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Teaching First Year Engineering Design and Design Criteria—The Thames Barrier*

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The Thames Barrier is an iconic engineering structure protecting London from dangerous storm surges that might otherwise flood the city. Built in the 1970s, engineers considered many different designs before settling on the final one featuring six rising sector gates and four falling radial gates. The design of the Barrier and the many different design iterations that the engineers went through in response to the changing requirements of the client provide an excellent context within which to teach first year general engineering students design and design criteria in an introductory context. The design process of the Thames Barrier has been used as a case study in a general first year engineering subject at the University of Melbourne for several years. This paper describes several of the original designs proposed to close the Thames before the final design was developed. A detailed description of the Thames Barrier as built is given before the application of the case study to the classroom is discussed. An analysis of 226 concept maps prepared by the class 10 weeks after the material was delivered provides an insight into how the students integrated and retained the material from the case study.

Keywords: engineering education; design; first year; Thames Barrier; concept mapping

1. Introduction—the need for a barrier

Before human settlement the land surrounding the Thames as far upstream as present-day Richmond was very marshy, prone to constant flooding. The Thames is a tidal river rising and falling twice a day with the tide. Today with its banks clearly defined by wharves and walls the river rises and falls by as much as 6½ m twice a day at London Bridge. Before settlement the changing tide levels would not have been so significant, as the surrounding land would have been inundated twice a day, relieving the river of its torrent of water.

With the establishment of a permanent settlement and later the development of a coastal trade the river banks began to become more defined. The construction of the original London Bridge was accompanied by the development of wharves immediately downstream of the bridge. As only the smallest of boats could pass up through the piers of this first London Bridge the coastal traders that initiated London's maritime trade demanded the construction of more wharves and jetties along the river banks. The settlement that sprang up behind the wharves needed protection from the flooding waters of the river tides and so embankments were constructed still further down the river. Behind these wharves and embankments the once marshy land began to dry out causing the ground to subside. With the land now lower than the river, any breach of the river walls or embankments would be devastating to the community.

The Thames estuary has always been prone to flooding by storm surges. Most North Atlantic storms pass to the north of Scotland and make landfall somewhere along the Norwegian coast, causing water to surge up the many fjords along the coast. As the water rushes along the ever-narrowing inlets of the fjords the water rises ever higher until surging with ferocity at the end of the fjord. Depending on the weather patterns accompanying these North Atlantic storms, some of them do swing south into the North Sea between the British Isles and the European mainland. The surges accompanying these storms often channel further south towards the English Channel and the mouth of the Thames.

Over the years London has been flooded by many storm surges that have swept up the Thames from the North Sea. Should the arrival of a storm surge coincide with high tide in the river, or even worse a king tide when the high tide is at its highest, then the flood could be devastating. The diarist Samuel Pepys recorded one such flood in London in December 1663 in which the settlement was inundated [1]. Careful records of flood heights in London have been kept since 1750. Figure 1 presents the record flood heights in the Thames recorded at London Bridge since 1750 [1–3]. The first record was set in 1791 when a flood height of 4.2 m was observed. It was not until 1834 when this record was surpassed with a flood height of 4.5 m. Since that time, and until 1953, new record heights have been observed easily surpassing the earlier records. Here students

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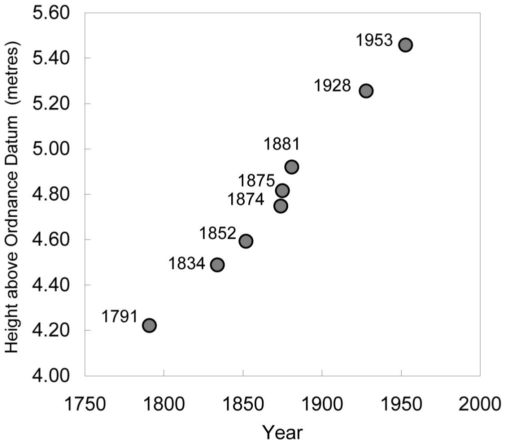


Fig. 1. Record flood heights recorded at London Bridge (Gilbert and Harmer [1]).

might be asked to consider the reasons why the record flood heights appear to be increasing almost linearly with time over the last two hundred and fifty years.

The three factors which contribute to the steady increase in the record heights are believed to be:

1. the increase in the mean sea level worldwide due to factors including global warming;
2. the gradual sinking of the south-east corner of England due to the movements of tectonic plates;
3. continued development of the river and sea walls to prevent flooding of low-lying areas either side of the river. It is perhaps ironic that the construction of river walls and embankments downstream of London to protect local communities actually increases the dangers upstream by confining the river's flow to an ever-narrowing path. It is this third factor that contributes most to the increase in record flood heights observed in the Thames.

On 31 January 1953 a huge storm swept down through the North Sea generating storm surges that swept the English and Dutch coasts. Over 4000 people lost their lives in the floods in Holland while the storm claimed 300 people in south-east England. The aftermath of the flooding led to the establishment of several government enquiries on storm surge protection. The first of several of these enquiries recommended the construction of some form of flood protection scheme across the Thames somewhere between its mouth and the city of London. The authorities realized how many people lived and worked within the flood zones surrounding the Thames (Fig. 2). Authorization for the construction of some form of flood defense system was granted by the British Government in the mid-1960's and detailed design work then began.

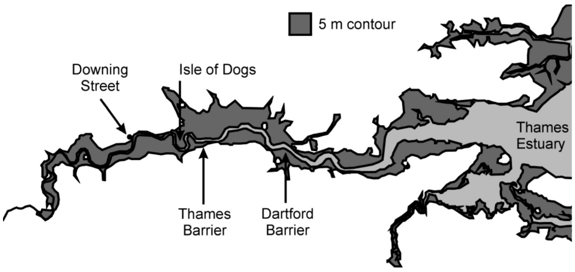


Fig. 2. Flood zones of the Thames river and estuary.

2. 1954 Design criteria proposals

In 1954 the various arms of government came together to develop a series of design criteria for the design of any form of Barrier to be built across the Thames River as part of a flood defense system [2]. London has always been one of the world's great centres for maritime trade. Nineteenth century engineers built networks of impounded water docks on the Thames in which the water level remained constant even when the tides in the river ebbed and flowed. With the massive investment in shipping infrastructure in and around the Isles of Dogs area of London, the Port of London Authority was reluctant to permit the construction of any Barrier that might restrict the free movement of ships to and from these docks.

