the permanent system.

The steel structure of the main span, like the rest of the steel bridge, will require periodic re-painting. To gain access to the underside would require either a fixed scaffolding or a mobile travelling platform to reach all parts. With the lifting bridge and the swing bridge, this scaffolding can be fixed and will move with the span whether it be open or closed, but this is not an option for the bascule bridge. The scaffolding would result in an approximately 2m infringement of the navigation clearance envelope, requiring the bridge to open more frequently while the painting works are in progress. In the case of the lifting bridge, the likelihood of a vessel which could snag the scaffolding in the fully raised position is extremely low, but the work could be planned to avoid this if necessary.

6 Discussion of principal options

This section reviews the main operating mechanisms in the light of some of the principle factors discussed above which affect the decision about which mechanism to adopt.

6.1 Bascule bridge

It has already been pointed out that a bascule bridge here would be about twice the size of any other similar structure anywhere in the world, and there must therefore be significant questions to answer regarding its feasibility. Because of the need to function as a cantilever its appearance will be more bulky than the simply supported vertical lift bridge, added to which there will need to be a substantial counterweight which add further visual bulk.

The power required to lift such a span (an approximately 95m cantilever) without counterweight assistance, and the costs of operating such a system, would be prohibitive, so counterweights would certainly be required on a bridge of this scale. The size of the counterweight reduces as its distance from the fulcrum increases. However, as the bridge span rotates upwards so the counterweight moves downwards, and the design must ensure that it does not touch the water. This presents a significant challenge for a bridge which is only 12m above water level but has a cantilevering bascule span of 95m. For this project, a counterweight that swings only below deck level is unlikely to be suitable, so it would need to be held above the deck level, perhaps on backward-leaning masts. The physical size of the counterweights and their supporting masts would become very large, given the scale of the opening span. Such a concept has been illustrated in some of the TfL reports, and in the Sustrans report [Ref.2], although in that case the slenderness of the elements for a bascule bridge of this scale appears unrealistic.

In the open position the visual impact of the open leaves can be very unsightly. These would be extremely long (over 100m) and the wind load on these would be very high, dominating the design of the mechanical operating systems.

All double bascule bridges face the challenges of nose alignment when opening and closing. The combined effects of fabrication tolerances, differential temperature and wind can lead to difficulties of aligning the locking pins or span locks at midspan, which in turn increases the risk that the span may not be able to open in some circumstances, or that opening the span may be delayed.

During construction, temporary supports are required for the span while the trunnion bearings and all the operating equipment and mechanical items are properly installed and aligned. This adds time and extends the period of disruption to river traffic.

The opening cycle time tends to be longer than for the vertical lifting bridge.

6.2 Swing bridge

The swing bridge also serves as two cantilevers, and would therefore appear relatively bulky, but at least in this case they don't have to be lifted up into the air. They do, however, need to swing through about 90 degrees, in which position they would present a significant visual obstruction to views across the river. Depending on the length of the back span containing the counterweight to balance the roughly 95m long main span, these two sections could each be about 110m or 120m long.

Swing bridges are always problematic in situations where they cross water used by many boats and vessels. They are more suitable in locations where they do not cross over busy waterways. In swinging through their opening arc, they effectively "sterilise" an area of water that cannot be used by vessels as a result. There can be no moorings there and boats should not occupy those areas where the bridge can open above them. Furthermore, the open bridge deck remains vulnerable to impact from large vessels, and a long span swing bridge such as in this case would need an additional support in the river to support the nose in the open position.

The extra ship impact protection structures around the open span will add considerable extra visual clutter and cost. The large tidal range in the Thames creates a challenge for the design of the vessel impact structures. The appearance of the bridge piers also needs to be considered at high and low tide, but these have a function which makes them legible and logical in both conditions, making it easier to achieve a satisfactory aesthetic outcome. Stand-alone vessel impact structures can be much more challenging to design as they tend to look very intrusive and ugly at low tide. This is why floating systems are often used where possible, but the design impact forces in this case may rule out that option.

The swing bridge experiences similar difficulties to the bascule bridge regarding alignment of the locking pins or span locks at midspan, although not quite so severely. Adjustments need to be built in to allow for re-alignment if necessary after some time in service.

