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Design and Implementation of the Analytic Hierarchy Process to identify the most suitable manufacturer of the High Speed Trains of the UK Infrastructure project, HS2

Abstract

The aim of this paper is to provide an answer to the strategic issue 'Identifying the most suitable manufacturer for the High Speed Trains of the UK Infrastructure project, HS2', using a suitable strategic decision-making method to identify over potential alternatives, primarily forms of Cost - Benefit Analysis, and implemented: the Analytic Hierarchy Process. This allowed for effective comparison of the four primary Rolling Stock manufacturers: Bombardier, Siemens, Hitachi and Alstom. The process involved conducting Pairwise Comparisons with respect to designed criteria. Eigenvectors formed the individual priorities of the manufacturers which were combined to produce the final priorities of each manufacturer and hence the most recommended manufacturer.

Keywords: Roiling Stock, Manufacturer, Analytic Hierarchy Process, Comparisons

1. Introduction:

HS2 is the current proposal to implement a High Speed Railway in the UK. It is split into two phases and is estimated for full completion by 2033 (HS2 Ltd, 2014b). The manufacturer for the High Speed vehicles has not yet been chosen, however the current investment budget for rolling stock stands at £9.2bn (£7.5bn with £1.7bn of contingency), (HS2 Ltd, 2014a). This amounts to approximately a fifth of the entire expected project cost, a very significant component and, hence, why the decision as to which manufacturer is receiving the investment, and delivering the High Speed vehicles, is of high importance.

Due to the substantial amount of resources to be invested in this project, decisions for how to best use them must be made in an appropriate and justified manner. However, there have been several discrepancies within the projects current decision and appraisal methodology. There have been cases where decisions have been forced by biased assumptions and uncertain demand forecasting (Aizlewood and Wellings, 2011). This has resulted in setbacks which could have been avoided. Therefore, it is crucial that initial decisions are made using an appropriate and defensible methodology. The aim for this investigation is to identify a decision making approach, which can be adapted and implemented to large strategic decision making for the UK infrastructure project, HS2. Once identified, this process will be implemented to reach a valid decision.

Upon identifying the method, the contribution of this study is the completion of a critical strategic decision that is yet to be made: 'Identifying the most suitable manufacturer for the High Speed Trains of the UK infrastructure project, HS2'. This is to be achieved by the use of a mathematically – justified, strategic decision making method known as the Analytical Hierarchy Process (Saaty, 1999). A conclusion will be presented of which rail manufacturer would be most suitable to manufacture and deliver the High Speed Trains of HS2. The reasons behind this concluded recommendation will be investigated and, hence, the validity of the model evaluated. Potential, future applications of the model, and this analysis, will be considered.

1.1. Objectives:

The objective of this investigation is to identify the most suitable manufacturer of the High Speed trains of HS2 using an appropriate strategic method.

1.2. Methodology:

This project involves a four step approach: Firstly formulating the strategic objective of identifying the most suitable manufacturer and what is meant by the 'most suitable manufacturer', secondly, identifying the most appropriate method to employ by critical analysis. Thirdly, designing the model and application of it to the problem and finally, concluding the most suitable manufacturer and evaluating the results and their potential future application.

2. Brief overview of HS2:

Due to the complexity of the HS2 project, it is important to understand the fundamentals of the proposal.

2.1. The Route:

The current proposed route for HS2 is split into two phases. Phase 1 is from London to Birmingham and is around 140 miles long. Phase 2 incorporates two lines, a Western leg, about 95 miles long, from Birmingham to Manchester and an Eastern leg, about 116 miles long, from Birmingham to Leeds. (HS2 Ltd, 2014a) These routes are shown in Figure 1.

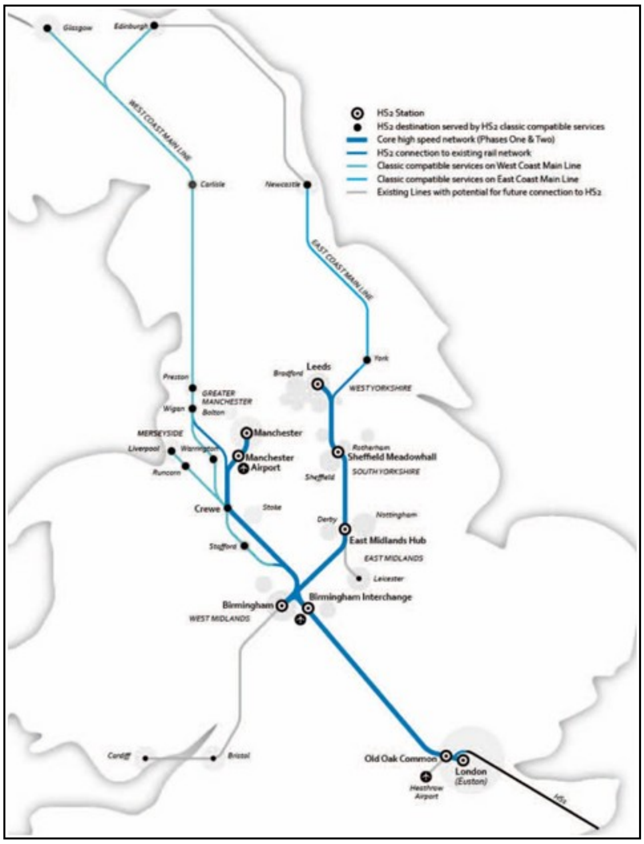


Figure 1 - HS2 Proposed Route (Cross, 2013)

Figure 1 also shows the stops where the HS2 line will pass through and the connectivity with the existing rail network. The planned route will provide improved connectivity to all areas of the North, including Newcastle and Edinburgh, and may provide the basis for construction of new high speed lines in the future.

2.2. *The High Speed Trains:*

The specific design requirements for the rolling stock have been outlined. The trains are to operate at speeds of 200 - 225mph, with the capability of operating at 250mph, faster than any current operating speeds in Europe. They are to be 400m long with up to 1,100 seats per train. Once Phase One has been completed, trains are scheduled to run 14 times per hour and, upon completion of Phase Two, this frequency will increase to 18 times per hour. Several of the vehicles will also be required to be 'classic compatible' which involves the ability to travel on conventional lines North past the High Speed Infrastructure beyond Leeds and Manchester (HS2 Ltd, 2012), (HS2 Ltd, 2014a), (HS2 Ltd, 2013) (Gov.uk, 2014).

2.3. What makes a 'suitable manufacturer'?

Aside from these specific design constraints there are also technical requirements that must be met, for example adhering to Technical Specifications for Interoperability (TSIs) (RSSB, 2013). However, the most important factors are based on the capability of the manufacturer to be able to deliver and maintain the vehicles, coupled with the assurance that the trains will be reliable (HS2 Ltd, 2012). These are quite intangible variables. Hence, being the reason it is difficult to compare the manufacturers easily in terms of suitability using a simple scale. Therefore, it was necessary to identify an appropriate strategic model that can incorporate these variables.

2.4. Motivations for HS2:

To choose the most suited manufacturer, the primary motivations for HS2 must be studied. According to the New Economics Foundation (NEF) the primary objectives of HS2 can be summarised from official documentation and ministerial statements as to:

- *'Provide essential future rail capacity;*
- *Catalyse economic growth and job creation in Britain;*
- *Rebalance the nation's economic geography and tackling the North – South economic divide;*
- *Contribute to Britain's low – carbon future' (Kersley and Theiss, 2013, p.3).*

The two principal objectives, as outlined in the Strategic case for HS2, are given below:

- *'The capacity objective is to create sufficient capacity to provide for long term demand for rail travel and improve rail network resilience and reliability, ensuring that people and goods are able to make the journeys they want.*
- *The connectivity objective is to improve journey times, making travel quicker, easier, more punctual and more convenient for people and goods, including supporting end-to-end journeys with effective integration and interchange between transport modes and with good connections, including with major airports, for international travel.' (DfT, Atkins and Network Rail, 2013, p.77)*

These objectives need to be at the forefront of the decision making process, coupled with the factors deemed most important.