Agreement between the various government instrumentalities including the Port of London Authority on the design criteria to be used for the design of a Barrier that might be built across the Thames to seal off the river in the event of a flood or storm surge. The design criteria, simplified for use with first year engineering students are:

- when open the Barrier should not interfere with the free movement of river traffic;
- the Barrier should be able to close within 30 minutes of the close decision being taken;
- the Barrier should be able to be closed even if a small obstruction (e.g. a small sunken boat) is in the way;
- disruption to the free flow of river traffic should be minimized during the construction process, and during the construction process there should be no period of longer than 24 hours in which the river is required to be completely closed to traffic;
- the Barrier mechanisms must be relatively easy to maintain and service;
- the finished structure should be visually-acceptable;
- the design should incorporate two navigable channels 152½ m (500 ft) wide and two channels 76¼ m (250 ft) wide.

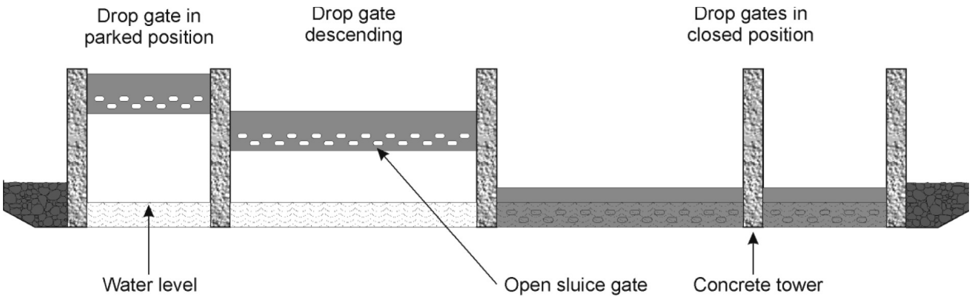


Fig. 3. A four sector drop gate Barrier proposed in response to the 1954 design criteria. The gates are shown in various stages of descent. In actual operation the gates would be raised or lowered together.

The intended location for the Barrier was a point along the river at Long Reach.

In response to this design challenge teams of engineers working for several organizations began developing their ideas based upon adapting existing technology [1, 2, 4]. The three main competing designs that emerged were all vastly different but yet satisfied the design criteria.

2.1 The four sector drop gate

One design made use of four massive drop gates that in normal times would have been suspended above the river, hung from five high towers [1, 2, 4]. The gates would have been high enough to permit normal river traffic to pass unimpeded beneath them. When they were needed to seal off the river they would descend down the towers to rest on a giant concrete sill that would have been in place on the river bed. Each gate would have included a number of sluice gates which would have been open while the gates were being raised or lowered through the water. These smaller sluice gates would have helped relieve the pressure on gates as they were near the fully closed position. Once in place the sluice gates would have been closed fully sealing the gates. Figure 3 shows the gates at various stages of operation. In reality the gates would have moved up and down together.

Precision in lowering the gates would have been essential. If one of the gates had moved out of precise horizontal alignment while being lowered it could have jammed, rendering the entire structure ineffective. In the open position, the structure had the potential to be an eyesore detracting from its surroundings. An advantage of the design was the fact that all the equipment needed to raise and lower the gates was in the towers above the water. Any small obstruction resting on the concrete sill would not have prevented the massive gates from closing.

2.2 Low level retractable drop gates

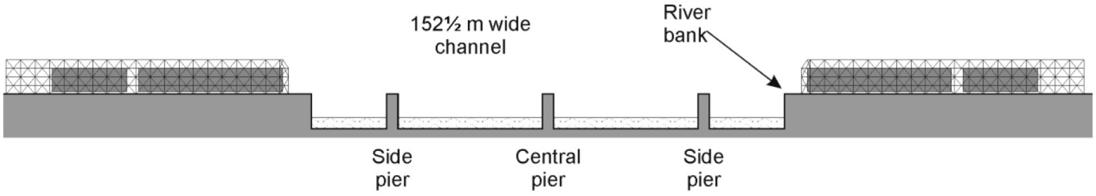
To eliminate some of the issues with the four sector drop gates another proposal called for suspending the drop gates within two huge retractable structures [1, 2, 4]. When required the retractable structures would be pushed out from the river banks, across two concrete intermediate side piers before coming to rest on a central pier in the middle of the river. Just before meeting at the central pier the two projecting structures would have formed cantilevers 152½ m long. A guide system on the three piers would have been used to guide the two structures to meet precisely in the middle of the river. Once the retractable structures were locked in place the four drop gates would then be lowered into position closing off the river. As before open sluice gates would allow the drop gates to withstand the unequal pressures on either side of the gates. This sequence is depicted in Fig. 4.

When the gates were fully open with the retractable structures on shore there would have been no impediment to the free movement of traffic on the river. The gates and the retractable structures would have been housed in buildings that would have been designed to blend in with the environment. The gate operation would have been more complicated than the simpler four sector gate design described earlier requiring one additional complicated activity—movement of the retractable structures. The use of such a retractable system added one more point of failure that could have increased the chances of the entire Barrier system failing.

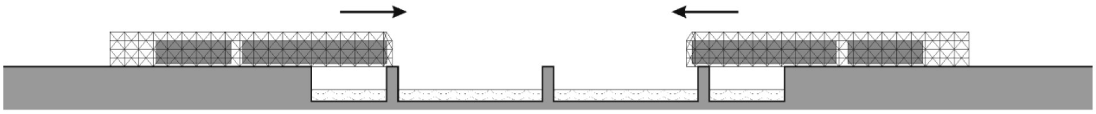
2.3 Swing Barriers

A further design called for the use of six drop gates suspended from three swinging structures (Fig. 5) [1, 4]. Each of the swinging Barriers would have been mounted on giant concrete piers built across the river running parallel with the axis of the river. The swinging structures would have been over 152½ m long with each arm projecting 76¼ m out from the pivot. Under normal conditions each of the Barriers would have been aligned with the axis of the river. When required to seal the river, each of the swing Barriers would have rotated about its pivots. The 76¼ m arms would link their ends to span the main

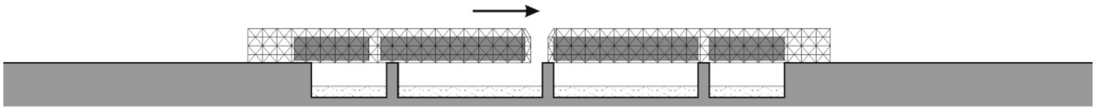
A) Retractable barrier in the fully open position



B) The barrier section begins to slide out from the river bank towards the concrete piers



C) Just before the barrier sections meet on the central pier the sections are cantilevered a distance of 152½ m across the Thames.



D) Once the barrier sections are closed the gates are lowered to rest on the concrete sill on the river bed. The sluices in the gates are then closed.

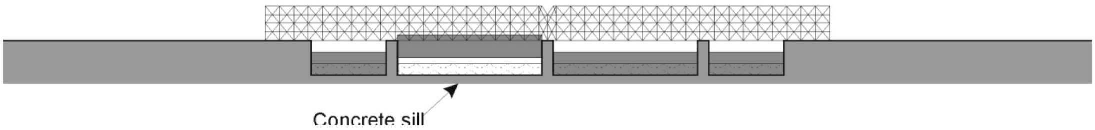


Fig. 4. A two part retractable Barrier proposed in response to the 1954 design criteria of the Port of London Authority.

