DEVELOPMENT OF A DESIGN AND COST OPTIMISATION MODEL FOR HEATHROW AIRPORT TERMINAL 5

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Introduction

BAA is one of the world's major airport operators, owning 7 airports in the UK, including London's Heathrow, Gatwick and Stansted Airports. Heathrow Airport is the busiest international airport in the world, taking 65 million passengers per annum on two runways, with over 50% of aircraft movements by wide-bodied aircraft.

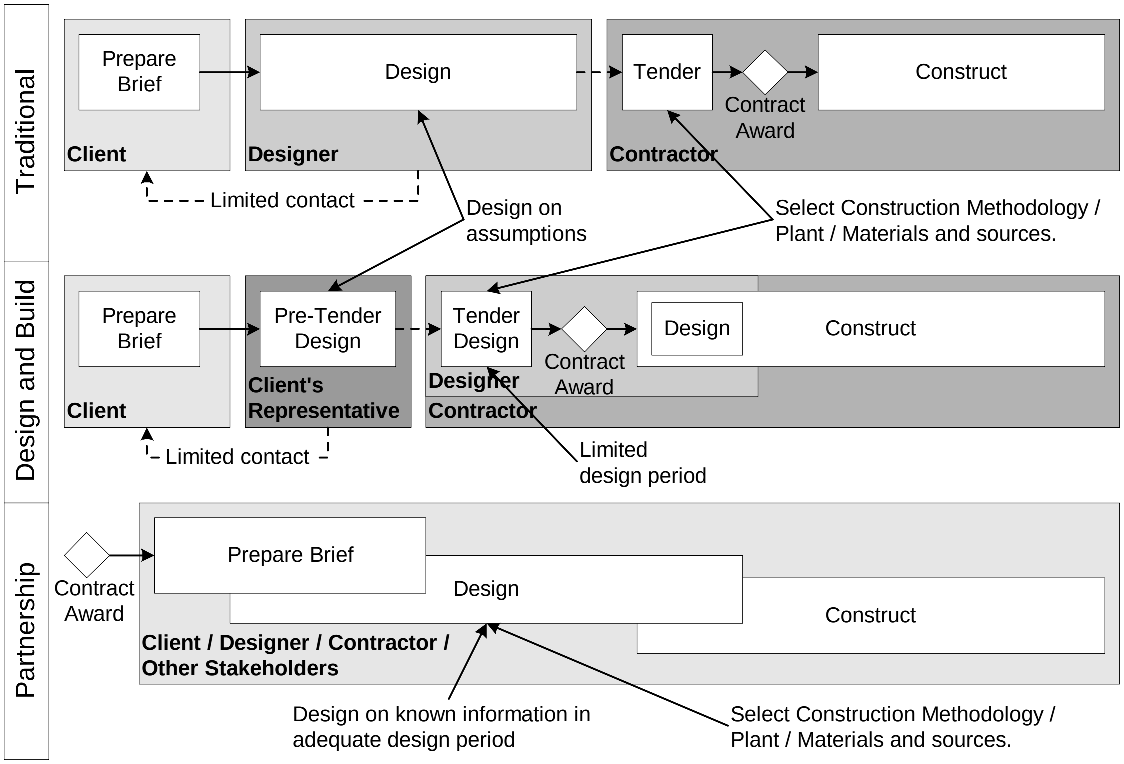
Between 1990 and 1995 BAA made two major innovations in the design and procurement of airfield pavements:

- The adoption of a partnership approach to procurement, with long-term framework agreements for a single paving contractor and pavement designer (The Pavement Team – comprising Amec Civil Engineering and BAA's own design team).
- The development of its own design method for airfield pavements to provide high reliability pavement designs suitable for the very heavy aircraft loadings and extremely high utilisation at the major BAA airports.

For the proposed Terminal 5 at Heathrow Airport (T5), BAA is targeting significant improvements in the construction process through the use of the partnership approach to supply chain management that, while common in other industries, is still unusual in construction. This builds on experience of The Pavement Team.

Traditionally airfield pavement design is carried out by the designer without access to the contractor because of the competitive tendering process (Figure 1). While it may be possible to discuss possible improvements to the design with the client, the contractor who will actually do the work is not known while the design is in progress. Any attempt to optimise the design is done without accurate knowledge of key factors such as:

Figure 1.
Construction Procurement.



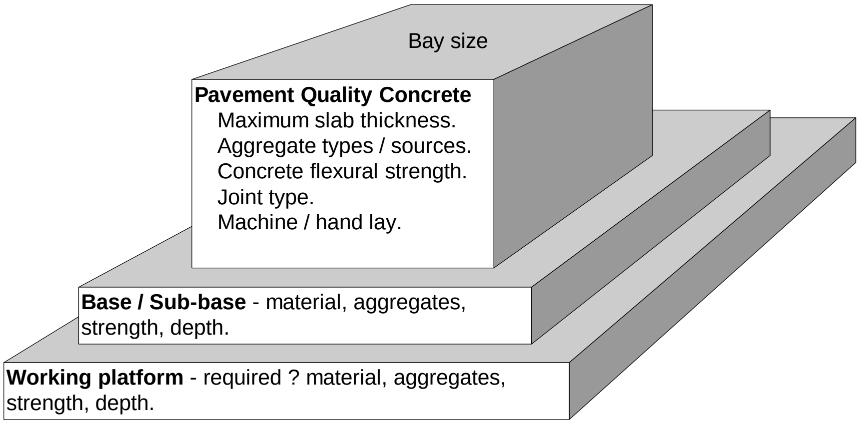
- costs,
- materials – e.g. aggregates for concrete and bases or sub-bases.
- construction methodology – including plant, production and laying rates, specialist construction techniques..

Developments in construction procurement such as Design and Build have fostered a relationship between the final designer and the contractor, but have two disadvantages (Figure 1):

- The designer has no contact with the client and so is unable to discuss innovative ideas, which will often mean non-conformance with the pre-tender design or specification, with him.
- The tender design period, when the critical decisions must be made, is often very short allowing inadequate time for consideration of multiple possibilities and design optimisation.

Generic design methods such as the PSA (Reference 1), BAA (Reference 2) or FAA (Reference 3) design guides are usually used, with related specifications. These design methods and specifications are based on common construction practice, and the lowest denominator for materials quality (Figure 2). Major assumptions for the two principle UK design methods are shown in Figure 3.

Figure 2 .
Typical design assumptions.