Construction can be carried out with relatively little disruption to shipping as the spans can be installed in the open position where all the necessary adjustment and commissioning of the operating machinery can be done. Then, when ready, the spans can be swung into position across the channel and final commissioning adjustments carried out.

This type of bridge has the advantage of precedent at this scale, although not for a footbridge. But the need for an elegant design is of paramount importance in this location, and this would lead to a very different type of structure to those already in existence.

The opening cycle time is probably the longest of the three types considered.

6.3 Vertical lifting bridge

There is no doubt that the operating mechanism for the vertical lifting bridge is the simplest and most reliable. The bridge is always behaving the same way as a simply supported beam and the lifting equipment simply lifts the bridge up and controls its descent under gravity assisted by a counterweight.

There are precedents for this type of bridge at a similar scale, although as a pedestrian bridge in this location this will demand a more slender and elegant design than those. The lifting span could be designed either as a slender tied arch or as a truss, and I believe that further work is needed to optimise the design in this respect. Figure 11 shows a tied arch design which has the greatest potential in my view for a pleasing aesthetic outcome.

The towers are the most obvious visible element of the design and demand very careful treatment in the design. They will be visible from some considerable distance and provide the opportunity to create a clear landmark structure as the gateway to London. They also act as way markers, showing the way to the place where you can cross the river for approaching pedestrians and cyclists. Their visual intrusion is subtly different to that of the open bascule spans, not least because they will be shorter. The tower design will be substantially concerned with their appearance as vertical elements and their ability to carry vertical load and wind load. This is their primary function and this is what they will be designed for. Whereas the bascule bridge decks will primarily be designed for their service function as a horizontal bridge deck which tends to be at odds with the visual demands of a vertical supporting element.

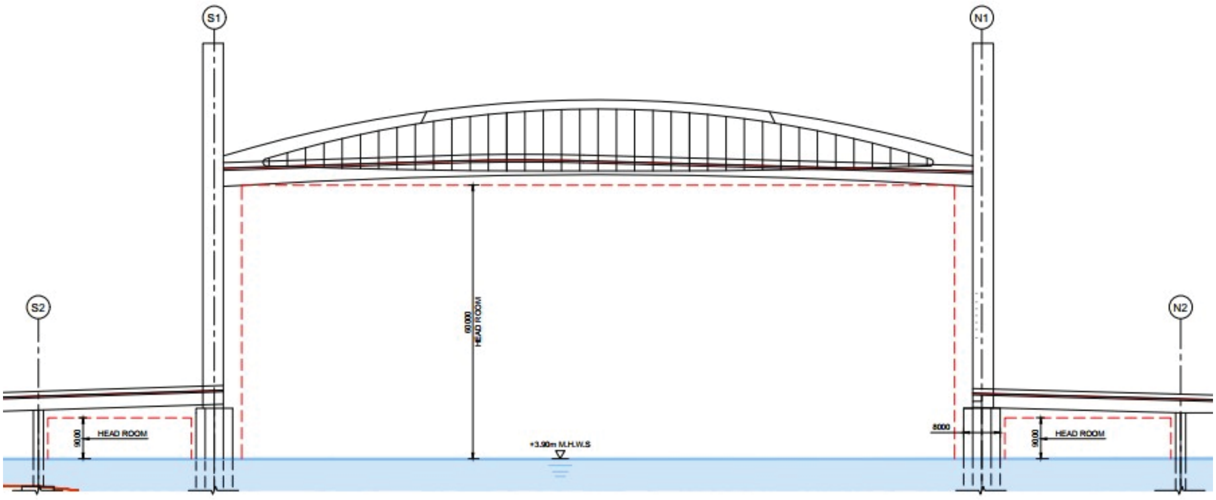

Figure 11 *Elevation of the proposed lifting bridge, as a tied arch, in the open position. [From Ref 18.]*

Construction requires placing the main span by floating crane in a single operation during which the navigation channel will need to be closed for several hours. But once installed it can be lifted up out of the way for any final adjustments and commissioning works, although these are nothing like as complex or time-consuming as the bascule and swing options.

Replacement of mechanical equipment can be relatively straightforward in this case, without the need for extensive disruption to bridge or river users. The system can be designed with sufficient redundancy to enable components to be replaced one at a time while still in service, using temporary lifting gear if necessary. This would be a considerable advantage to the bridge operator and demands further investigation to ensure the necessary requirements are included in the detailed design specification.