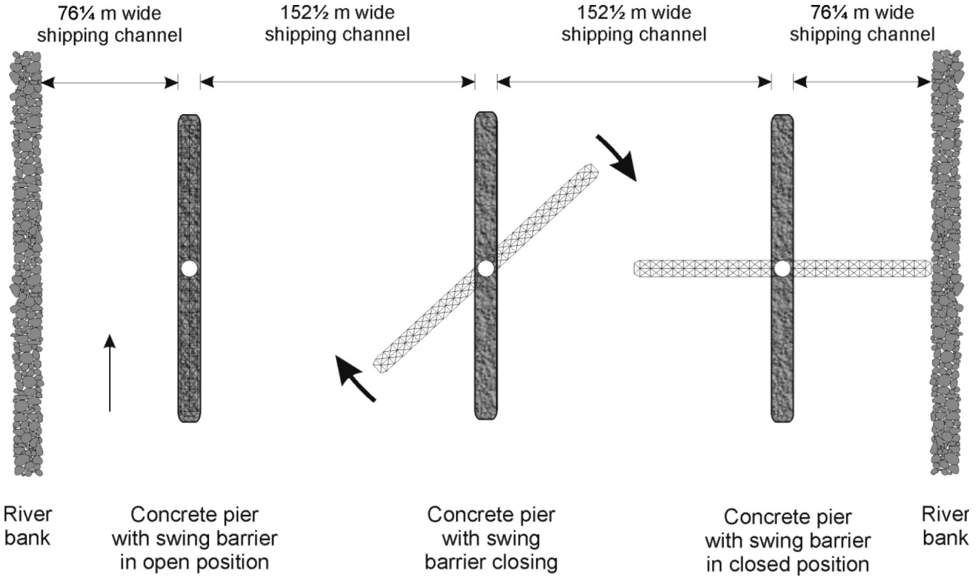


Fig. 5. Three swing Barriers proposed in response to the 1954 design criteria of the Port of London Authority.

152½ m wide ship channels. Once the structures had rotated and were locked in place, drop gates would have been lowered into place creating the Barrier and sealing the river. The technology to design and build such swinging structures existed at the time though the scale of the structures would have been challenging. Again small sluice gates in the drop gates would have been used to control the forces acting on the gates as they were raised and lowered.

This design reduced the footprint required on the banks of the river by the retractable gates. The concrete piers were longer than required by the four sector drop gate design. Housed in appropriate shells the swinging structures might have been visually acceptable to the public.

3. The 1965 design criteria proposals

In 1965 the Port of London Authority (PLA) observed that it had allowed jetties to be constructed close to the proposed site for the Barrier at Long Reach and that a new site would have to be chosen. The PLA finally selected a site at Crayfordness on a bend in the river. Because of the perceived difficulties in navigating a ship through an opening at a bend in a fast-flowing river the PLA specified that a single navigable channel of 427 m (1400 ft) width was required. This was about twice the length of any ship that would normally be expected to navigate through the Barrier. Thus the last design criterion listed above was changed to reflect the requirement for a single very wide opening.

This one change meant that much of the work already completed on the three designs proposed above had to be set aside while new designs were developed. In the event three new designs were proposed to allow a 427 m span of the river to be closed off [1, 4].

3.1 River bed level retractable Barrier

Two giant gates would be run out of the banks of the river along a concrete roadway on the river bed, meeting in the middle of the river. These retractable gates would have been housed in dry docks running back hundreds of metres of the river banks. In operation the dry docks would have been flooded and the dry dock gates opened. The two retractable gates, one from each bank of the river, would have been rolled out across the river bed on hundreds of tyres. Both gates would have featured sluices which would have been kept open during deployment allowing some water to flow through, but which would have been closed once the two halves of the Barrier met in the centre of the river. The main concern for engineers designing this structure was the lateral forces placed on the structure by the flowing water during deployment, and by the difference in water levels upstream and downstream once the Barrier was in place. There was also the worry that the two halves might not meet in the middle of the river. The engineers planned to spray high pressure jets of water ahead of the closing gates to help clear the submerged concrete roadway of debris and silt.

3.2 High level retractable drop gates

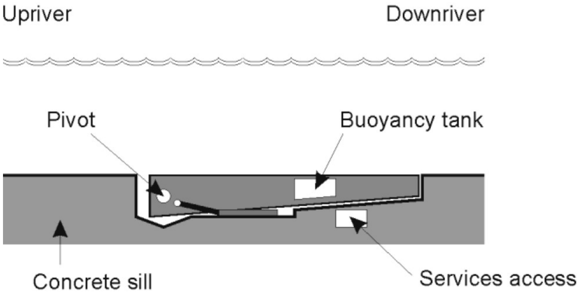
One engineering team returned to the idea of high level retractable drop gates [1, 2, 4]. They proposed two retractable structures projected out from the river banks until they met above the centre of the river. Each of the retractable structures would have housed a drop gate 213½ m long. Once locked together above the centre of the river the two gates would have been lowered into river, coming to rest on a control sill spanning the river bed . Again the lateral forces on the structure during its operation would have been immense. In addition it was vital that the two halves of the drop gate would mate adequately providing a sufficient seal to stop the flow of the river. Of all the designs considered this was perhaps the one with the most possibilities of failure and was twice the cost of the proposed river bed level retractable gates.

3.3 Hinged shutter gates

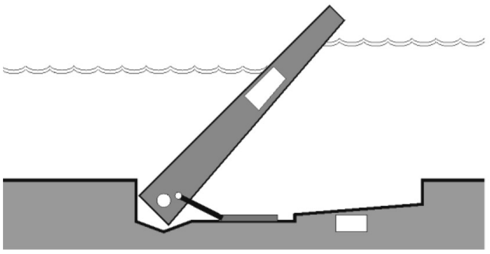
A third engineering team came up with a very different design that did not make use of drop gates [1, 2, 4]. They proposed the use of a series of hinged shutter gates, each gate perhaps 30 m in length, that would rise up from the river bed when required. Each gate unit would have consisted of a concrete base with a steel gate hinged at the upriver end. When not in use the steel gate would have lain horizontally on the river bed. When required the gates would have been raised by hydraulic mechanisms to the vertical position. Since the hinge or pivot of the gate was at the upriver end of the structure, the rising levels of the incoming tide would actually help to keep the gate upright. A buoyancy tank within the heavy gate would help to raise the gate. Operation of the hinged shutter gates is shown in Fig. 6. The river would have been closed by a line of perhaps twelve to fourteen such gates.