3. Identification of the strategic decision method:

The three methods chosen for analysis are: Cost- Benefit Analysis (CBA), Multi Criteria Analysis (MCA) and the Analytic Hierarchy Process (AHP).

3.1. Cost - Benefit Analysis (CBA)

CBA involves weighing up the benefits and costs of an idea against each other to form the basis of a decision for a particular choice or course of action. The pros and cons of each potential choice are identified and an assessment of these made to produce a final recommendation. Its simplicity is its effectiveness (O'Farrell, 2014). Benefit – Cost Ratio (BCR) analysis is a primary tool used as part of a CBA approach to making effective strategic decisions. An example of this approach in strategic application is demonstrated in *Table 1*:

		Extra capacity	Costs	Benefits (excl. WEIs)	BCR (excl. WEIs)	Benefits (incl. WEIs)	BCR (incl. WEIs)
		%	£ billion NPV	£ billion NPV		£ billion NPV	
London–West Midlands							
HS2		>100	14	19	1.4	23.1	1.7
Strategic alternatives	'RP2'	56	2	8	4.0	9	4.7
	'RP2A'	56	3	7	2.7	8	3.1
	'51M'	56	1	6	5.2	7	6.1
Y network							
HS2		>100	25	41–47	1.6–1.9	47–59	1.8–2.5
Strategic alternatives	'Scenario B'	56/133/114	10	14	1.4	16	1.6

Note: 'RP2', 'RP2A', '51M' and 'Scenario B' are names given to conventional alternatives to high-speed rail. These strategic alternatives are packages of enhancements to the conventional network rather than new conventional lines. The alternatives to HS2 are primarily upgrades to the West Coast Main Line, while the alternative to the Y network also includes upgrades to the East Coast Main Line.
Source: Atkins (2012), 'High Speed Rail Strategic Alternatives Study Update Following Consultation', January.

Table 1 - Comparison of HS2 against other strategic alternatives using Benefit-Cost Ratios (Oxera, 2012, p.2)

Table 1 depicts the performance of HS2 against the other main strategic alternatives using BCRs. Combined with *Table 2*, which has been reproduced from the Department for Transport's (DfT's) own documents, shows HS2, without 'Wider Economic Impacts' (WEI's) included, presents only 'medium' value for money. With WEI's included this may move into the high boundary however since WEI's are relatively intangible (eg. Agglomeration), it is not sufficient to rely upon them to provide evidence for the economic value of a project. According to the DfT's own Transport Business Case, publically supported infrastructure projects should generally have a BCR greater than 2.0 (Worsley, 2013), where the DfT's BCR is the ratio of the "monetised benefit to society" to the "net cost to government". It is also important to mention the Eddington Transport Study (2006) found that the average BCR for UK rail investments was 2.83, significantly higher than the calculated value for HS2.

Value for Money Category	*Benefit Cost Ratio*
Poor	Less than 1.0
Low	Between 1.0 and 1.5
Medium	Between 1.5 and 2.0
High	Between 2.0 and 4.0
Very High	Greater than 4.0

Table 2 - Benefit Cost Ratio Value for Money categories (Kersley and Theiss, 2013, p.10)

When comparing HS2 to the strategic alternatives it is clear the BCR for HS2 London–West Midlands is also much lower in comparison to each alternative and their net benefits are slightly greater than the London–West Midlands section of HS2. However, when examining the proposed full Y–Network it is clear that the BCR of the Y –Network is greater than the strategic alternatives. This makes logical sense since High Speed Rail is utilised best over greater distances, as the actual high speed is maintained for longer causing more significant time savings. It is reasonable to assume Phase One of HS2 is not designed to perform as a standalone infrastructure project, more so as the first half of the project; even from the Y network it is plausible to assume further north construction of High Speed lines to reach Edinburgh and Newcastle may be on the future agenda. This is also backed up by Oxera (2012, p.3) who stated '*Although analysis of the Y network extension is much less advanced, the proposition that the case for the first phase is predicated on later extensions is likely to be well-founded, given that high-speed rail is more competitive over longer distances.*' This is one of the major flaws in the BCR analysis as it is hard to include and value qualitative concepts such as this. The BCR and other measuring tools of CBA, such as Net Present Value (NPV) can only be valid when measuring financial and economic factors. Their application when valuing non-monetised factors is much less accurate as it becomes a subjective opinion. These points cannot be directly addressed or used as part of a CBA decision making approach.

Taking into account qualitative concepts for comparison, by assigning a financial or monetised value, is often inaccurate. This is demonstrated by how the DfT valued time in their appraisal of HS2.

The issue which is the primary criticism of the DfT's economic case for HS2 is the value of time saved. More specifically, how they valued time saved to monetise the benefits in a way that could be compared to the costs. The DfT's case is heavily based on the benefits of time savings for travellers and the assumption they used was that all time spent on a train is not productive at all and therefore has a value of zero. '*The methodology then argues that that time on board a train is entirely wasted for business travellers so that a minute saved in journey time is an additional productive minute.*' (Aizlewood and Wellings, 2011, p. 28). This is completely mistaken as merely travelling on a train and observing will show business travellers working on laptops, taking calls, reading journals etc. This is all clearly productive and not a waste of time. Oxera (2012, p.2) also identified this criticism and stated it is an '*unrealistic assumption, given that casual observation on any train journey would find some evidence of passengers working*.'

In addition to this the DfT have used a very high value of time:

'For the appraisal of HS2, the DfT's value of time for rail passengers is based on passenger earnings of approximately £70,000 per annum or above, in 2010 values. Mean annual pay for workers in the UK in 2010 was £26,510, with even the 90th percentile only earning a mean salary of £46,428. If the average of £46,428 were used to estimate the value of time savings from HS2, still arguably a high value, the BCR would fall to the bottom of the "low" value for money category.' (Kersley and Theiss, 2013, p.7)

This clearly demonstrates skewed assumptions, therefore, an over-estimation of the value of time, which will have led to inflated and exaggerated user benefits which are at the heart of the economic case for HS2. This also shows how easily manipulated and biased the CBA can be, a methodology employed due to its simplicity and hence, usually, unified clarity in decision making.

'Put simply, without a high value for time saved, the economic case for HS2 is seriously degraded. 55 per cent of the benefits of HS2 according to the DfT's analysis are based on the value of travel time savings.' (Kersley and Theiss, 2013, p.7)

This lowers confidence in the entire economic case for HS2 and was even acknowledged by KPMG (2013), who were commissioned by HS2 Ltd to demonstrate the potential economic impact. In their report a study was carried out to calculate the impact of lowering the value of time of business users on the economic productivity benefits. A sensitivity analysis was used to understand the impact of using a 50% reduction in the value of business traveller's time on the total productivity impact for the British economy. The results showed HS2 could still potentially generate £12bn per annum in productivity gains in 2037 (2013 prices) which is a 20% reduction from the initial forecast of £15bn per annum. This is a relatively small impact however The Institute of Economic Affairs noted the effect it would cause on the user benefits of HS2. By, again, applying the assumption only '*50% of business travel time is unproductive, without any other change it immediate has the effect of reducing the BCR for the HS2 full Y route to less than 1.5.*' (Aizlewood and Wellings, 2011, p. 29). This is a significant reduction and greatly reduces the value for money of the entire scheme. Yet this demonstrates how easily a measurement tool of CBA can be manipulated and how invalid the actual outputs can be; which are then used as the basis for important decisions.