The bridge does not require locking pins to hold it down. For this and other reasons, this option presents the lowest risk that the bridge would not be able to open on demand and thus the least risk to shipping disruption.

The lifting bridge is expected to have the shortest opening cycle time and has the distinct added advantage that it does not need to be opened fully to allow intermediate sized vessels to pass. I would expect the bridge to have three or four vertical lift positions, for example providing clearance heights of 20, 30, 40 and 60 metres, and for the majority of vessels it would need to be lifted to the 20m or 30m levels. It would be a rare occurrence that it would need to go to the full 60m height. This further reduces typical cycle times and costs in operation.

6.4 Other opening mechanisms

The only other type of solution which might conceivably have been feasible at this site is the retractable bridge, as described in Section 3.4. This option would demand two long cantilevers, similar in scale to the swing or bascule bridges, and would possess all the same problems with the locking systems at the midspan joint. Although the moving spans would not necessarily need counterweights, they would require an additional length of moving girder to act as the back span to support the cantilevers as they roll forwards and backwards. Furthermore, the spans would need to run on rails which would themselves need to be supported at regular intervals, requiring additional piers in the river to support the spans in the open position. This all adds to the cost of this option. In addition, in the open position, the spans may block the approach spans, thus preventing small craft from using them, and would remain vulnerable to potential vessel impacts. For these reasons, this type of option is not preferred for this location.

6.5 Summary table

Table 2 presents a brief summary, in qualitative terms of some of the main factors influencing the choice of the three main operating systems considered in this report. A green dot represents the best option and a red dot represents the worst.

Decision Factor	Vertical Lift	Swing	Bascule
Opening cycle time	🟢	🔴	🟡
Simplicity of operating mechanisms	🟢	🟡	🔴
Risk of failure to open to navigation	🟢	🟡	🔴
Vessel impact protection requirements	🟢	🔴	🟡
Precedent at this scale	🟡	🟢	🔴
Navigation delay during installation of span(s)	🟡	🟢	🔴
Replacement of operating equipment in service	🟢	🟡	🔴
Other long term maintenance considerations	🟢	🟡	🔴

Table 2 Operating mechanism comparison summary table

I have deliberately omitted the visual impact and aesthetic arguments from the table as these are so subjective. In my view the visual impact of the bascule and swing bridges, particularly in the open position, would be significant and hard to manage successfully. The depth of the cantilevers, the scale of the counterweights and the size of the supporting piers containing the operating machinery all contribute to it being very difficult to achieve an acceptable appearance. The extra piers and vessel impact measures in the water for the swing bridge creates further problems. Whereas the vertical lifting bridge, although very significant and visible in the landscape, can be designed to achieve a much more satisfactory overall composition. Others may disagree, but in the right hands I am convinced that the design will be really elegant. However, it will be important that the procurement process is specifically targeted towards achieving high quality in the design, and does not merely reward lowest cost proposals, and this is true for whatever system and type of bridge is adopted.

From this very generally summary of these key issues, the vertical lifting bridge appears to be the preferred option. This agrees with the findings of the more rigorous and thorough evaluations carried out by TfL to date.

7 Other observations

In passing, while considering the specific issue of the operating mechanism in response to the brief for this review set by TfL, I have made some other observations which I offer here as items for consideration. These are given in Appendix B.

8 Conclusion

The proposed Rotherhithe to Canary Wharf crossing presents a unique challenge for the design of an opening bridge. The large main span for the bridge, required for navigation reasons, means that this will be among the longest opening bridges in the world, and by far the longest opening pedestrian bridge. Only vertical lift bridges and swing bridges exist at this scale, and the TfL studies have understandably concentrated on these forms for this project. Bascule systems and other forms of opening mechanism are considered too risky at this scale. I have considered the possibility of a large double bascule solution, but everything points to this being the least preferred option.

An evaluation of the relative merits and challenges of vertical lift and swing bridge types leads to the conclusion that the vertical lift option presents the fewest risks and the greatest benefits and is therefore the preferred design solution in this case.