There were, however, several problems with this design. Scale models tests conducted in the design laboratory showed that with this type of gate a big difference in water levels quickly built up on either side of the gate. Provided that all the gates were able to be raised together within about ten minutes then this would not present a problem. If, however, one of the gates was a little slow in rising for some reason then the pressure of the water flowing through this gate's vacant position in the Barrier might exert an excessive closure force on the gate. This would cause

A) The steel gate in the fully open position



B) As much as possible the gates must all closed together



C) The force of the high tide helps to keep the gates closed

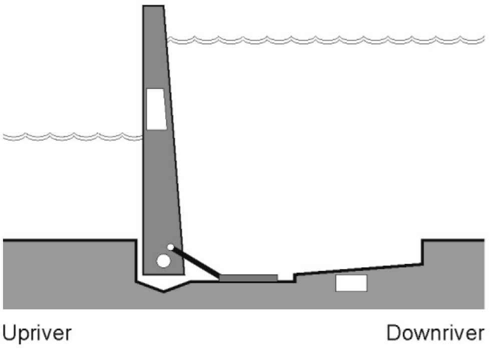


Fig. 6. Hinge shutter plate Barrier proposed in response to 1965 design criteria.

the gate to snap shut, possibly damaging the gate, its hinge and the hydraulic mechanism. The model studies showed that such damage would lead to failure of the gate and therefore of the Barrier. Another disadvantage of the design was that all the mechanisms to operate the gate including the hinge and the hydraulic systems were located on the river bed. Maintenance would only have been possible underwater with the gates fully closed. The operating mechanism would also have been subject to clogging by river silt. The original design proposed the use of de-silting jets which would hopefully have cleared the gate recess of silt while the gate was being lowered back into place.

4. The final design

None of these plans was eventually built as the requirements laid down by the Port of London Authority changed yet again. The introduction of standardized shipping containers in the 1960s revolutionised the handling of maritime cargo. In response, modern container terminals were built well downstream of the existing cargo wharves. As a result, several of the older docks nearer to the centre of London were closed and the PLA scaled down their demands on the engineers. Instead of having one channel 427 m wide the PLA now required six navigable channels; four of 61 m width, and two of 31½ m width. The four wider channels would be in the centre of the river for shipping while the two narrower openings would be for smaller pleasure craft [3].

The narrower navigable channels allowed the engineers to reconsider a range of options including drop gates, and low level retractable gates. One team of engineers, however, came up with the idea of the rising sector gates that would rotate out of recesses on the river bed into a vertical position forming the Barrier. The final Barrier as built uses six rising sector gates (four 61 m wide and two 31½ m wide) for the navigable channels and four falling radial gates to seal off the river near its banks. The gates are supported by nine concrete piers and two concrete abutments set in the river banks [1, 5].

Each of the six rising sector gates has the cross-section of a segment of a circle. The radius of curvature of the curved face of one of the gates is 12.2 m and the chord length is approximately 20.1 m. The maximum section depth is 5.3 m at the centre of the segment. The gates are hollow with a skin of steel plates up to 40 mm thick hung on an internal lattice skeleton. Attached to each end of the gate are massive hollow steel disks 24.4 m in diameter and 1.5 m thick. The gate rotates about the axis through the centre of the disks. The 1300 tonne weight of each 61 m rising sector gate is counterbalanced by weights located in both of these end disks. The gates rotate on giant trunnion shafts set into the sides of the concrete piers. These shafts pass through the centre of the gate assembly end disks.

When the gate is in the open position the gate segment lies in a recess in the concrete sill that's set in a trench in the river bed between adjacent concrete piers (Fig. 7). Vessels can safely navigate through the open channels between the piers. To close the gates, the rising sector gates are rotated through 90° with their curved face downstream. The gate is