There is undoubtedly an obvious weakness to the methodology being employed by the DfT for the appraisal of HS2 and therefore the decisions made based upon this analysis cannot be very reliable and hence, in this case, due to the involvement of many unclear and intangible factors, the use of the CBA method is flawed. This was also the case with the current investigation therefore a more comprehensive method, that can involve both qualitative and quantitative factors weighted fairly, was used. A CBA based decision making method is far too subjective and can be skewed by the biases and assumptions of the analyst undertaking it. '*The ambiguity and uncertainty involved in quantifying and assigning a monetary value to intangible items leads to an inaccurate cost benefit analysis*'(Plowman, 2011); the impact from the different values of time, which may all have justification, clearly shows the discrepancies using a cost – based analysis method. This increased inaccuracy may lead to poor risk analysis and hence poor decision making. Assessing the decision using a CBA approach could not suffice when choosing the most suitable manufacturer for the HS2 rolling stock, as there are many qualitative factors and variables to take into consideration and it is too inaccurate to justify such large, uncertain decisions.

3.2. Multi-Criteria Analysis (MCA):

Multi-Criteria Analysis (MCA) is an alternative method for decision making that takes into account both the effects that are valued in monetary terms and others that aren't. A major flaw of CBA is its requirement for all costs and benefits to be valued under a common unit, usually monetary terms. However MCA places a weighting factor on the individual effects of each cost and benefit. These weighting factors are often derived by asking a variety of experts, individuals and decision-makers and are based on the primary objectives of the project. The fundamental difference between MCA and CBA is that economic efficiency is not the sole objective. Qualitative factors are much more effectively taken into account and diverse objectives are integrated into the decision making process. (Bekefi, Tanczos and Kiss, 2003). MCA was a much more suitable decision making method for this strategic decision, as the extensive range of factors can be fairly taken into consideration. EuropeAid (2005) summed up MCA's purpose as: '*Multi-criteria analysis breaks down the components of complex situations and structures them, in order to progressively find a solution in a transparent way*'. This was a desirable method for such a large and significant decision.

However, a clear framework was required, where the weightings can be more accurately calculated. The success of using MCA relies on its design. If done improperly, without agreement and a thorough structure, its application is very limited and has no true value (Steevens and Linkov, 2014). Therefore the issue was not whether or not to employ a MCA, but rather which structure to use. Once an appropriate framework is chosen and administered MCA can actually be more efficient than CBA in evaluating part of a project like HS2 (Durrant, 2013).

The importance of the structure is due to the overwhelming number of intangible, qualitative variables and factors that have affect and are, therefore, difficult to assign a value. For example, in this case, 'experience', which can then be measured in terms of experience (in years) involved in High Speed Rail, experience implementing large rolling stock projects in different countries and experience of application in the UK. This is only one example and there are many layers, factors and variables concerning this decision; an effective, logical and mathematically-just structure which can relatively incorporate these elements must therefore be applied. There are many subjective components to this strategic decision which need to be measured and weighted as fairly as possible. This leads to the structure deemed most applicable to such a complex strategic decision, involving not just several subjective factors but also different levels and aspects within these factors, being the Analytic Hierarchy Process.

3.3. The Analytic Hierarchy Process (AHP):

An established model of MCA which is renowned for its ability to approach and solve complex, strategic problems is the 'Analytic Hierarchy Process' (AHP) designed by Thomas L. Saaty in the 1970s. AHP is a method which involves breaking down unstructured and complex decisions or situations into their primary components. These components are then organised into a hierarchy and their relative numerical values assigned through judgments on their relative importance with regards to each element. Finally these judgments are synthesised to determine the most important alternative and hence, what should be acted upon to best influence the outcome. (Saaty, 1999)

This model provides a framework which breaks down complex decisions into smaller simpler comparisons which, together, produce a final, mathematically calculated, order of priority and subsequently a final, mathematically recommended, decision.

The validity of the Analytic Hierarchy Process, as a decision making method, has been confirmed and supported in a variety of cases. There are several examples in Saaty's book (Saaty, 1999) where the validity has been established by comparing the final derived priorities from the analysis with those achieved by decision makers. For instance, Saaty describes the discussion of top planners within a corporation where they were asked 'how the chairman of the board viewed the various sectors of the corporation's activity'. The priorities were derived from pairwise judgments on the allocation of effort. Afterwards, these final priorities were compared against the actual amount of capital invested in each sector. The results were closely matched, hence demonstrating the validity of the AHP pairwise judgements and method.

The reason for choosing AHP for application in this study was due to its primary purpose being for strategic level decision making (Saaty, 1999). It provides a clear, logical and relatively simple framework to breakdown a complex decision into its fundamental components, hence, providing the structure needed for MCA. It is able to fairly assess quantitative and qualitative factors, thus, outperforming CBA. Therefore the AHP method was chosen to implement and therefore, make this decision.

3.4. Outline of the AHP method:

1- Defining the problem and desired solution;
2- Structuring of the Hierarchy;
3- Construction of the Pairwise comparison matrices;
4- Complete all the pairwise judgments using the fundamental scale;

5- Transferral of the judgments into matrices;
6- Perform steps 3, 4 and 5 for all pairwise comparisons;
7- Use the synthesis method to produce the eigenvectors and priorities for each matrix and hence calculate the final priorities. (Saaty, 1999).

4. Application of the Analytic Hierarchy Process:

The most suitable manufacturer for the HS2 rolling stock was chosen from the four primary manufacturers, identified from research as:

- Bombardier
- Siemens
- Hitachi
- Alstom

The possibility of a consortium forming and political influence has been discounted for the purpose of simplifying the analysis.

4.1. Define the problem and specify the solution desired

The problem was choosing the most suitable manufacturer out of the 4 primary manufacturers to design and build the rolling stock for HS2: Bombardier, Siemens, Hitachi and Alstom. The primary objective was therefore: 'Identifying the most suitable manufacturer for the High Speed Trains of HS2' and the solution being a recommendation of the manufacturer to be chosen for the £9.2bn investment in rolling stock.

4.2. Designing the Hierarchy:

The Hierarchy is a simple model which outlines the framework of the process.

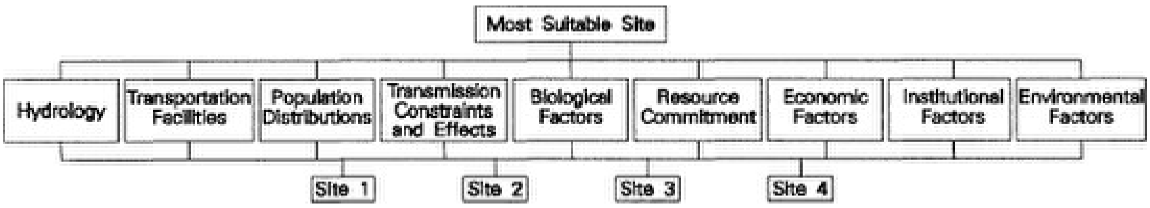


Figure 2 – Example Hierarchy (Saaty, 1999)

The Hierarchy is designed where the bottom level consists of the 'alternatives' or choices the decision is to be made from. As shown in the example Hierarchy, *Figure 2*, the different possible sites and, in the case of this investigation, the different potential manufacturers for the HS2 rolling stock. The middle level consists of the criteria selected to judge the alternatives, such as: 'Population Distributions' or 'Economic Factors' in *Figure 2*. In the case of this investigation the criteria were designed as shown in *Section 4.3.* Finally, the top level is a single element known as the 'focus' or 'overall purpose'. This is the broad, overall objective of the analysis, in the case of the example 'Most Suitable Site'. The objective for this study is 'Identifying the most suitable manufacturer for the High Speed trains of HS2' which formed the focus for this analysis.