The T5 Pavements task team is utilising the benefits of the partnership approach to make substantial improvements on the cost of pavements designed in accordance with the BAA design guide and the current BAA specification through consideration of a wide range of options in construction practice and materials (Figure 4).

The objectives of the team are:

- Compliance with functional requirements; i.e. design reliability, surface durability including joint performance, and friction must not be compromised.
- Lowest capital cost.
- Reduction in maintenance requirements and whole-life cost compared to current pavements.
- Control of risk.
- A construction programme compatible with the planned opening date.
- No import of materials for subgrade improvement.

Figure 3.
Assumptions of standard UK design methods.

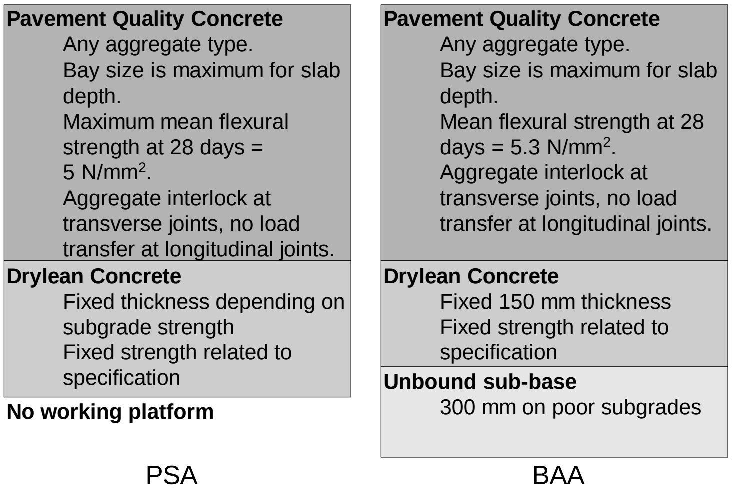
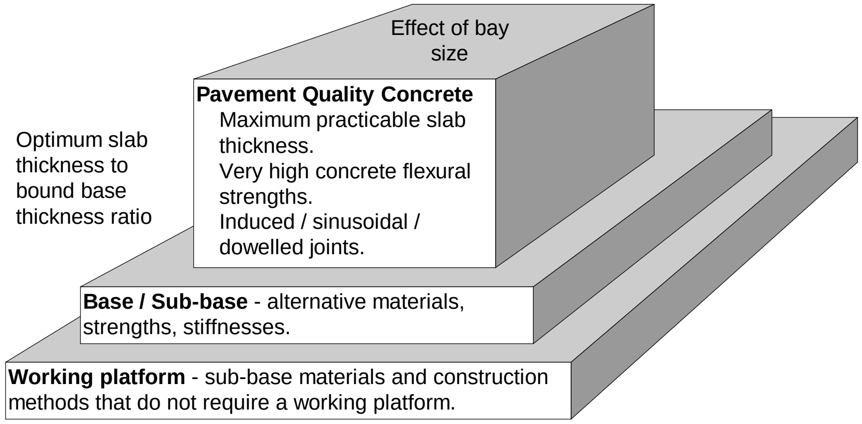


Figure 4.
T5 Proposals.



- Reduced environmental impact; through reductions in the use of natural aggregates, reduced CO_2 emissions through lower Ordinary Portland Cement (OPC) use, and increased use of re-cycled materials.
- Reduced health and safety risks; by avoiding potentially dangerous materials.

To achieve these objectives a key action at the start of the project was a workshop involving the whole team at which over 60 opportunities were identified for cost savings, programme savings and better pavement performance. The resulting Opportunity Register is a live document that has been added to as further opportunities have been suggested. Each opportunity has then been assessed using the process shown in Figure 5, which requires numerous cost calculations.

Significant opportunities identified included greater Pavement Quality Concrete (PQC) slab thicknesses and higher concrete strengths than previously used, possibilities that could only be developed by an integrated supply chain, including the contractor and material and plant suppliers.

To undertake the cost comparisons the team has developed:

- A cost model able to give comparative costs on a square metre basis to within 2% of accurately billed estimates. The cost model allows accurate comparisons of alternative pavement designs and constructions.
- An integration of a design programme implementing The BAA Design Guide for Heavy Aircraft Loadings (BAA, 1993) and the cost model; enabling the cost to be optimised for various design and construction options for each area of differing construction type, subgrade type and aircraft trafficking.

Figure 5.
Method of assessing alternatives.

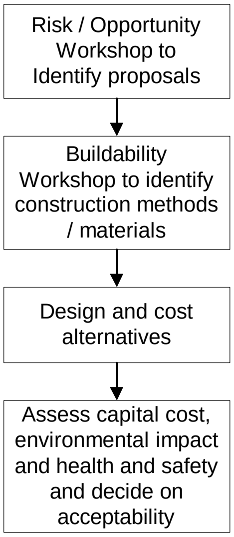
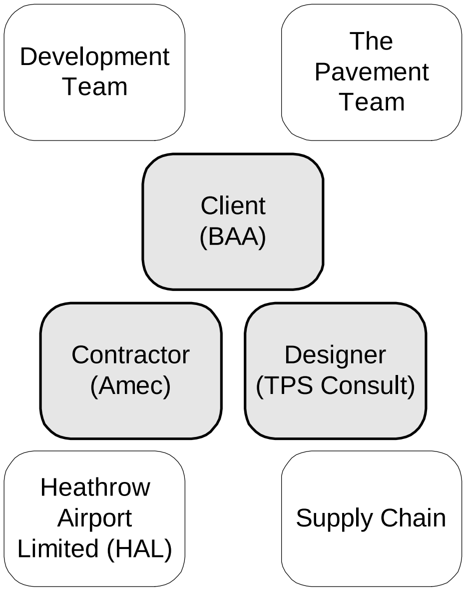


Figure 6.
Components of Pavements Task Team



The Team

The Pavements task team for T5 is comprised of all of the members of the supply chain (Figure 6). The core of the team is the client, contractor and designer; but in addition it includes the client's Development Team, responsible for preparation and development of the Brief, the airport Operations department responsible for safe operation of the pavements, the key suppliers and also The Pavement Team who carry out all other pavement work for BAA.

However, the key to the successful working of the team is the fact that it is not a loose grouping of disparate companies, but a single unified team with the core co-located in one office, and including all the skills needed to optimise the design (Figure 7). During the design stage, the team is lead by a designer, but leadership will change as it moves into construction.