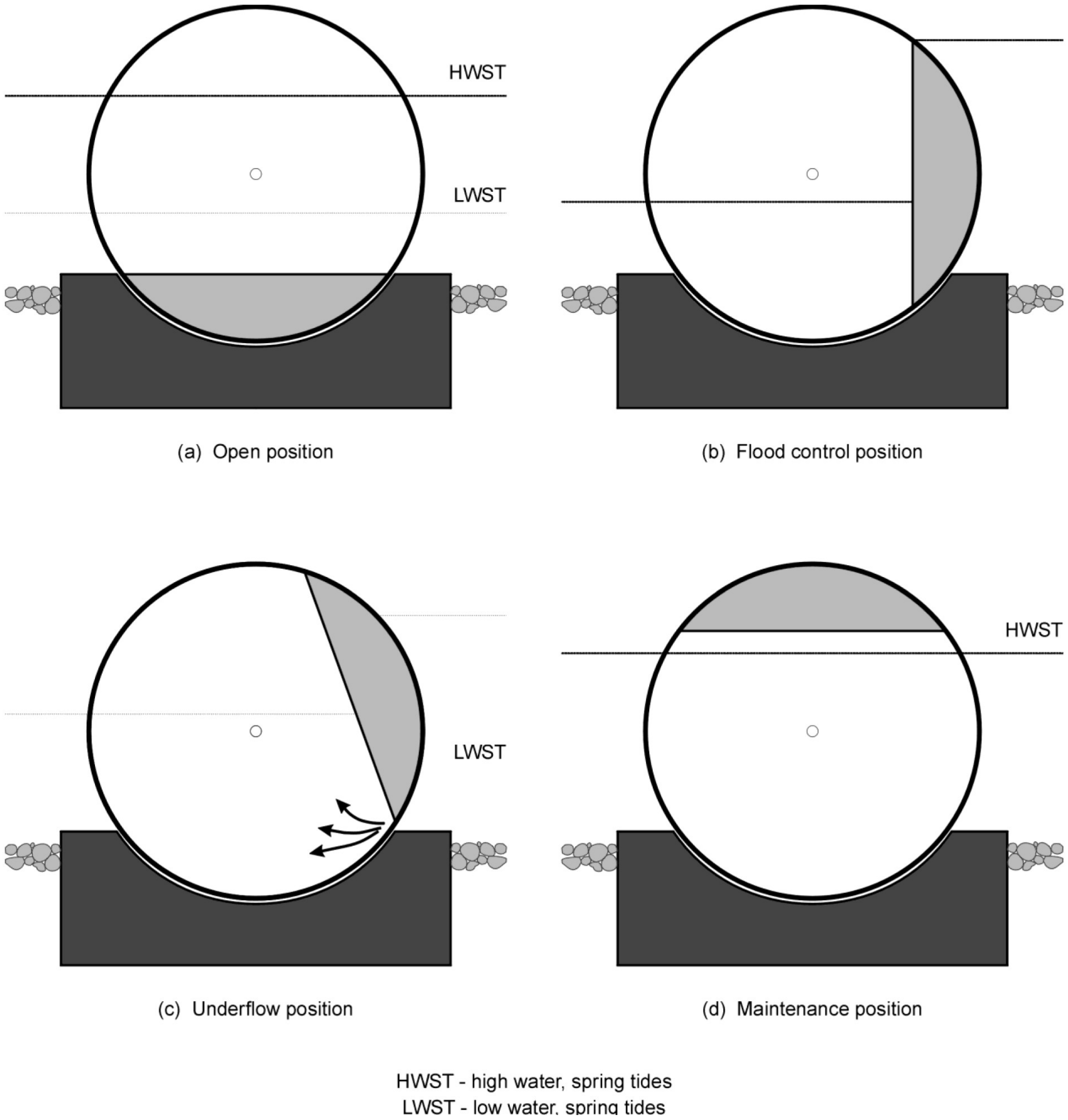


Fig. 7. The four main positions of the rising sector gate: (a) in the fully open position the gate does not obstruct river traffic; (b) in the fully closed position the pressure of the water on the downstream side is transferred to the trunnion shaft; (c) the gate is place in the underflow position to wash any silt away from the sill before closing; (d) the raised position allows maintenance to be conducted clear of the water.

locked into the closed position using a latching mechanism that prevents it from rotating out of position. It takes about half an hour for a gate to be raised from the fully open to the fully closed position. As the water level builds up on the downstream face the pressure on the gate is transmitted back to the trunnion shaft set into the concrete piers. In the closed position the trailing edge of the gate span remains well within the recess in the concrete sill preventing significant flow past the lower edge of the gate.

Once the peak of the storm surge has passed and the water level on the downstream face is falling away the gate is rotated further to the underflow position. Rather than water pouring over the top of the gate, the water is allowed to flow under the trailing edge of the gate. This helps to scour out of the sill recess any river silt that might have settled there while the gate was in the fully closed position. Once the difference in water levels upstream and downstream is within appropriate limits the gate is rotated back to the fully open position. The gate may also be rotated until it is completely inverted and out of the water. In this position maintenance work can be done safely out of the water.

The gates themselves are hollow with vents in the flat, upstream face. When in the open position, the gate span is flooded with water. When it is rotated into the closed position, the water is allowed to drain out, reducing the weight of the gate. The rotating gates fit tightly into the concrete piers and double rubber seals are used so that the amount of water seepage around the gates is minimal. The rising sector gates are designed to withstand a maximum difference in upstream and downstream water heights of 9.9 m when closed for a storm surge (i.e. when the downstream level is higher than the upstream level) and 6.1 m when closed for a river flood (i.e. when the upstream level is higher than the downstream level possibly due to heavy rains flooding the river). They are also designed to withstand the collision of a large vessel or smaller ship.

Four falling radial gates are used to seal the river at its northern and southern banks—three at the northern bank and one at the southern bank. These are much simpler in design than the rising sector gates as these falling radial gates are used to seal off parts of the river too shallow for navigation. In their open position the gates are held in the air above the river. When needed to close the river the gates are simply lowered into position.

The mechanisms to rotate the gates are located well above the water line in each of the concrete piers [1, 6, 7]. Two hydraulic rams cause a radius arm to rotate around a secured pinTo the end of the radius arm is attached the link arm which in turn is attached to an end plate of the gate assembly. As the radius arm moves, this rotation is transferred to the end plate. While there are drive mechanisms at both ends of the gates, each mechanism can rotate the gate by itself if the other mechanism is inoperative. Thus, if power is lost to one pier, equipment housed in the pier at the other end of the gate can be used to move the gate. This is an example of the redundancy built into the system to prevent total failure of the system in the event of failure of a single component of the system.

The concrete sills resting in trenches in the river bed between the concrete piers carry two tunnels that link the piers to the river banks [1, 8]. The tunnels are of circular cross-section about 2 metres in diameter. They carry power as well as communication and control lines to each pier. They also allow workers access to the piers from either river bank. The tunnels come into the concrete pier well below the water line. Access to the machine and control rooms in the piers is via either stairs or lift. Below the water line there is no direct connection between the tunnels so that the flooding of one tunnel will not endanger the other tunnel.

The Barrier gates are controlled from a central control complex on the south side of the river. While the gates can be and usually are, operated from this central location each pier has its own control room allowing it to directly control the operation of each of the two gates connected to it. This also means that each gate can be operated from either of the two piers that support it, or from the central control room.

Power to operate the Barrier comes from the national electricity grid with separate connections to the grid from the north and south sides of the river [1, 8]. As the Barrier was constructed in the 1970s to early 1980s when industrial disputes were prevalent, the Barrier was given its own set of emergency generators to power the facility in the event of an industrial dispute disrupting power supplies. While two generators would be sufficient to provide power to operate the gates, a third generator is also provided. In an extreme emergency one generator could provide sufficient power to close the Barrier but not all gates would be closed simultaneously. These generators are housed at the control complex south of the river.

Even if one of the flood gates failed to close, the Barrier's other closed gates would still restrict the flow enough to prevent the catastrophic flooding of London upstream of the Barrier.

One major advantage of the Barrier's design is that all the powered mechanical equipment used to operate the gates is located well above the water line. This makes for easier and speedier maintenance. Some alternative designs considered made use of equipment such as hydraulic rams that would have been housed in recesses deep in the river bed. Such mechanisms could only have been serviced underwater with the gate fully closed.

Once the gates and supporting piers had been designed there was concern that the finished structure would look like an ugly, unfinished bridge with the nine piers stepping their way across the river. For this reason the superstructures of the piers were given distinctive curved roofs, reminiscent of the famed Sydney Opera House that had only been completed a few years earlier [1, 9]. The roofs are formed from wooden structures to which are attached curved and reflective steel plates.

Construction work on the Thames Barrier commenced after many years of detailed design studies in 1974 [1]. These design studies included the use of both scaled physical models as well as complicated mathematical models of the structure and the flow within the river. Work progressed over many years with significant time being lost to industrial disputes. The process was also complicated by the requirement for the waterway to be kept open to commercial traffic. The Barrier became operational in October 1982 and was first used to protect London from a storm surge on 1 February, 1983.

At the same time as the Barrier was being built across the Thames other river defenses were being built and upgraded. The river walls from the Barrier to the sea were strengthened and raised in height. Other Barriers were built where rivers flowed into the river downstream of the Thanes Barrier. At Dartford a giant drop gate was installed across the

Dartford River ready to seal off that smaller river in an emergency. Elsewhere other flood control mechanisms were put into place.

Today every month the Barrier is fully closed in order to test its operation. One of the piers survived the collision of a ship, which later sank on top of one of the open rising sector gates. The pier sustained no significant damage and the gate was quickly repaired once the wreckage of the ship had been cleared away.