The main advantages of a simple vertical lifting system can be summarised as follows:

- Shortest opening cycle time, so fewest delays to bridge users
- Doesn't have to be opened fully every time, but can be opened partially for intermediate height vessels, further reducing delay times.
- Has the simplest operating mechanism.
- Avoids the need for span locks or locking pins at midspan which often cause difficulties and can prevent the bridge from opening, creating unacceptable risks to shipping.
- Most efficient structural system - moving span behaves the same under all conditions.
- Maintenance works can be carried out with minimal disruption to bridge or river users, including the incremental replacement of the operating machinery.

The main challenges to be addressed in the detailed design of the vertical lifting bridge include achieving an elegant and visually acceptable appearance for the two supporting towers. In addition, a failure mode analysis needs to be carried out consider the behaviour in the event of critical system or component failure. This would be required for any of the possible operating systems but is potentially more critical in the case of a vertical lifting bridge because the consequences of catastrophic failure could be greater.

9 Recommendations

It is recommended that the following aspects are included in the ongoing investigations as the design develops through the next stages.

- Failure mode analysis to review the consequences and likelihood of various potential component or system malfunctions.
- Analysis of views of the bridge in the open and closed positions from key vantage points near and far from the site to inform the refinement of the bridge appearance in all conditions, day and night.
- Optimise the design of the lifting span for minimum weight and elegant appearance, considering the benefits of the tied arch vs. the truss type, and also examining the possibility of using modern lightweight and low maintenance materials such as aluminium or polymer composites in place of structural steel.
- Develop the principles and design features associated with enabling replaceability of the lifting bridge mechanical components while minimising loss of service.

10 References

The following documents (numbered 1 to 24) were received from TfL and have formed the basis for this review:

1 Sustrans Thames Bridge Feasibility Study. Ramboll/Whitby Bird report 4920.4.03.T.6B, March 2008

2 Sustrans Thames Cycle Bridge Chapter 3 Site Parameters and Constraints v002, November 2015

3 Mechanical Considerations. Arcadis Technical Note UA009638-ARC-MEM-000035, August 2017

4 Notable examples of movable bridges of different types. Arcadis Technical Note UA009638-ARC-MEM-000048, August 2017

5 Opening times. Arcadis Technical Note UA009638-ARC-MEM-00007, September 2017

6 Options Report Draft 1 - 5 Opening mechanism. Arcadis & Knight Architects Draft Report ST PJ585C-ARC-BAS-ZZ-REP-ZZ-21001 170905, September 2017

7 Bridge Typology. Arcadis Technical Note UA009638-ARC-MEM-000016, October 2017

8 Bridge Options Study. Arcadis & Knight Architects Report ST PJ585C-ARC-BAS-ZZ-REP-ZZ-100008, November 2017

9 Options Study Appendix E. Appendix to Arcadis & Knight Architects report, November 2017

10 Construction Methodology. Arcadis draft report ST_PJ585C-ARC-BAS-ZZ-REP-CE-100015 Rev 00.005, January 2018

11 Revised Bridge Opening Cycle Times. Arcadis Technical Note UA009683-ARC-MEM-000062, January? 2018

12 Construction Report. Arcadis draft report ST_PJ585C-ARC-BAS-ZZ-REP-CE-100015 Rev 00.v08, February 2018

13 Options Development. Arcadis Technical Note UA009638-ARC-MEM-000083, February 2018

14 Bridge Feasibility Report. Arcadis & Knight Architects report ST_PJ585C-ARC-BAS-ZZ-REP-CE-100014, February 2018

15 Opening Type. Atkins Technical Note. 5162977-45-0087 P01, April 2018

16 TfL Alignment and Mechanism Option Decision Workshop Record (version 3), June 2018

17 APPENDIX 3 Opening Mechanism preferences v1, June 2018

18 Opening Mechanism Option Selection. Atkins report ST_PJ585C-ATK-MEC-ZZ_21-REP-ME-00001 P01, July 2018

19 Main Span Structures Approval in Principle Atkins report ST_PJ585C-ATK-BAS-ZZ_09-REP-ST-00001 P01, October 2018

20 Draft M&E Approval in Principle Atkins report ST_PJ585C-ATK-MEC-ZZ_12-REP-ME-00001 P01, October 2018

21 Factsheet 2 - Option process and alternatives KM 24 10 18, October 2018

22 Factsheet 3 Preferred Bridge Design KM 23 10 18, October? 2018

23 Draft Concept Design Summary Report Atkins & Knight Architects Report ST_PJ585C-ATK-ZZZ-ZZ_12-REP-ZZ-00001 P01, November 2018