4.3. Identification and design of the criteria:

The primary objectives of HS2, design constraints and expectations of the High Speed Trains have been studied to design the most definitive criteria for this analysis.

From the primary motivations for HS2 (see section 2.4) it was clear the trains of HS2 must meet certain desired criteria yet, the most important and foremost being:

Operate at speeds of 200 (320kmph) - 225mph (360kpmh) with capability of operating at 250mph (400kmph). *(HS2 Ltd, 2012)*

This is responsible for the time savings predicted and provides the foundation for the economic case. Without such substantial time savings created by the speed of operation of the High Speed Trains of HS2, the case for its construction would be heavily undermined (Aizlewood and Wellings, 2011); '55 per cent of the benefits of HS2' are due to the time saved *(Kersley and Theiss, 2013, p.7)*. Therefore, this was an issue of high priority, hence why the operation/experience of Very High Speed Trains (≥320kmph) was a criterion which can demonstrate the suitability of a manufacturer. This was measured in terms of experience, the more the better. The reliability of the trains is of high importance. Design constraints of trains running 14 times per hour for Phase One and 18 times per hour for Phase Two (HS2 Ltd, 2012) are not minor requirements, therefore, reliability of the trains is very important and a method to predict future reliability is by measuring experience. Experience in the High Speed sector, measured in terms of time and countries of application, demonstrates extensive knowledge and application of High Speed which is an important factor in predicting the reliability of the potential HS2 trains produced.

Another element of experience is application, of not just High Speed, but High Speed on a large UK infrastructure project. An obvious choice was HS1; this provided a basis to how the manufacturer has performed implementing High Speed on new UK infrastructure in a large new infrastructure project. Since the primary objectives of HS2 include to '***Catalyse economic growth and job creation in Britain'*** *(Kersley and Theiss, 2013).* It was important that this was taken into account. A practical measure was 'UK Factory Location' since this demonstrated the potential job creation in the UK from the manufacture and maintenance of the future rolling stock. Yet, in addition, this also demonstrated potential reliability. More maintenance factories in the UK, such as TrainCare facilities, enable any breakdowns to be dealt with more easily and the actual prevention of breakdowns in the future. The capability to provide and service the trains produced greatly relies on the location of UK factories, the more the better. The actual company behind the manufacture of the trains was also studied and compared due to the size and duration of the HS2 project. It must be clear the manufacturer, to be invested in, has the size and strength to be a safe investment. This means their future must appear to be strong and not unpredictable. A measure of this was the current size and strength of the company measured by its size in revenue and number of employees. Profits were also studied to delve further. A high level of confidence is required to substantiate the investment of £9.2bn.

For a final criterion the technical element of railway traction was studied. More specifically the traction of the Very High Speed Trains the manufacturer is currently offering and implementing. Huge advancements in Electrical traction and locomotive technology are responsible for the rise of High Speed (Lozano et al, 2012). The adaptability and flexibility of the HS2 trains is important, some of the Trains produced will need to be able to run on the conventional infrastructure (HS2 Ltd, 2012) as well as the HS2 infrastructure. Also if future links with HS1 and Europe are created, the adaptability of the vehicles to be able to perform on varying traction, such as DC and AC, of varying ratings in Europe, may become significant. Therefore the versatility of their traction, within different electrical modes, is what has been studied and used to form the comparison measure; a greater degree of flexibility being more desirable. Therefore the final six criteria designed for the AHP analysis to identify the most suitable manufacturer for the HS2 Trains:

- Very High Speed Train in Operation (≥320kmph);
- Experience in High Speed sector;
- Application in HS1;
- UK Factory Location;
- Size and strength of company;
- Traction of Very High Speed Trains.

4.4. Constructing the Hierarchy:

By compiling the Focus, Alternatives and designed criteria, the Hierarchy for this analysis was constructed, see *Figure 3*:

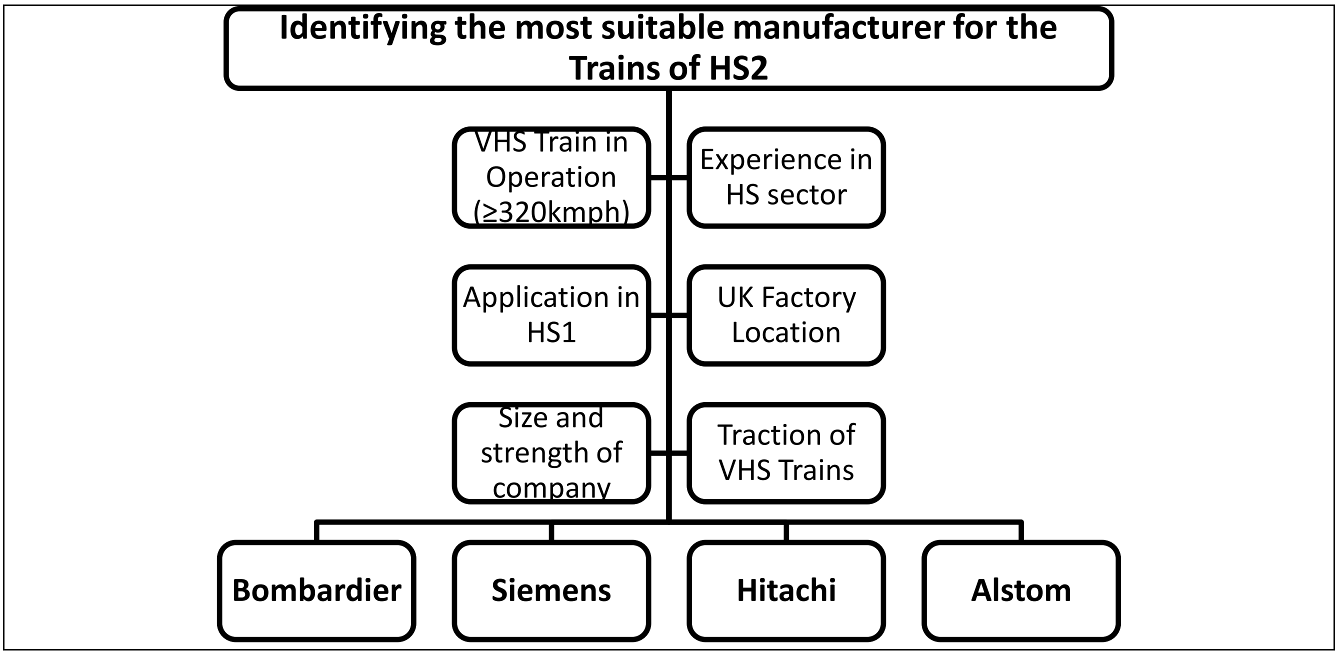


Figure 3 – The Hierarchy for this investigation

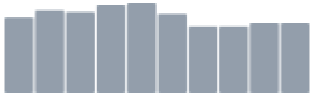
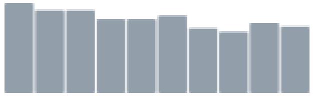
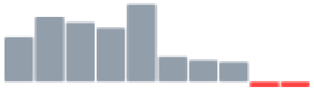
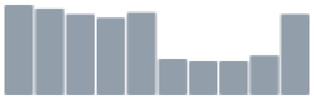
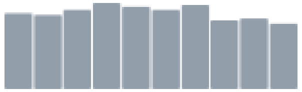
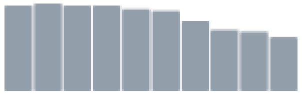
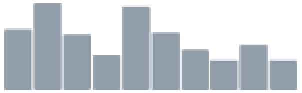
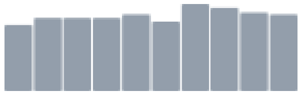
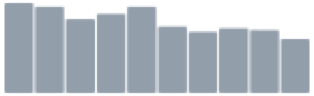
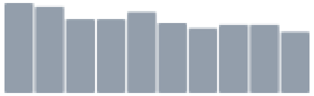
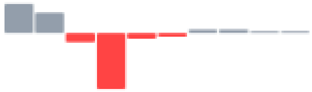
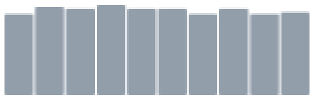
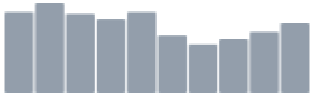
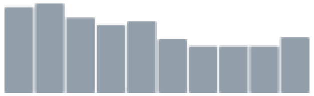
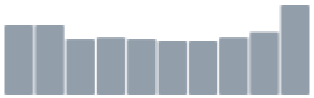
The bottom level alternatives are assessed by 'Pairwise Comparison' against each other, with respect to each of the Criteria in the middle level. Once this has been completed, the Criteria are then assessed by the same method against each other with respect to the focus.