5. In the classroom

The design of the Thames Barrier is used as a case study in teaching design and the importance of design criteria to first year engineering students in their first month of study at the University of Melbourne. All students intending to take any undergraduate engineering programme at Melbourne are required to enroll in two first year general engineering subjects, Engineering Systems Design 1 and 2, one in each of their first two semesters of study. Engineering Systems Design 1 centres on the engineering method, the approach to problem solving and engineering design. Professional ethics, safety and sustainability are also covered in the subject. The Thames Barrier case study is introduced to students in a single 50-minute lecture around the fourth week of the semester. Students have previously had lectures on engineering design, problem solving and the logical application of selection criteria to engineering decision making. The lecture introduces the students to the need for the Thames Barrier, the various different designs considered and the final design that was implemented. It features many visual elements including diagrams, animations and photos of the proposed and as-built designs.

Since 2008 the case study lecture has been given twice a year to succeeding cohorts of students. In Semester 2 of 2009 a class of 230 students were enrolled. Approximately 30% of these students had come to Australia to study engineering and English was not their first language. In order to assess how much the students had learnt from the Thames Barrier case study some 10 weeks after the lecture each student was asked to prepare a hand-written concept map with “Thames Barrier” as the domain. Students were given up to 30 minutes to complete the activity. The class previously had instruction and training in the preparation of concept maps and so 226 maps were prepared by the class.

Concept maps were first developed in the 1970s to graphically represent knowledge and understanding of particular domains or topics. In a typical map the domain is written in the centre and then other concepts are linked to the domain via connecting lines and propositions. These first generation concepts are in turn connected to second generation concepts by more connecting lines. Interconnecting lines between concepts of the same and/or different generations from the central domain allow the maps’ authors to demonstrate the links that they see between different concepts. In the last decade a number of workers have turned to concept maps to assess the understanding of student cohorts of a range of topics. As examples, Iuli and Helldén [10] constructed concept maps based upon student interviews to assess student conceptions of various aspects of science while concept maps have also been used to explore student understanding and learning around sustainable development [11–13] and in nursing education [14, 15]. Daley and Torre present a useful review of the use of concept maps in medical education [16].

Preparation of a concept map on any topic requires the student to analyse, synthesize and evaluate information in a high level manner. This is not a simple task. The manner in which the concept map is constructed reveals much about the thinking, maturity and knowledge of the student in the particular domain [17].

As Turns et al. [18] note, when used for assessment concept maps may either be developed using concepts generated by the students or from a list of predefined concepts prepared by the instructor. Student generated concepts require students to both recall and then order their thoughts on a topic while the use of a predefined list of concepts allows the resulting maps to be analysed using appropriate automated algorithms [19].

For our study we allowed students to identify their own concepts. Interpretation of the maps involves scoring them along several dimensions including:

(1) the number of concepts in several different categories,
(2) the total number of links and the links between different categories,
(3) the number of cross-links between branches and sub-branches resulting in loops,
(4) the number of hierarchical levels or generations out from the domain [18].

While it is also possible to analyse the maps in a more subjective manner giving scores for comprehensiveness, organization and correctness [17, 18], this was not done in the current study. We chose instead to analyse the concept maps by classifying each of the concepts into one of seven different categories according to the following taxonomy:

- Category 1—Purpose—purpose of the Barrier, i.e. flood prevention, flood protection;

- Category 2—Failure consequences—flooding, death, civil disruptions, financial loss;
- Category 3—Design criteria—criteria used in the design including number and width of gates, location, clearance;
- Category 4—Design alternatives—alternatives to the rising sector gate proposed including drop gates, pivoting plates, hinged shutter plates;
- Category 5—Barrier physical systems and operation—physical elements of the structure and its operation such as gates, piers, connecting tunnels, opening and closing;
- Category 6—Barrier non-physical systems and operation—non-physical elements of the structure and its operation such as maintenance, monitoring systems, management;
- Category 7—Actors and stakeholders—people and institutions including companies, government and government instrumentalities such as Port of London Authority;

The number of concepts in each of the seven categories was counted for each concept map along with the number of interconnecting links. Where a concept did not obviously fit into one of the seven categories it was assigned to the one closest in meaning. The number and distribution of concepts across the seven categories allows conclusions to be drawn on the extent of student learning and how the students link the key concepts of design and design criteria. It would not be expected that all categories would be equally represented in the concept maps.

Figure 8 presents a typical concept map prepared by a student. This map contains 30 concepts with an emphasis on the physical systems and operations of the Barrier. The student's map also includes ele-