24 Opening Mechanism Option Selection Report - Comment Sheet, December 2018

The following additional documents have been referred to in preparing this report:

27 ICE Moveable Bridge Design (ISBN 978-0-7227-5804-01)

28 Sustrans Design Manual – Bridges and other structures (February 2015)

Appendix A

BRIEF FOR INDEPENDENT ADVISORY SERVICES

BRIEF FOR INDEPENDENT ADVISORY SERVICES FOR ROTHERHITHE TO CANARY WHARF CROSSING

OPENING BRIDGE MECHANISMS

Background

Transport for London (TfL) has been investigating the feasibility of providing a new walking and cycling crossing of the River Thames between Rotherhithe and Canary Wharf.

This project is one of a number of proposed new river crossings for London which are intended to improve cross-river connectivity. These proposed crossings would consist of new public transport, vehicular, pedestrian and cycle links.

The forecast continuation of a combination of strong growth in cycling across London, employment growth in Canary Wharf, and population growth due to new residential and mixed use development, particularly at Canada Water are generating an increase in travel trips including walking and cycle demand in the area. Both of these areas are designated Opportunity Areas (OA) identified the London Plan. With the Jubilee line operating at close to capacity at peak times and a lack of appropriate or sufficient infrastructure to accommodate cyclists and pedestrians wishing to cross the river east of Tower Bridge to access Canary Wharf, there is a case for considering the delivery of a new river crossing to cater for this demand, whilst also providing an alternative to the London Underground for shorter journeys.

A number of project objectives were identified, including:

- To connect the two OAs of Canada Water and the Isle of Dogs
- To improve connectivity from the Rotherhithe peninsula, particularly the area beyond the walking catchment of Canada Water station
- To encourage more people to cycle and walk in the area
- To provide additional capacity and routes for cyclists as an alternative option to existing crossings in the area
- To produce a well designed and convenient link which achieves value for money and is fundable
- To provide an alternative link to the Jubilee Line between Canada Water and Canary Wharf.
- To maintain navigation rights on the River Thames.
- Following a thorough assessment process and extensive stakeholder engagement, a 12m high (from MHWS) vertical lifting bridge was selected as the provisionally preferred option to meet these objectives, with the southern access to the bridge located at Durand's Wharf. On the northern bank of the river, the crossing would tie in to the existing highway network at Westferry Circus.

Outline question

The Rotherhithe to Canary Wharf Crossing team (part of TfL Surface Transport) has completed their assessment of the different opening bridge mechanisms which may be used in the design of a bridge for the crossing.

The team are continuing work to develop this option, including testing assumptions and assuring provisional decisions. As such, the team is seeking an independent review of the decision relating to the selection of a preferred opening mechanism for a navigable bridge at this location. The reviewer(s) will be provided with a number of reports, technical notes and other records supporting the decision making process.

TfL are seeking powers to construct the crossing through a Transport and Works Act Order (TWAO). The decision making process will be a key focus at inquiry stage, so ensuring that the decision making processes are robust will ensure the application is as strong as it can be and have the best chance of success. TfL would like the outcome of the review to be presented in a report from the reviewer(s) which will inform our development of this option, and as part of our decision making process the report is therefore likely to be scrutinised during the TWAO process.

Due to the high profile nature of the project, the team requests further independent assurance.

Specifically the team requests a review of the following question:

- Has TfL appropriately considered different mechanism options and chosen the most appropriate for this scheme?

together with any other issues you may identify.

The purpose of the ICE Panel review is to provide independent assurance of the assessment and decision reached and, where issues are identified, they should be articulated with an assessment of their severity.