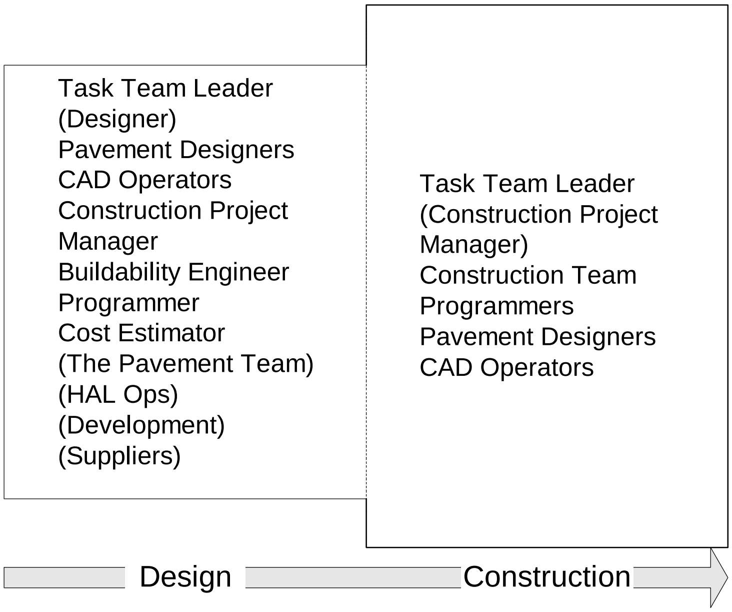
Key design drivers

The key drivers for the airfield pavement design are:

- User aircraft – the full range of existing and proposed wide-bodied aircraft, with varying use on different taxiways and stands.
- Subgrade – varying from very poor clay to gravel.
- Construction constraints – phasing of works to match a very complex earthworks, sub-structures and buildings programme, and restricted access to head of stand areas due to terminal building construction and complex stand services.

To deal with the variations in the design drivers for different pavement areas, the site has been divided into 74 Construction Locations, depending

Figure 7.
The Pavements Task Team.



on the phasing, whether the predominant method of laying will be machine or hand lay, the aircraft traffic and subgrade strength.

The implications of any design alternative vary with the Construction Location, and therefore to accurately assess possible cost savings it is necessary to calculate the pavement thicknesses for all 74 locations.

Modifications to the BAA Design Guide

The background to the BAA design guide has been described by Lane et al (Reference 4). The guide contains design graphs for a limited range of specific aircraft types and four subgrade strengths, and a methodology for dealing with a mix of aircraft types. The guide comes with some standard spreadsheets that can be used for the calculations.

For the T5 pavement designs it has been necessary to adapt the BAA design guide for:

- Different subgrade strengths.
- Higher concrete strengths.
- Alternative aircraft types.

In addition the design methodology has been modified to:

- Replace the stress calculation by multi-layer elastic analysis (MLEA) with a 2D plate analysis calibrated against the MLEA, to allow modelling of very heavy loads on joints.
- Modify the failure criterion to take account of expected temperature related stresses in the slabs based on a known coarse aggregate source.

The Cost Model

The T5 Pavements task team aim to further develop much of the learning and best practice initiatives achieved by The Pavement Team during the last 6 years. Consequently, the T5 cost model has utilised the “best practice rates” currently employed by The Pavement Team. Current production and cost rates have been extracted directly from the Pavement Team's Estimating system (CCS).

The T5 cost model operates in a similar manner to CCS but has been tailored specifically to suit the constraints of the T5 project. These have included the development of an input/output interface which contains a comprehensive range of design and construction variables.

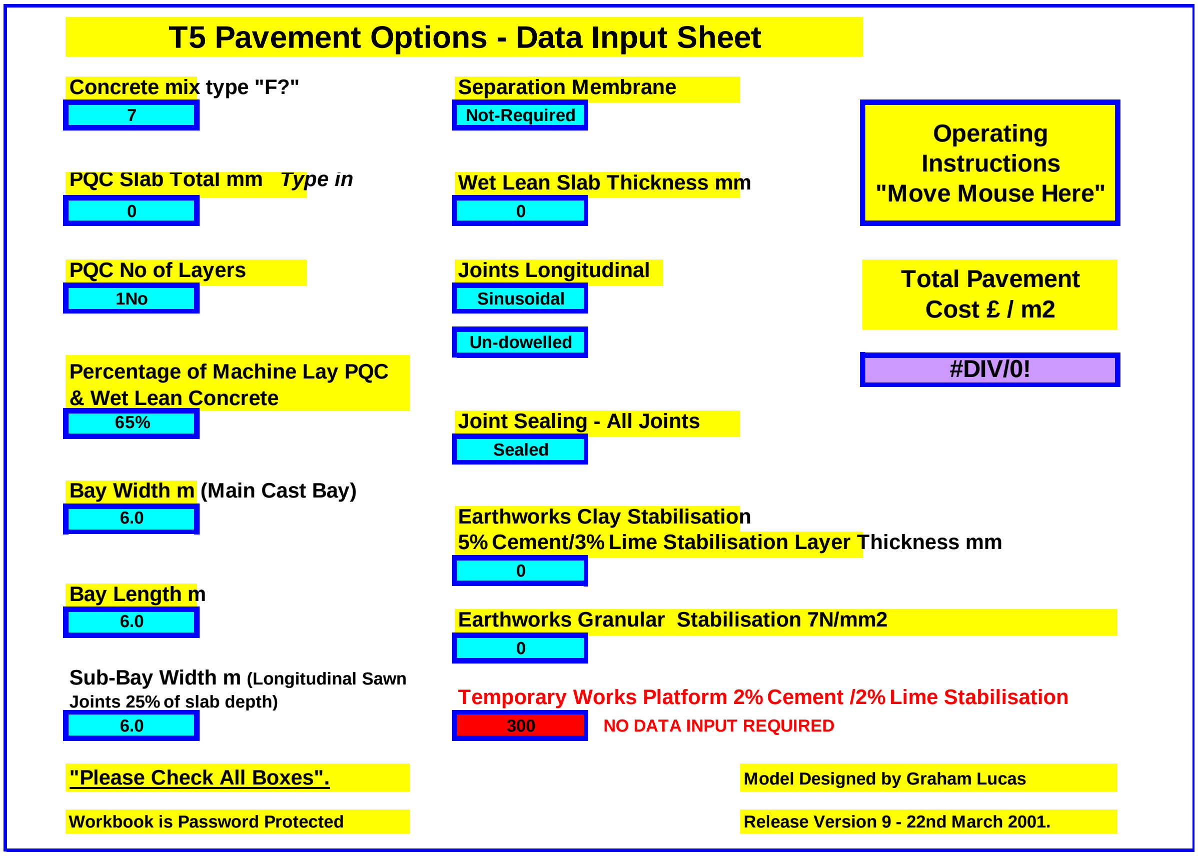
As the pavement design and construction methodology has been developed, laboratory testing and full scale site trials have provided more accurate production rates and costing data. The cost model has been constantly updated to reflect these developments. Examples have included revised paver production rates and more accurate costing of the concrete mix designs.