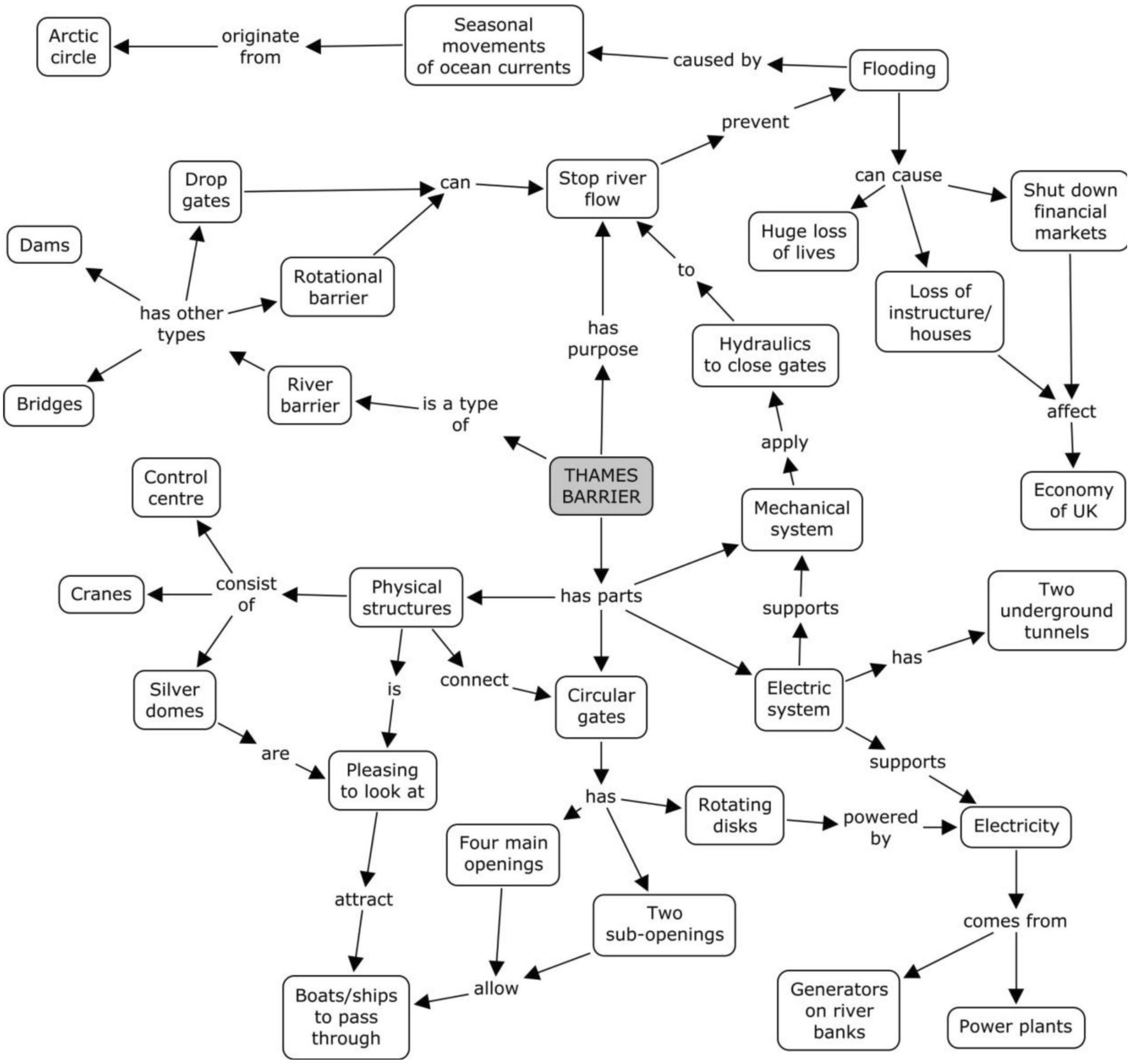


Fig. 8. Concept map generated by a first year student.

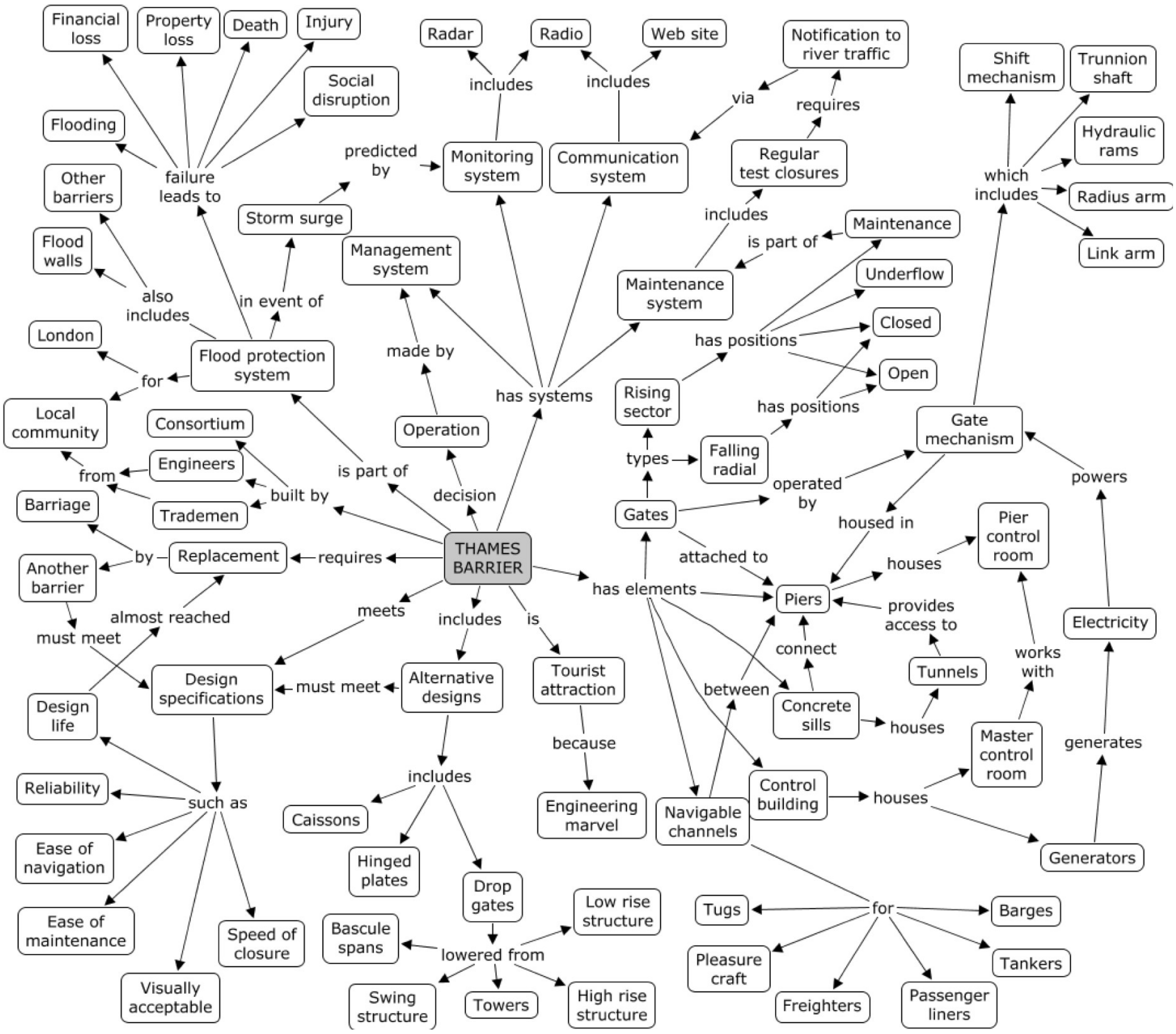


Fig. 9. Concept map generated by instructor.

ments relating to its purpose, the consequences of failure and design alternatives. This particular map does not show any concepts relating to the non-physical systems of the Barrier such as management, maintenance, monitoring or communication systems. By comparison Fig. 9 presents a concept map prepared by one of the authors (Shallcross). As expected the instructor's map is more extensive reflecting the deeper understanding of the issues and elements of the Thames Barrier .

The 226 concept maps analysed contained an average of 26.4 concepts and 32.2 links indicating that the maps were not strictly hierarchical in nature but contained a number of cross-links between different areas. Some students drew maps with fewer than 15 concepts while one student developed a map of 51 concepts.