Attachments, all in draft:

Document File Reference	Purpose
ICE Review of Bridge Mechanism – Context and Project Update	Introductory slide presentation for background, context and current/future progress
2008_Sustrans.Thames.Bridge.Tech.Feasibility	Earlier feasibility report examining the provision of a bridge between Rotherhithe and Canary Wharf examining the various types of moving bridges and concluding a concept of a lifting bridge in a central location.
Sustrans Thames Cycle Bridge Chapter3 Site Parameters and Constraints v002	Sustrans feasibility report for a cycle and footway crossing between Rotherhithe and Canary Wharf in a central location, various opening mechanisms explored but report does not state a preferred solution.
UA009638-ARC-MEM-0007 Opening Times	Initial assessment for opening durations (bridge opening cycle times).
UA009638-ARC-MEM-00016 Bridge Typology	Arcadis early assessment of moving bridge typologies.
UA009638-ARC-MEM-00035 Mechanical Considerations	Technical considerations for moving bridges.
UA009638-ARC-MEM-00048 Notable examples of movable bridges of different types	A technical note on bridge typologies to inform the project and seek out likely precedents.
UA009638-ARC-MEM-00082 – Options Development	Brief outline of the various designs considered for the Bridge Feasibility Report.

Document File Reference	Purpose
UA009638-ARC-MEM-00062 Revised Bridge Opening Cycle Times	Revised bridge opening cycle times to reflect the maturity of the concepts in the Bridge Feasibility Report.
ST_PJ585C-ARC-BAS-ZZ-REP-ZZ-100008_Bridge Options Study	Arcadis Bridge Option study report; the precursor to the Feasibility study and report.
Options Study Appendix E	Arcadis Bridge Option Study Appendix E: Bridge Mechanism
ST_PJ585C-ARC-BAS-ZZ-REP-ZZ-21001_170905_Options Report Draft 1 – 5 Opening Mechanism	Early Arcadis draft, considering suitable opening mechanisms for further design, to inform the Bridge Feasibility Report. (the draft work in progress prior to writing Appendix E above)
ST_PJ585C-ARC-BAS-ZZ-REP-ZZ-1000014_Bridge Feasibility Report 01	Arcadis Bridge Feasibility Report produced to enable a greater understanding of a moveable bridge at the shortlisted locations.
ST_PJ585C-ARC-BAS-ZZ-REP-ZZ-1000015_Construction Methodology Report 00.V05	Construction report to aid pricing and check “buildability” of the options in the Bridge Feasibility Report.
ST_PJ585C-ARC-BAS-ZZ-REP-ZZ-1000015 Construction Report 00.V08	Construction report to aid pricing and check “buildability” of the options in the Bridge Feasibility Report.
5162977-45-0087 P01 Opening Type Technical Note	Atkins technical paper summarising the previous work by Arcadis and concluding the need for a separate multi-criteria study to reach a decision on bridge opening mechanism.
18-08-07 ST_PJ585C-ATK-MEC-ZZ_21-REP-ME-00001 P01 Opening Mechanism Option Selection Report	Atkins bridge option report concluding the preferred option of a lifting bridge. The option report is independent of location.
2018-09-12-Opening Mechanism Option Selection Report-Comment Sheet	TfL comments on the Atkins bridge option report and Atkins planned responses. The responses are to be incorporated into the next iteration of the Atkins bridge option report as part of the final Concept Design Report.
Alignment and Mechanism Option Decision Workshop Record (version 3)	Draft notes of Option Decision Workshop. To be re-drafted in support of TWAO application.
APPENDIX 3 Opening Mechanism preferences v1	Draft multi-criteria matrix for bridge opening mechanism. To undergo a “back-check” before being incorporated into the TWAO application.
ST_PJ585C-ATK-ZZZ-ZZ_12-REP-ZZ-0001 P01 DRAFT Concept Design Summary Report (compressed)	Atkins early concept design summary report.
Factsheet 2 – Option process and alternatives KM 24 10 18	Draft text for the abandoned second public consultation on the crossing selection process. Text intended for lay persons and provided by TfL communications.
Factsheet 3 Preferred Bridge Design KM 23 10 18	Draft text for the abandoned second public consultation on the bridge design. Text intended for lay persons and provided by TfL communications.

Document File Reference	Purpose
ST_PJ585C-ATK-BAS-ZZ_09-REP-ST-0001_P01_DRAFT Structures_Mainspan AIP	Draft Main span (including towers) Approval in Principle document.
ST_PJ585C-ATK-MEC-ZZ_12-REP-ME-0001_P01_DRAFT M&E AIP	Draft Mechanical and Electrical Approval in Principle document for the lifting span.