Comparisons have shown that the cost model delivers costed solutions which are to within 2% of accurately billed estimates.

Cost Model Structure and Operation:

The input/output interface on the cost model allows a variety of design and construction variables to be selected. By using real time cost and production information, the cost model outputs a pavement cost based on a square metre rate. An example input/output screen is shown in Figure 8.

Figure 8.
Cost Model - Data Input / Output Interface.



T5 Pavement Options - Data Input Sheet

Concrete mix type "F?": 7

PQC Slab Total mm *Type in*: 0

PQC No of Layers: 1No

Percentage of Machine Lay PQC & Wet Lean Concrete: 65%

Bay Width m (Main Cast Bay): 6.0

Bay Length m: 6.0

Sub-Bay Width m (Longitudinal Sawn Joints 25% of slab depth): 6.0

Separation Membrane: Not-Required

Wet Lean Slab Thickness mm: 0

Joints Longitudinal: Sinusoidal, Un-dowelled

Joint Sealing - All Joints: Sealed

Earthworks Clay Stabilisation 5% Cement/3% Lime Stabilisation Layer Thickness mm: 0

Earthworks Granular Stabilisation 7N/mm2: 0

Temporary Works Platform 2% Cement /2% Lime Stabilisation: 300 NO DATA INPUT REQUIRED

Operating Instructions "Move Mouse Here"

Total Pavement Cost £ / m2: #DIV/0!

"Please Check All Boxes".

Workbook is Password Protected

Model Designed by Graham Lucas

Release Version 9 - 22nd March 2001.

The cost model comprises a number of linked worksheets within Microsoft Excel (Figure 9).

All basic rates are extracted directly from the Pavement Team Estimating system within the "Resource Costs" worksheet. The build up of these rates is carried out in conjunction with the key construction methodology assumptions (e.g. paver speed, delivery truck turnaround times and carrying capacity of delivery trucks).

The "Cost Build-up by Construction Process" worksheet then uses the basic resource costs to calculate a cost per square metre for each construction operation. The PQC laying cost for machine lay is a good example of how the costs are built-up (Table 1).

Table 1.
Rate calculation.

Item Code No.	Item	Unit	Cost per Unit	Rate per m^2
220550	Slipform Paver	m^2	#	#
220551	Paver Consumables	m^2	#	#
23201	Fuel-Gas Oil	litre	#	#
41853	PQC Curing Agent	m^2	#	#
14143	Paver Foreman	hr	#	#
141111	Paver Operative Skilled	hr	#	#
14112	Paver Operative Labour	hr	#	#
14107	Skilled Labourer	hr	#	#
210120	Wheeled 360° Excavator	hr	#	#
220852	Floor Saw	wk	#	#
2208521	18" Diamond Saw Disc	wk	#	#
			TOTAL COST	£#/m^2

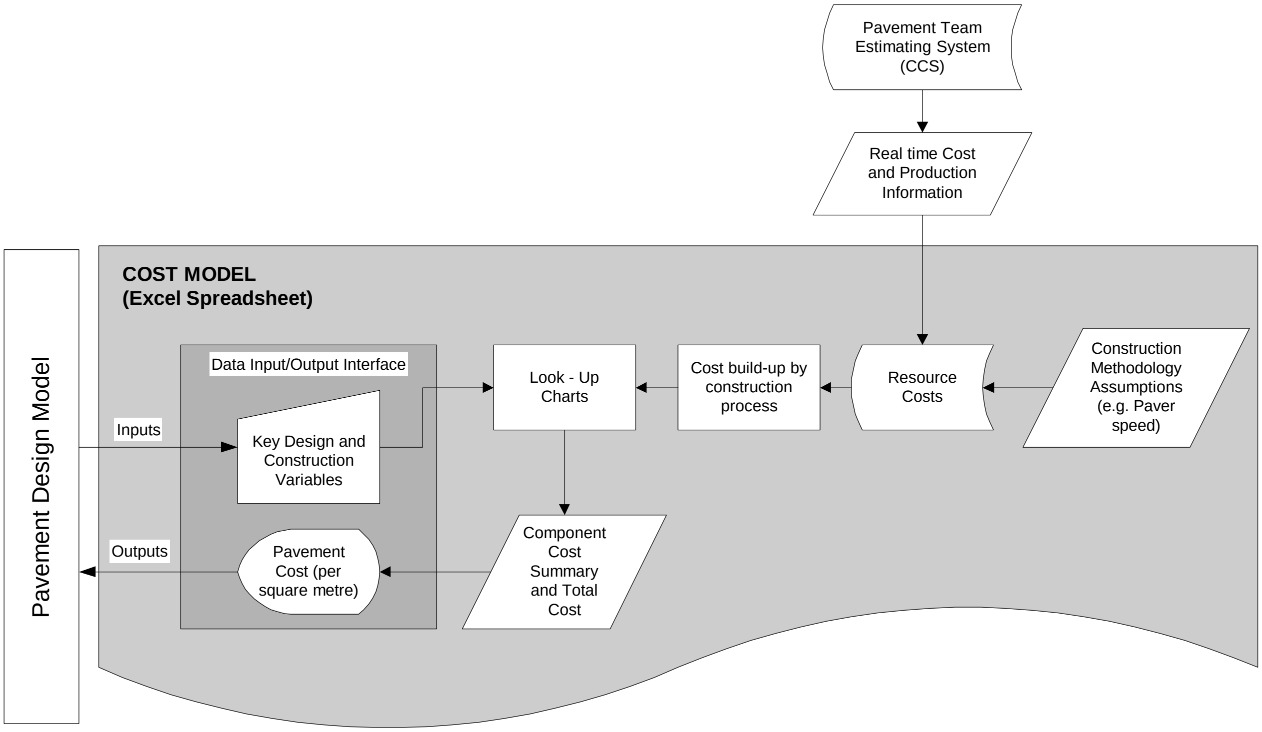
The "Look-Up charts" worksheet is pivotal in the calculation of a final cost per square metre of pavement. It queries the information provided by the pavement design programme on the Input interface and compares the required input variables with the data contained in the cost build-up worksheet. A typical example is the proportion of machine lay and hand lay PQC. The look-up charts worksheet reads the percentage split given in the input sheet and calculates the cost based on the production rates stated in the cost build-up worksheet.