Figure 10 presents the distribution of the total number of concepts for 226 maps. The average numbers of concepts in each of the categories is presented in Fig. 11. The results indicate that the class generally had very good appreciation of the physical structure and operation of the Barrier together with knowledge around the design criteria. Concepts relating to the non-physical aspects of Barrier systems and operation including maintenance, management and monitoring were also prevalent. The purpose of the structure and its relevance to the stakeholders were also apparent. Nearly two-thirds of the class included at least five different concepts relating to the physical systems and operation of the Barrier. At the other end of the scale, almost half the class failed to list any concepts relating to the consequences of the failure of the Barrier. Of the seven categories, that relating to the design alternatives ranked lowest but this might be due to the choice of the domain, "Thames Barrier". It might be that the use of a domain such as "Designing the Thames Barrier" might have yielded a higher proportion of maps including concepts in this category. Two-thirds of all maps contained concepts drawn from five or more of the seven

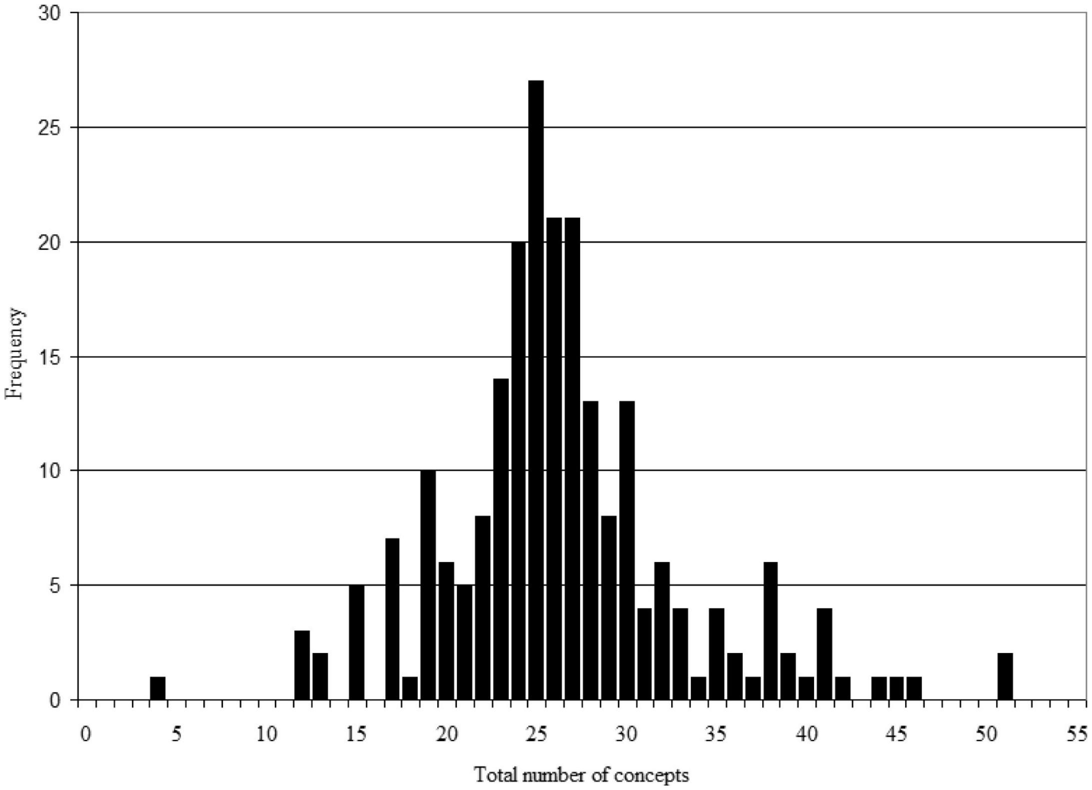


Fig. 10. Distribution of total number of concepts for 226 concept maps. The average is 26.4.

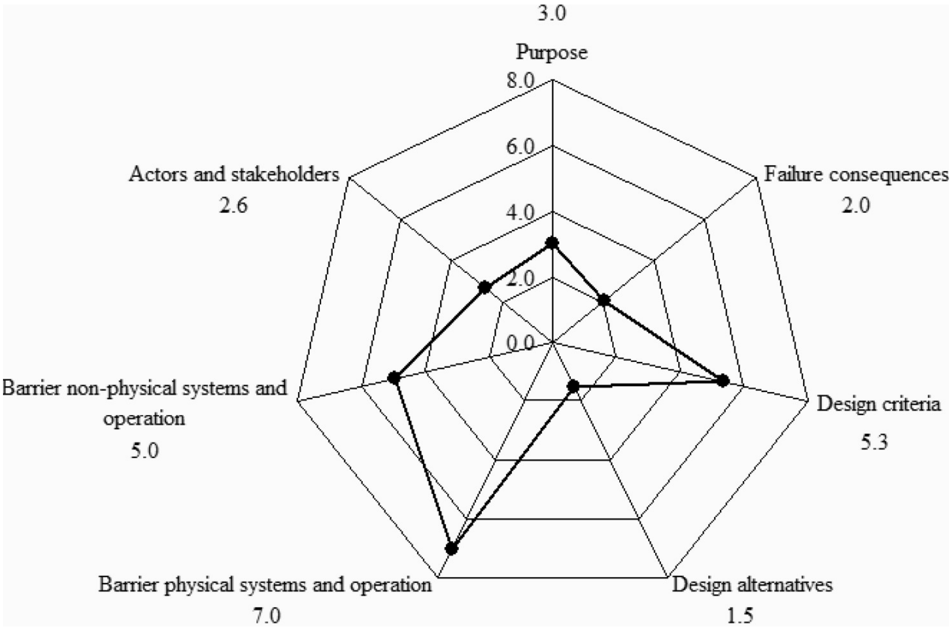


Fig. 11. Distribution of average number of concepts in each of seven categories for 226 concepts maps.

categories. Fewer than 10% of the maps were purely hierarchical having no cross-links between branches. More than half the class had at least five cross-links indicating they were able to see links between different areas of their maps.

6. Concluding remarks

The process followed in designing the Thames Barrier provides an excellent opportunity to discuss how the specification of design criteria affects the final design adopted. The engineering solution evolved as the client changed the basic design criteria. Different designs ranging from retractable barriers to drop gates to the rising sector gates are all valid design solutions. The context is also one that students can readily understand.

A detailed analysis of the concept maps suggests that 10 weeks after the lecture on the Thames Barrier case study students still retain an understanding of the key aspects of the design and design criteria around its construction. In this study the use of concept maps identified weaknesses in the delivery of the case study relating to the importance of the different design alternatives and the consequences of failure. Interpretation of the completed maps suggests that students failed to retain information on the differing design alternatives nor on the consequences of failure of the system. Further, it was the experience of the authors that the case studies were easier to assess than a conventional essay as misconceptions that existed in the minds of the students could be readily identified upon inspection of the maps. Concept maps are a powerful tool for instructors to gauge information and knowledge assimilation.

Further work on the development of assessment rubrics for scoring the such concept maps is currently underway that will measure the quality of the maps in a more holistic manner.

The Thames Barrier is an appealing case study to work with as its purpose and relevance can be easily demonstrated to students and it contains aspects of civil, electrical and mechanical engineering.

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