Appendix B

OTHER OBSERVATIONS NOT RELATED TO THE OPENING MECHANISM

OTHER OBSERVATIONS NOT RELATED TO THE OPENING MECHANISM

In passing, while considering the specific issue of the operating mechanism in response to the brief for this review set by TfL, I have made some other observations which I offer here as items for consideration.

Opening span structure

The opening span illustrated in the final Arcadis report [Ref. 18] is an elegant and slender tied arch structure. However, the latest design described in the Atkins Concept Design Stage report [Ref. 23] is a Pratt truss design. The Atkins report gives a short explanation for this change in section 11.3 of their report and illustrates the two designs in Figure 11.7 which is repeated below. (Figure B1) However, I am not convinced that their arguments are sufficient justification for the change which in my view loses much of the elegance of the original without gaining significant benefit. I am concerned that the truss elements would appear too heavy, particularly in oblique view for bridge users looking along the line of the bridge. However, it is also acknowledged that the visual bulk of the ends of the arch option also seems high in the top image, and perhaps this could be reduced to achieve a less obtrusive appearance if the arch solution is developed.

Figure B1 *Comparison of tied arch and truss designs. [From Ref 23.]*

I note that Knight Architects, one of the world's leading bridge architects, are named as part of the team in both cases. I would hope that they continue to be involved and that their influence remains strong as the design develops through its next stages with the view to achieving a high aesthetic quality in the finished bridge.

Wind loading on the open bridge will be a significant design factor for the towers, as already noted, and it should be possible to achieve greater slenderness and transparency in the tied arch so as to minimise wind drag effects.

Plan alignment

The approaches on the Canary Wharf side run along the edge of the river because of the need to connect with Westferry Circus, and meet the bridge in a relatively sharp bend. This means that users can enjoy changing views of the bridge as they approach the main span. There is potentially scope to refine and sweeten the plan alignment even more, particularly in relation to the proximity of the adjacent buildings, and also avoid making the bend radius too tight.

On the opposite side, the western approach spans are currently shown as being in a straight line with the main span. This is a missed opportunity, and even a very slight change in direction at the western end of the main span would improve user experience markedly. Moving Pier S1 northwards slightly (which may mean a change to the foundation layout to avoid the Jubilee Line tunnel exclusion zone) and/or moving the curved ramp in Durand's Wharf slightly southwards, would introduce a small change in direction to allow users to see the bridge, at least in a shallow oblique view as they approach it.

Opening span material

Most opening bridges are in steel, mainly to reduce the weight of the opening section(s), and it is no surprise that the designs in this case have all concentrated on steel solutions. However, consideration could also be given to the possible use of modern polymer composites, aluminium and/or other lightweight materials as an alternative. The cost, understanding, performance and reliability of such materials are all improving, and there are many bridges built in these materials already. There is no doubt that the use of such materials will continue to increase in future bridge structures.

There are several benefits that follow from the lighter weight of the opening structure(s), not least the reduction in operating power requirements and the ease of installation. The (currently) slightly higher initial material costs tend to be offset by savings in the supporting foundations and operating machinery, and in the costs of installation. In addition, these materials also tend to be relatively maintenance free as they require no painting to prevent corrosion, further reducing long term operating costs.

Shelters

Pedestrians and cyclists waiting to cross the river when the bridge opens may find themselves waiting for 10 – 15 minutes or even more. This would not be pleasant in cold, wet, windy conditions. A shelter at each end of the bridge, designed as an integral part of the overall composition and not added as an afterthought (which may otherwise happen) could be seen as a considerable improvement. These shelters could be accommodated in the widened areas immediately alongside the towers.

Design freedom for contractors

Assuming the bridge will eventually be procured through a design-and-build type of construction contract, it will be important to consider to what extent the design should be fixed before inviting tenders. Clearly the all-important navigation clearances and minimum bridge widths must be defined, and no doubt the alignment and overall dimensions of the structure will need to fixed within relatively narrow margins, but some flexibility in the design is needed to give the contractors scope to devise competitive solutions.

One option might be to allow relatively wide freedom of design expression, but to require the contractors to present their early ideas at a mid-tender interview. At that point, TfL and their consultants can provide feedback and comment on the acceptability or otherwise of the contractor's proposals before they are then developed into their final tender submission. This works well, and generally leads to appropriate, economic and elegant final solutions.