A cost per square metre for each item is then calculated in the "Component Cost Summary and Total Cost" worksheet which outputs the final result to the Output interface.

Integration of the BAA Design Method and Cost Model

Optimising the design for a wide range of parameters to find the lowest cost requires a large number of design calculations. When these must be repeated for 74 Construction Locations the number of calculations is very large. Although there are a number of quite sophisticated computer design packages available they calculate a design requirement for a single set of input parameters. Running many calculations with varying inputs is time consuming and difficult to document.

Figure 9.
Cost Model Structure.



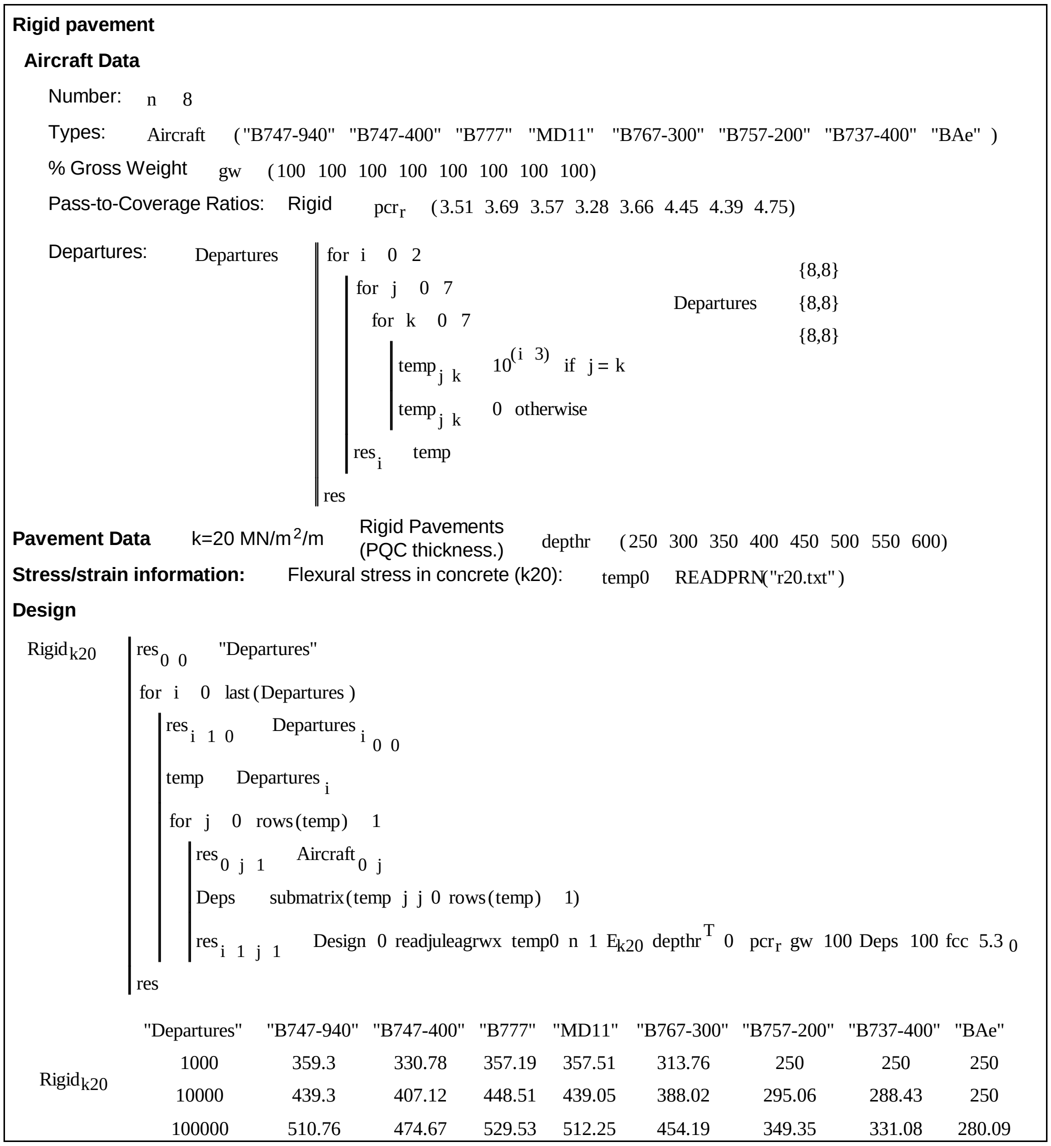
The spreadsheets provided with the BAA design guide have similar problems, and varying parameters such as aircraft types is difficult because of the need to import a new range of stress values.

The standard calculation method used by the T5 Pavements task team is an implementation of the BAA design method using the mathematics programme Mathcad, which has been verified against the BAA design guide and associated spreadsheets. The method allows relatively simple loops through a range of parameters, as shown in Figure 10 which presents 24 pavement designs. However, the method does not allow loops through multiple variables, and testing showed that Mathcad could not pass sufficient variables to the cost model to enable a cost to be retrieved or carry out the proposed design optimisation at practicable speeds.

It was therefore decided to write a new design model capable of calculating design requirements based on all necessary input parameters, and returning the cost from the cost model to find the minimum cost and the optimum pavement design. The design model is shown in Figure 11.

The core of the model is an ActiveX Dynamic Link Library called APCM, written in Visual Basic 6, which can be called from Visual Basic for Applications in an Excel spreadsheet. APCM finds stresses for a given aircraft, subgrade strength and pavement structure from a file of stresses using database queries via ActiveX Data Objects (ADO).

Figure 10.
Example Mathcad Calculation (verification against BAA Design guide for k = 20 MN/m^2/m).