4.5. Manufacturer Profiles:

A table of all the required data to make the decisions has been created; this allowed the judgments to be made efficiently and fairly. It also made tracing decisions easier which can ensure accuracy; it can allow amendments to be implemented more easily and allowed more thorough comparison when conducting the analysis multiple times. To compare each manufacturer with respect to each criterion, a table of data and facts was compiled from extensive research. The data was collated from a range of sources including the manufacturer's own portfolios, articles and several other sources. The consistency of the data was kept to a high level to try and make the decisions as unbiased as possible. The Final Manufacturer Profiles are shown in *Table 3* and all sources the information has been gathered from.

<table>
<tr><th>Bombardier</th><th>Siemens</th><th>Hitachi</th><th>Alstom</th></tr>
<tr>
<td>Very High Speed Trains:
Bombardier Zefiro 380 beginning operation this year in China
Bombardier Zefiro v300 (Frecciarossa 1000) beginning regular service 2015/2016
Bombardier-Alstom consortium delivering Duplex
Bombardier helped construct – Siemens ICE 3 Class 403/406 – over 320 kmph since 2000
Experience in High Speed:
Bombardier accumulated over 20 years’ experience in HS sector (from website)
Sweden X50 models service since 2000
BR Class 370 “Advanced Passenger Train” since 1980
BR Class 91 since 1988, both by BREL which is now part of Bombardier
HS Trains in: Spain, Britain, Italy, China, France, Sweden, Germany, Switzerland, Netherlands
Individual – BR Class 220,221,222 and all Sweden X50, X52 and X54 models</td>
<td>Very High Speed Trains:
Siemens ICE 3 Class 403/406 (greater than 320kmph) since 2000.
ICE 407 (Velaro D) by Siemens. Service since 2011
Velaro e320 for HS1 starting 2014/15
Experience in High Speed:
Siemens involved in ICE 1, service since 1991, but not primary manufacturer
ICE 2 since 1996
ICE 3 individual since 2011
HS Trains in: UK, China, Germany, Netherlands, Austria, Denmark, Russia, Czech Republic, Spain, Turkey
Individual – ICE 3, Eurostar e320, AVE class 103, Railjet</td>
<td>Very High Speed Trains:
Shinkansen E6 – with Kawasaki service since 2013
Shinkansen E 5 – with Kawasaki service since 2011
Experience in High Speed:
Shinkansen 0 service since 1964, Shinkansen 200 since 1982 -2013, Shinkansen 100 since 1985 – 2012
Shinkansen series 300 service since 1992
BR Class 395 since 2009
Extensive portfolio and very strong experience in HS but only in Japan, collaboration with Kawasaki mainly
HS Trains in: Japan, Taiwan and UK
Individual - BR class 395 and Shinkansen 800 (2004)</td>
<td>Very High Speed Trains:
TGV Réseau – service since 1993
TGV Duplex – service since 1995
TGV POS – service since 2006
Thalys PBA – service since 1996
AGV – service since 2012
Experience in High Speed:
TGV Sud- Est since 1981
HS Trains in: UK, Czech Rep, Poland, Italy, Switzerland, France, Belgium, Finland, Russia, Germany, Netherlands, Sweden, Spain, China, South Korea and US
Individual – BR Class 180, 390, CD Class 680, ED 250, ETR 575 (AGV), 600, 610, Eurostar class 373, TGV Sud-Est, Atlantique, Réseau, Duplex, POS, Thalys PBA, Thalys PBKA, X3,40</td>
</tr>
</table>

Bombardier	Siemens	Hitachi	Alstom
Application in HS1: • Bombardier no direct application in HS1 **UK Factory Location:** • Derby – Production Engineering, Plymouth–Engineering/ Rail Control solutions–production, • **27 sites overall, 19 services, 3 manufacturing, 2 engineering** **Size and strength of Company:** • Using Forbes Global 2000 (May 2013): • Sales = $16.77bn • Employees= 71,700	**Application in HS1:** • Siemens chosen and won tender for **Class 374** – Eurostar Velaro e320 to begin service in 2015 – travel 320kmph **UK Factory Location:** • Leeds Neville Hill Traincare Facility • No manufacturing sites, rolling stock would have to be manufactured in Germany • **11 sites overall, 6 Traincare facilities** **Size and strength of Company:** • Using Forbes Global 2000 (May 2013): • Sales = $100.64bn • Employees= 365,000	**Application in HS1:** • **Class 395 –** Javelin, service since 2009 delivered 6 months ahead of schedule, successful implementation, reliable and high satisfaction rates, speed 225kmph **UK Factory Location:** • Ashford Train Maintenance Centre • Constructing new manufacturing plant–Merchant Park, Newton Aycliffe, county Durham • Operational from 2015 to construct next generation of intercity trains, therefore could manufacture rolling stock in UK • **2 sites overall, 1 Maintenance centre, 1 manufacturing site under construction** **Size and strength of Company:** • Using Forbes Global 2000 (May 2013): • Sales = $116.76bn • Employees = 328,278	**Application in HS1:** • **Class 373 –** Service since 1994, one accident, few minor technical incidents. Speed up to 300kmph. Longest and fastest train in UK service at present **UK Factory Location:** • Birmingham International Traincare point • Liverpool Traincare centre • No manufacturing sites in UK, rolling stock built in Europe • **19 sites overall, 13 Traincare points** **Size and strength of Company:** • Using Forbes Global 2000 (May 2013): • Sales = $26.61bn • Employees = 85,449

Bombardier	Siemens	Hitachi	Alstom
Market Cap **$7.27 B** Employees **71,700** Cash on Hand **$2.9 B** Debt **$5.36 B** Revenue **$16.77 B**  Assets **$25.79 B**  Profit **$588 M**  Employees **71,700** 	Market Cap **$91.92 B** Revenue **$100.64 B** Employees **365,000** Cash on Hand **$14.72 B** Debt **$29.28 B** Revenue **$100.64 B**  Assets **$134.45 B**  Profit **$5.73 B**  Employees **365,000** 	Market Cap **$28.46 B** Employees **328,278** Cash on Hand **$8.68 B** Debt **$26.19 B** Revenue **$116.76 B**  Assets **$113.18 B**  Profit **$4.19 B**  Employees **328,278** 	Market Cap **$13.95 B** Employees **85,449** Cash on Hand **$2.81 B** Debt **$6.7 B** Revenue **$26.61 B**  Assets **$39.39 B**  Profit **$977.3 M**  Employees **85,449** 