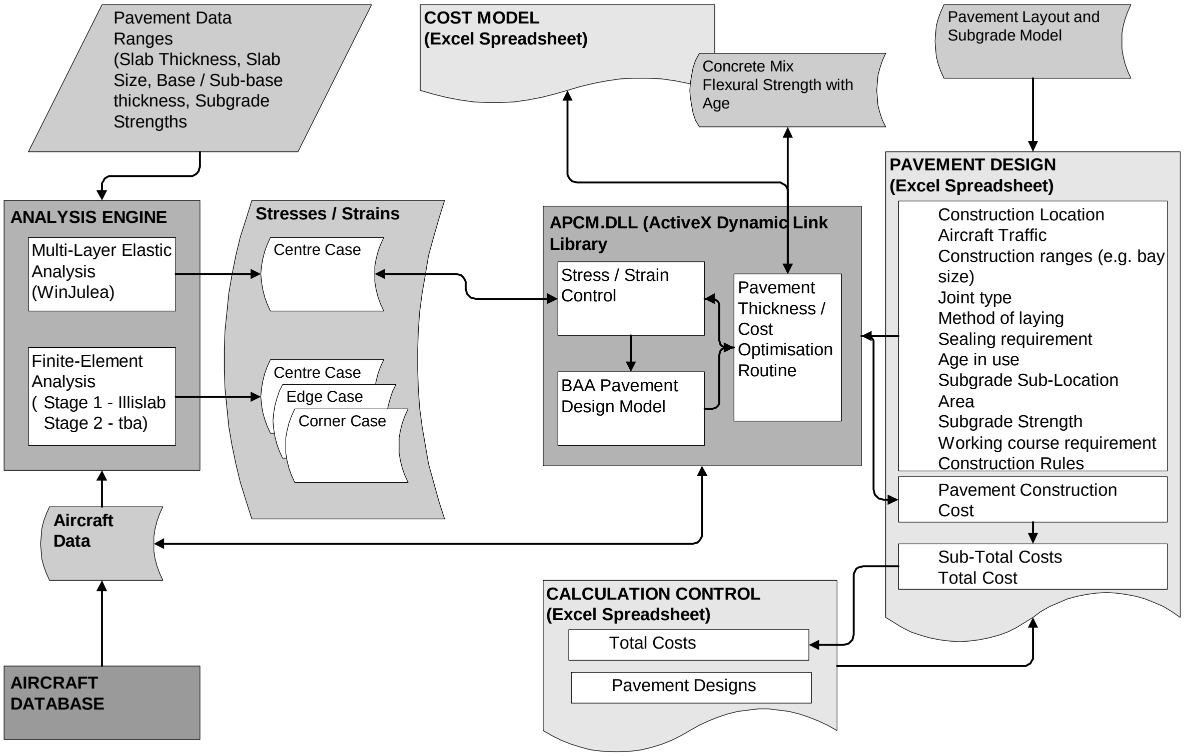
```
Rigid pavement
 Aircraft Data
   Number:      n    8
   Types:       Aircraft   ("B747-940"  "B747-400"  "B777"  "MD11"  "B767-300"  "B757-200"  "B737-400"  "BAe" )
   % Gross Weight    gw   (100  100  100  100  100  100  100  100)
   Pass-to-Coverage Ratios:   Rigid     pcr_r   (3.51  3.69  3.57  3.28  3.66  4.45  4.39  4.75)

   Departures:      Departures   | for  i   0  2
                                 |   for  j   0  7                                  {8,8}
                                 |     for  k   0  7              Departures        {8,8}
                                 |       temp_j k     10^(i  3)   if  j = k         {8,8}
                                 |       temp_j k     0  otherwise
                                 |   res_i    temp
                                 | res
Pavement Data    k=20 MN/m^2/m    Rigid Pavements     depthr    (250  300  350  400  450  500  550  600)
                                  (PQC thickness.)
Stress/strain information:    Flexural stress in concrete (k20):    temp0   READPRN("r20.txt")
Design
  Rigid_k20   | res_0 0      "Departures"
              | for  i    0   last(Departures)
              |   res_i 1 0      Departures_i 0 0
              |   temp     Departures_i
              |   for  j   0   rows(temp)    1
              |     res_0 j 1      Aircraft_0 j
              |     Deps      submatrix(temp  j  j  0  rows(temp)    1)
              |     res_i 1 j 1      Design  0  readjuleagrwx  temp0  n  1  E_k20  depthr^T  0   pcr_r  gw  100  Deps  100  fcc  5.3 _0
              | res

               "Departures"   "B747-940"   "B747-400"   "B777"   "MD11"   "B767-300"   "B757-200"   "B737-400"   "BAe"
                  1000          359.3        330.78     357.19   357.51    313.76        250          250         250
  Rigid_k20       10000         439.3        407.12     448.51   439.05    388.02       295.06       288.43       250
                  100000        510.76       474.67     529.53   512.25    454.19       349.35       331.08      280.09
```

An overview of how APCM works is shown in Figure 12. The Construction Data, Construction Rules, Pavement Structure and Aircraft Data are supplied for each Construction Location in turn by the design spreadsheet. APCM calculates a design requirement and obtains a cost for it. The minimum cost per square metre is found and returned to the design spreadsheet.

The system allows:

- Construction rules to be applied to match the construction methodology.
- Multiple variables to be handled, so that for instance the thickness of both PQC slab and bound base layers can be varied to find the optimum ratio of the layer thicknesses. If the PQC slab reached the limit of the construction range, the bound base can continue to increase until sufficient support is provided to control the PQC slab thickness.

Figure 11.
Integrated design and cost model.



A separate design spreadsheet is created for each alternative, holding the construction data, construction rules, and specific data for each Construction Location including the aircraft mix and traffic. A costed pavement construction is calculated for each Construction Location.