Bombardier	Siemens	Hitachi	Alstom
Traction: • **Bombardier Zefiro:** • 'Scalable Traction Power' HS and VHS Trains 'Up to 4 power supply voltages (1.5 & 3kV DC, 15 & 25kV AC) • Allows cross-border operation on all AC and DC powered lines.	**Traction:** • **Siemens Velaro:** • Options depend on configuration • Velaro E = 25kV AC • Velaro D/ e320 = 25kV AC/ 1.5kV DC • Velaro RUS = 25kV AC/ 3kV DC • Traction Power is about 8MW	**Traction:** • **Shinkansen:** • E5 Series = 25kV AC • E6 Series = 20kV AC/ 25Kv AC • H5 Series (service entry 2016) = 25 kV AC	**Traction:** • **TGV:** • Réseau (Thalys PBA) = 25 kV AC/ 1.5kV DC/ 3kV DC • Duplex = 25kV AC/ 1.5kV DC • POS = 25kV 50Hz AC/ 15kV 16.7Hz AC • **AGV:** • Depending on speed Variable traction (25kV AC/ 15kV AC/ 3kV DC/ 1.5kV DC) • Interoperable on all AC and DC traction

Table 3 – Manufacturer Profiles – All final collated information used to make final judgments for AHP analysis

Sources: *(Forbes, 2013a), (Bombardier.com, 2014a), (Alstom.com, 2014a), (Hitachi-Rail.com, 2014a), (Mobility.Siemens.com, 2014a), (Railway-technology.com, 2014a), (Hitachi-Rail Europe, 2014), (japan-guide.com, 2014), (Businessdurham.co.uk, 2014), (Smith, 2014), (RailwayGazette, 2013), (Siemens, 2014), (Alstom, 2014b), (Zefiro.bombardier.com, 2014), (Bombardier.com, 2014b), (Alstom Transport, 2014a), (Alstom Transport, 2014b), (Bombardier Transportation, n.d.), (Railway-technology.com, 2014b), (Railway-technology.com, 2014c), (Smith, 2014), (Forbes, 2013b), (Forbes, 2013c), (Forbes, 2013d), (Mobility.Siemens.com, 2014b), (Hitachi-Rail.com, 2014b).*

4.6. Pairwise Comparisons – Criteria 1:

The first step to establish the final priorities of the alternatives was to complete judgments, comparing two alternatives at a time, with respect to each criterion. The method involved using a specific scale developed by Saaty to compare and numerically value each comparison. Every combination of alternatives was compared to complete a full comparison. Once completed the values were then transferred to a matrix to compute the overall weightings for each specific criterion. To make the comparisons easier to evaluate, brief qualitative justifications for the comparisons were included. The fundamental scale is shown in Table 4.

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it.
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A comparison mandated by choosing the smaller element as the unit to estimate the larger one as a multiple of that unit.
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix
1.1-1.9	For tied activities	When elements are close and nearly indistinguishable; moderate is 1.3 and extreme is 1.9.

Table 4 – Saaty's Fundamental Scale of comparisons (Saaty, 1999)

The first step of completing a judgment was to identify the manufacturer that is weakest with regards to the criteria in question, in this case: 'VHS Train in Operation (≥320kmph)'. This was done by using the profiles of the manufacturers. Once the weakest has been identified this manufacturer is assigned the value '1', the value assigned to the other manufacturer was then identified using the fundamental scale. The qualitative justifications (in note form) have been included for each assigned value. Once completed, the values from the Pairwise comparisons were transferred into a matrix. The weaker alternative with value '1' in the pairwise comparisons was assigned the reciprocal value of the stronger alternative, whilst the number assigned to the stronger alternative was directly transferred. Both steps are shown in *Table 5* and *Figure 4* below for the analysis of the Manufacturers, with respect to the first criterion.

Table 5 – Criteria 1: Very High-Speed Train in Operation (≥320kmph) Pairwise Comparisons

Bombardier	1	**Siemens**	3	**Moderate favour Siemens** – The ICE 3 Class 403/406 operating since 2000, consortium of both Siemens and Bombardier. Bombardier's own Very High-Speed Train Zefiro 380 which will not begin operation until this year in China and v300 in Italy this year whilst Siemens Velaro D (ICE Class 407) has been in operation since 2011.
Bombardier	2	**Hitachi**	1	**Weak favour Bombardier–** Hitachi and Kawasaki Shinkansen models E5 and E6 in service since 2011 and 2013 respectively. Bombardier-Siemens consortium which produced the ICE 3 Class 403/406 operation since 2000. Both consortiums however.
Bombardier	1	**Alstom**	6	**Strong plus favour Alstom –**Alstom TGV Réseau in operation since 1993, Duplex since 1996, POS since 2006 and AGV since 2012. Significant experience in Very High-Speed Trains. Bombardier Zefiro models beginning operation this year.
Siemens	4	**Hitachi**	1	**Moderate plus favour Siemens –** Siemens Velaro D (Class 407) began operation in 2011, Hitachi has no sole VHS model in operation. Both have experience VHS Trains in consortiums, yet Siemens also for longer therefore moderate favour Siemens.
Siemens	1	**Alstom**	5	**Strong favour Alstom –** Significantly more experience Alstom, however Siemens solely introduced Velaro D (Class ICE 407) in 2011
Hitachi	1	**Alstom**	7	**Very Strong favour Alstom –** Significantly more experience Alstom, Hitachi do not have own VHS Train in operation or about to enter operation.

CRITERIA 1				
Criteria being assessed: 'Very High-Speed Train in operation (≥320kmph)'				
Pairwise comparison matrix				
	Bombardier	Siemens	Hitachi	Alstom
Bombardier	1.0000	0.3333	2.0000	0.1667
Siemens	3.0000	1.0000	4.0000	0.2000
Hitachi	0.5000	0.2500	1.0000	0.1429
Alstom	6.0000	5.0000	7.0000	1.0000

Figure 4 – Criteria 1 – Resulting Matrix

4.7. Synthesising the priorities – Criteria 1:

The final priorities (weightings) for the alternatives, with respect to this criterion, were synthesised using a method which derives the eigenvector for the matrix. This eigenvector formed the priority weighting for the alternatives and can be calculated in various ways, with varying levels of accuracy. The method implemented in this project was based on the tutorial by Haas and Meixner (1999) and method described by Saaty (1999).

matrix^2	Bombardier	Siemens	Hitachi	Alstom	Total	Weight	Weight percentage		
Bombardier	4	2	6.5	0.6857143	13.18571429	0.0904	9.04%		
Siemens	9.2	4	15.4	1.4714286	30.07142857	0.2061	20.61%		
Hitachi	2.607142857	1.38095238	4	0.4190476	8.407142857	0.0576	5.76%		
Alstom	30.5	13.75	46	4	94.25	0.6459	64.59%		
					145.9142857				Difference
									0.0036
	4	2	6.5	0.6857143					0.0003
	9.2	4	15.4	1.4714286		For calculation purpose			0.0027
	2.607142857	1.38095238	4	0.4190476					-0.0066
	30.5	13.75	46	4					
matrix^4	Bombardier	Siemens	Hitachi	Alstom	Total	Weight	Weight percentage		
Bombardier	72.26071429	34.4047619	114.34286	11.152381	232.1607143	0.0940	9.40%		
Siemens	158.6285714	75.8988095	250.68571	24.533333	509.7464286	0.2063	20.63%		
Hitachi	46.34285714	22.0238095	73.489286	7.1721088	149.0280612	0.0603	6.03%		
Alstom	490.4285714	234.52381	778	76.422619	1579.375	0.6393	63.93%		
					2470.310204				

N.B. Numbers highlighted red for reference purposes

	72.26071429	34.4047619	114.34286	11.152381				Difference	
	158.6285714	75.8988095	250.68571	24.533333		For calculation purpose		-0.0001	
	46.34285714	22.0238095	73.489286	7.1721088				0.0000	
	490.4285714	234.52381	778	76.422619				-0.0001	
								0.0003	
matrix^8	**Bombardier**	**Siemens**	**Hitachi**	**Alstom**	**Total**	**Weight**	**Weight percentage**		
Bombardier	21447.61001	10231.1573	33966.806	3322.3161	68967.88953	0.0938	**9.38%**	FINAL WEIGHT PERCENTAGES	
Siemens	47151.67347	22492.9127	74674.439	7303.9839	151623.0088	0.2063	**20.63%**		
Hitachi	13765.48397	6566.54021	21800.605	2132.3352	44264.96424	0.0602	**6.02%**		
Alstom	146175.4745	69730.6037	231500.23	22643.414	470049.7274	0.6396	**63.96%**		
					734905.59				

									Difference
	21447.61001	10231.1573	33966.806	3322.3161					0.0000
	47151.67347	22492.9127	74674.439	7303.9839					0.0000
	13765.48397	6566.54021	21800.605	2132.3352					0.0000
	146175.4745	69730.6037	231500.23	22643.414					0.0000
matrix^16	**Bombardier**	**Siemens**	**Hitachi**	**Alstom**	**Total**	**Weight**	**Weight percentage**		No difference to 4 d.p
Bombardier	1895626819	904273905	3.002E+09	293641142	6095668481	0.0938	**9.38%**		Therefore Final
Siemens	4167462278	1988011222	6.6E+09	645558700	13401091501	0.2063	**20.63%**		
Hitachi	1216651072	580381014	1.927E+09	188464737	3912321517	0.0602	**6.02%**		
Alstom	12919653846	6163083218	2.046E+10	2.001E+09	41545058317	0.6396	**63.96%**		
					64954139816				

Figure 5 – Calculating Priorities for Criteria 1 – Excel screenshots showing iterative method employed to calculate eigenvector and hence synthesise the priorities

This iterative method was adapted and created in excel for this analysis. This is shown, in full for Criteria 1, in *Figure 5*. Firstly, the matrix was squared and the resulting eigenvector (weight) calculated. This was done by summing the values in each matrix row and writing them in the 'Total' column; these totals are then summed underneath. The individual weight of each manufacturer is equal to the 'row total'/'overall total'. Together these weights form the overall eigenvector and have also been displayed as percentages for convenience. However, the accuracy of the first eigenvector from a single iteration was not high enough, therefore, the matrix has been squared again to produce a matrix that is the initial matrix^4 (to the power of four). The eigenvector for this new matrix was then calculated (the second iteration) and the difference between the first eigenvector and current eigenvector was noted. To ensure a high level of accuracy it was decided to ensure there must be no difference to 4d.p (to four decimal places) for the eigenvector to be valid. In all the analysis this point was reached when the matrix^8 had been computed (the third iteration);

this was checked by also calculating eigenvector for the initial matrix^16 (computing a fourth iteration). The analysis was all conducted on excel and the same procedure was used to compute all priorities.

4.8. Pairwise Comparisons and priorities – Criteria 2 - 6:

This analysis was conducted for all six criteria, from the initial Pairwise Comparisons to the final synthesised eigenvector (weight). This produced six final eigenvectors and, hence, mathematical weightings for each manufacturer in terms of each individual criterion. For example, the analysis of the first criterion (shown in *section 4.7.*) has produced the eigenvector which can be written as the priorities percentage, which clearly depict Alstom as being heavily preferred (63.96%) and by a significant margin (next highest Siemens = 20.63%). However, each criterion's resulting priorities were not enough alone and needed to be combined to express the accrued priorities of each Manufacturer with respect to the objective and, hence, reflect a decision for the most suitable manufacturer. Pairwise Comparisons for all criteria, their resulting matrix and priorities, are included see *Table 6 - Table 15* and *Figure 6 -Figure 110.*

Table 6 – Criteria 2: 'Experience in High Speed sector' Pairwise Comparisons

Bombardier	5	**Siemens**	1	**Strong favour Bombardier –** Bombardier (BREL) HS BR Class 370 service 1980 and BR Class 43 Intercity 125 service 1976, Siemens involved in ICE 1 since 1991 but not primary manufacturer and ICE 2 SINCE 1996. Both manufacturers have extensive range of countries where their HS trains are used. More individual HS models by Bombardier.
Bombardier	1	**Hitachi**	2	**Weak favour Hitachi –** Hitachi involved in Shinkansen 0 service 1964, Shinkansen 200 from 1982-2013, Shinkansen 100 from 1985 – 2012. Extensive portfolio, very strong experience in HS but only Japan, Taiwan and UK. Bombardier more experience in other countries and more individual HS models however Hitachi have clearly had significantly more experience in HS in terms of time.
Bombardier	1	**Alstom**	4	**Moderate plus favour Alstom –** Bombardier (BREL) service 1976, Alstom TGV Sud – Est service 1981, therefore Bombardier slightly more time experience. However Alstom has substantially more countries of HS application and significantly more individual HS models than Bombardier (see Manufacturer profiles).
Siemens	1	**Hitachi**	3	**Moderate favour Hitachi –** Hitachi HS since 1964, Siemens HS since 1991. Siemens only slightly more individual HS models and countries of application than Hitachi. Overall more experience Hitachi
Siemens	1	**Alstom**	7	**Very Strong favour Alstom –** Alstom significantly more experience in HS in terms of time, countries of application, and individual HS models (see Manufacturer profiles).
Hitachi	1	**Alstom**	2	**Weak favour Alstom –** Though Hitachi (1964) has much more experience in time than Alstom (1981), Alstom's portfolio of countries of application and individual models is very extensive and is substantially greater than Hitachi's which gives Alstom overall the edge in favour.

CRITERIA 2

Criteria being assessed: 'Experience in High-Speed sector'

Pairwise comparison matrix

	Bombardier	Siemens	Hitachi	Alstom
Bombardier	1.0000	5.0000	0.5000	0.2500
Siemens	0.2000	1.0000	0.3333	0.1429
Hitachi	2.0000	3.0000	1.0000	0.5000
Alstom	4.0000	7.0000	2.0000	1.0000

Figure 6 – Criteria 2 – Resulting Matrix

Table 7 – Criteria 2 – Priorities

Criteria 2	Weight
Bombardier	0.1759
Siemens	0.0606
Hitachi	0.2497
Alstom	0.5139

Table 8 – Criteria 3: 'Application in HS1' Pairwise Comparisons

Bombardier	1	**Siemens**	4	**Moderate plus favour Siemens –** Bombardier no direct application in HS1. Siemens chosen and won tender for Class 374 Eurostar Velaro e320 to begin service in 2015 and travel 320kmph. Significant tender to win and assuming chosen for good reason, though no experience yet, shows application in HS1 and advantage over Bombardier.
Bombardier	1	**Hitachi**	7	**Very Strong favour Hitachi –** Hitachi Class 395 service since 2009, delivered 6 months ahead of schedule, successful implementation, reliable and high satisfaction rates. Bombardier has no direct application in HS1. Hitachi still relatively recent service however.
Bombardier	1	**Alstom**	7	**Very Strong favour Alstom –** Class 373 service since 1994, speed up to 300kmph. Longest and fastest train in regular UK passenger service at present. However few minor technical and one accident during service. Bombardier has no direct application in HS1.
Siemens	1	**Hitachi**	5	**Strong favour Hitachi –** Siemens Velaro e320 yet to enter service, Hitachi Class 395 has proven reliability.
Siemens	1	**Alstom**	5	**Strong favour Alstom –**Siemens yet to enter service. Alstom has had application for long duration and has the longest and fasted train in regular UK passenger service currently.
Hitachi	2	**Alstom**	1	**Weak favour Hitachi –** Hitachi Class 395 has proven more reliable than Alstom Class 373, however has been in operation not as long (2009, 1994 respectively). However the reliability and early delivery shows high quality compared to the accident Class 373 had and few minor technical faults.