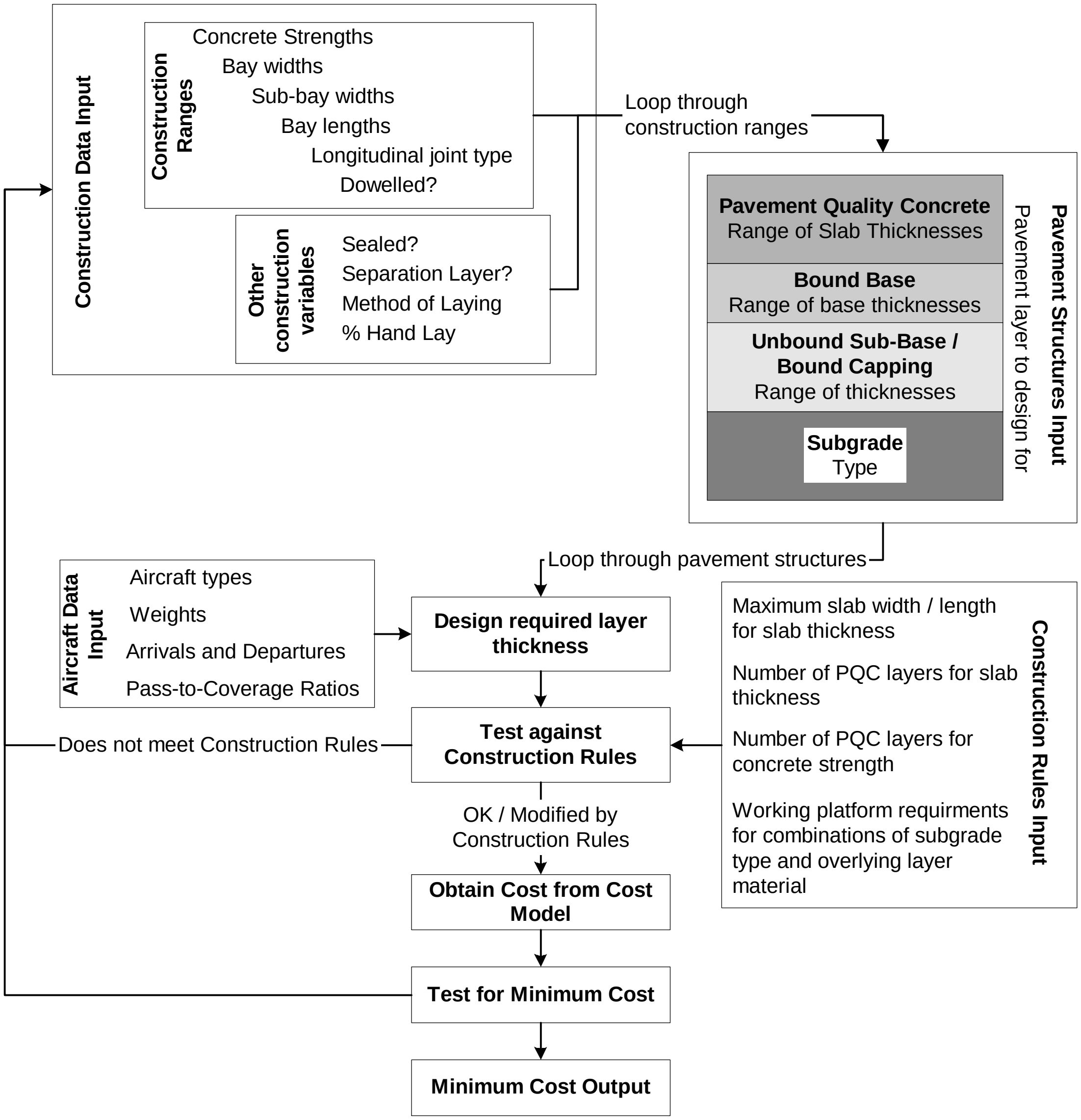
A control spreadsheet is used to hold references to all design spreadsheets, and the total cost for each alternative is returned to the control spreadsheet. An example control spreadsheet is shown in Figure 13.

Results

The integrated design and cost model has provided the team with a rapid and accurate method of considering the opportunities identified in the Opportunity Register and making an assessment of whether they are worth pursuing. Potential cost savings have been used to justify research and development, including trials, into the practicability of constructing very thick slabs and using very high strength concretes.

Figure 14 illustrates the potential cost savings at some key stages in the development of the design alternatives (Figure 15), in terms of a cost ratio to a conventional design mainly in accordance with the BAA design guide (the significant difference compared to the BAA design guide is the use of a 6 N/mm^2 mean flexural strength of concrete compared with the standard 5.3 N/mm^2 following development work be The Pavement Team). The potential cost savings are significant, and probably considerably greater than could be achieved by lowest-cost tendering for a design by a conventional design process.

Figure 12.
APCM.



Conclusions

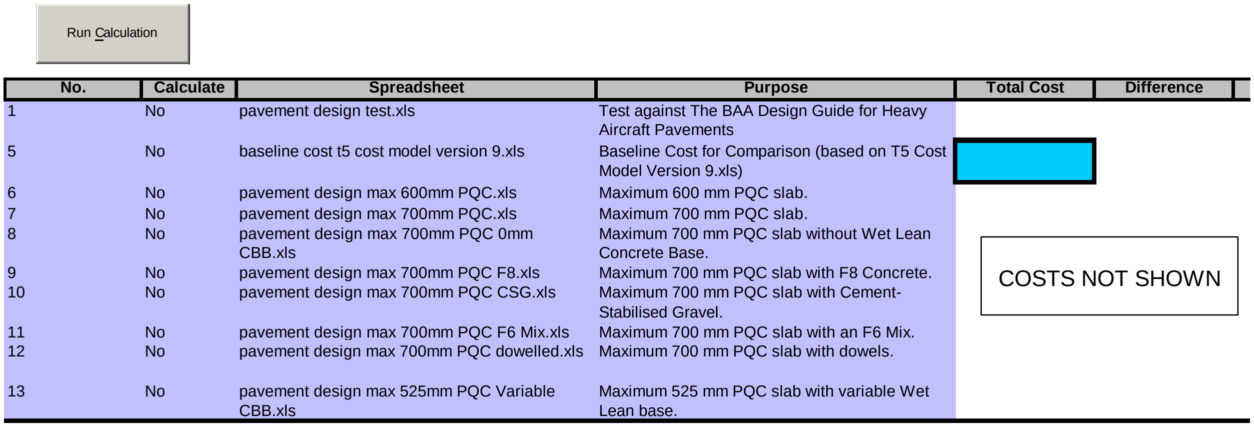
The T5 Pavements task team are taking advantage of the partnership arrangement for the construction procurement of the project to optimise the design for the construction methodology and known materials. The aim is to obtain the lowest practicable capital cost, while producing benefits in whole-life cost, environmental impact and health and safety.

An integrated design and cost model has been developed to provide rapid and accurate cost comparisons between alternative proposals, allowing a realistic assessment of their acceptability and justification for further work and trials where appropriate.

Siginificant opportunities for cost savings could only be developed by the integrated supply chain.

The team believe that the potential cost savings are considerably greater than could be achieved by conventional lowest-cost tendering.

Figure 13.
Example Control Spreadsheet.



No.	Calculate	Spreadsheet	Purpose	Total Cost	Difference
1	No	pavement design test.xls	Test against The BAA Design Guide for Heavy Aircraft Pavements		
5	No	baseline cost t5 cost model version 9.xls	Baseline Cost for Comparison (based on T5 Cost Model Version 9.xls)		
6	No	pavement design max 600mm PQC.xls	Maximum 600 mm PQC slab.		
7	No	pavement design max 700mm PQC.xls	Maximum 700 mm PQC slab.		
8	No	pavement design max 700mm PQC 0mm CBB.xls	Maximum 700 mm PQC slab without Wet Lean Concrete Base.		
9	No	pavement design max 700mm PQC F8.xls	Maximum 700 mm PQC slab with F8 Concrete.		
10	No	pavement design max 700mm PQC CSG.xls	Maximum 700 mm PQC slab with Cement-Stabilised Gravel.		
11	No	pavement design max 700mm PQC F6 Mix.xls	Maximum 700 mm PQC slab with an F6 Mix.		
12	No	pavement design max 700mm PQC dowelled.xls	Maximum 700 mm PQC slab with dowels.		
13	No	pavement design max 525mm PQC Variable CBB.xls	Maximum 525 mm PQC slab with variable Wet Lean base.		

Figure 14.
Potential cost savings.

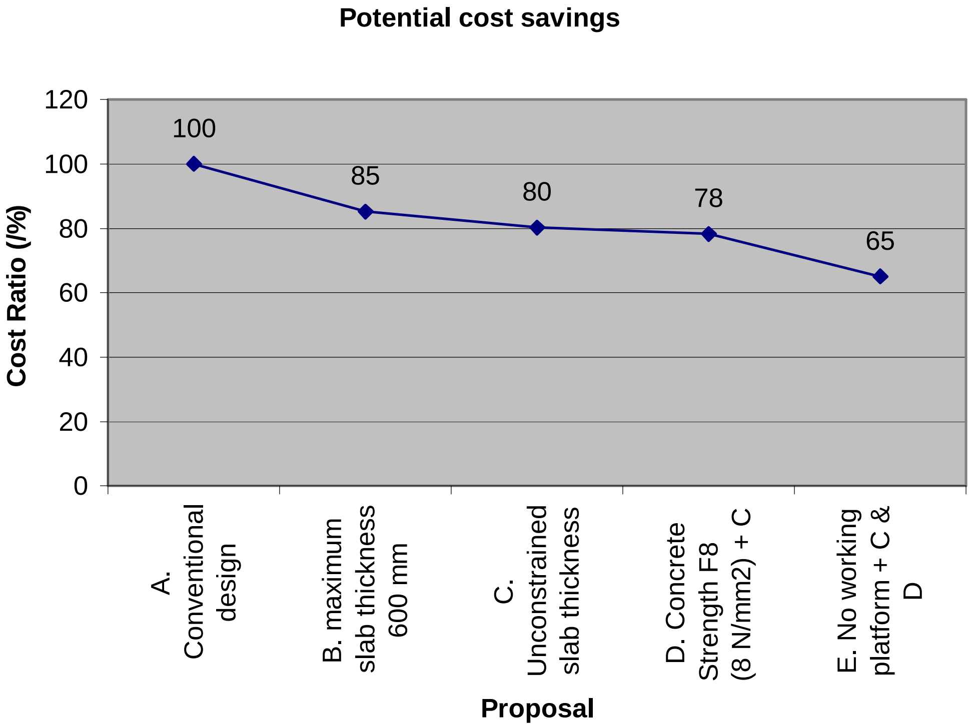
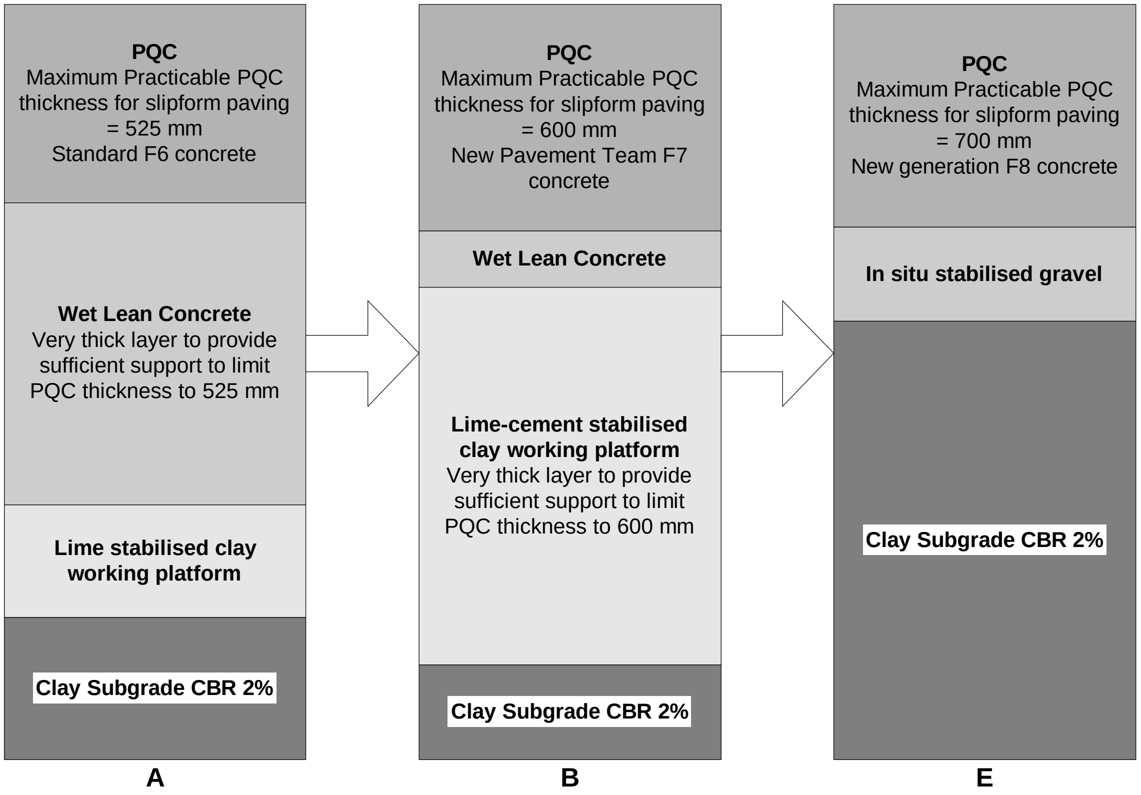


Figure 15.
Development of design proposals.



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