CRITERIA 3

Criteria being assessed: 'Application in High-Speed One'

Pairwise comparison matrix

	Bombardier	Siemens	Hitachi	Alstom
Bombardier	1.0000	0.2500	0.1429	0.1429
Siemens	4.0000	1.0000	0.2000	0.2000
Hitachi	7.0000	5.0000	1.0000	2.0000
Alstom	7.0000	5.0000	0.5000	1.0000

Figure 7 *Criteria 3 – Resulting Matrix*

Table 9 – Criteria 3 – Priorities

Criteria 3	**Weight**
Bombardier	0.0463
Siemens	0.1105
Hitachi	0.4927
Alstom	0.3506

Table 10 – *Criteria 4: 'UK Factory Location' Pairwise Comparisons*

Bombardier	5	**Siemens**	1	**Strong favour Bombardier –** Bombardier has 27 sites overall, 19 services and maintenance, 3 manufacturing, 2 engineering. Siemens has 11 sites overall, 6 Traincare facilities however no manufacturing sites. Rolling stock would have to be manufactured in Germany.
Bombardier	6	**Hitachi**	1	**Strong plus favour Bombardier –** Hitachi has 2 sites overall, 1 maintenance centre and 1 manufacturing site under construction. Bombardier has significantly more facilities however Hitachi will have a manufacturing site operational from 2015.
Bombardier	4	**Alstom**	1	**Moderate plus favour Bombardier –** Alstom 19 sites overall, 13 Traincare points however no manufacturing site in UK. Rolling Stock would have to be built in Europe. Bombardier considerable advantage.
Siemens	2	**Hitachi**	1	**Weak favour Siemens –** Siemens has 11 sites overall and 6 Traincare facilities however no manufacturing site. Hitachi has only 2 sites overall including only one Traincare site however will have an operational manufacturing site in the UK from 2015. Presents great UK job opportunities as is one of the primary aims of HS2. Hitachi however needs more Traincare sites.
Siemens	1	**Alstom**	3	**Moderate favour Alstom –** Alstom has more sites overall and Traincare however both do not have a manufacturing site in UK.
Hitachi	1	**Alstom**	2	**Weak favour Alstom –** Alstom has considerably more sites however no manufacturing site which Hitachi will have from 2015. Presents large potential with a UK based manufacturing site for considerable job creation. Nonetheless Hitachi needs more UK Traincare sites etc..

CRITICAL 4				
Criteria being assessed: 'UK Factory location'				
Pairwise comparison matrix				
	Bombardier	Siemens	Hitachi	Alstom
Bombardier	1.0000	5.0000	6.0000	4.0000
Siemens	0.2000	1.0000	2.0000	0.3333
Hitachi	0.1667	0.5000	1.0000	0.5000
Alstom	0.2500	3.0000	2.0000	1.0000

Figure 8 – Criteria 4 – Resulting Matrix

Table 11 – *Criteria 4 – Priorities*

Criteria 4	**Weight**
Bombardier	0.5984
Siemens	0.1123
Hitachi	0.0824
Alstom	0.2069

Table 12 – Criteria 5: 'Size and strength of Company' Pairwise Comparisons

Bombardier	1	**Siemens**	7	**Very Strong favour Siemens –** Bombardier revenue = \$16.77bn, number of employees = 71,700 however Siemens revenue = \$100.64bn and number of employees = 365,000. Siemens over 5x revenue and 5x employees. Profits Siemens about 10x Bombardier (May 2013).
Bombardier	1	**Hitachi**	8	**Very Strong plus favour Hitachi –** Hitachi revenue = \$116.76bn, number of employees =328,278. Almost 7x revenue and 5x employees. Profits Hitachi almost 10x Bombardier (May 2013).
Bombardier	1	**Alstom**	4	**Moderate plus favour Alstom –** Alstom revenue = \$26.62bn, number of employees = 85,449. Larger and stronger than Bombardier. Profit also Alstom (\$977.3m) vs Bombardier (\$588m). (May 2013)
Siemens	2	**Hitachi**	1	**Weak favour Siemens –** Hitachi has greater revenue yet lower number of employees (could be seen as greater sales per person) However Profits slightly greater Siemens (\$5.73bn) than Hitachi (\$4.19bn). (May 2013)
Siemens	6	**Alstom**	1	**Strong plus favour Siemens –** Siemens about 4x revenue and 4x number of employees compared to Alstom. Over 5x Profits also (May 2013).
Hitachi	6	**Alstom**	1	**Strong plus favour Hitachi –** Hitachi about 4x revenue and 4x number of employees compared to Alstom. Just over 4 x Profits also. (May 2013).

CRITERIA 5

Criteria being assessed: 'Size and strength of company'

Pairwise comparison matrix

	Bombardier	Siemens	Hitachi	Alstom
Bombardier	1.0000	0.1429	0.1250	0.2500
Siemens	7.0000	1.0000	2.0000	6.0000
Hitachi	8.0000	0.5000	1.0000	6.0000
Alstom	4.0000	0.1667	0.1667	1.0000

Figure 910 – Criteria 5 – Resulting Matrix

Table 13 – Criteria 5 – Priorities

Criteria 5	**Weight**
Bombardier	0.0433
Siemens	0.4965
Hitachi	0.3628
Alstom	0.0974

Table 14 – Criteria 6: 'Traction of Very High-Speed Trains' Pairwise Comparisons

Bombardier	5	**Siemens**	1	**Strong favour Bombardier –** Bombardier Zefiro 'Scalable Traction Power' for HS and VHS trains. 4 Power supply voltages (1.5kV & 3kV DC, 15 & 25kV AC). Siemens Velaro options depend on configuration. Velaro E = 25kV AC only, Velaro D =25kV AC/1.5kV DC, Velaro RUS = 25kV AC/ 3kV DC. Much more limited for Siemens compared to Bombardier's interoperable Zefiro models.
Bombardier	6	**Hitachi**	1	**Strong plus favour Bombardier –** Hitachi Shinkansen E5 Series 25kV AC, E6 Series 20kV AC/ 25kV AC, H5 Series 25kV AC. No DC options. Limited compared to Bombardier Zefiro's scalable traction.
Bombardier	3	**Alstom**	1	**Moderate favour Bombardier –** Alstom AGV model has variable traction depending on maximum speed. (25kV AC/ 15kV AC/ 3kV DC/ 1.5kV DC). Therefore interoperable on the 4 main European modes of Traction. Réseau (25kV AC/ 1.5kV DC/ 3kV DC), Duplex (25kV AC/ 1.5kV DC), POS (25kV AC/ 15kV AC). Most models operate variety of Traction modes however only AGV fully variable for all 4 modes of traction. All Zefiro models scalable.
Siemens	3	**Hitachi**	1	**Moderate favour Siemens –** Siemens Velaro D and RUS can run on 25kV AC in at least one mode DC. Hitachi Shinkansen E5, E6 and H5 can only run on AC Mode. Hitachi's traction for VHS trains more limited than Siemens'.
Siemens	1	**Alstom**	5	**Strong favour Alstom –** Alstom AGV completely scalable, other models run on most of 4 primary modes of electrical traction. Siemens none are completely scalable and run on 15kV AC.
Hitachi	1	**Alstom**	6	**Strong plus favour Alstom –** Hitachi models do not run on any DC mode or at 15kV AC. Alstom has fully scalable VHS Train.

CRITERIA 6				
Criteria being assessed: 'Traction of VHS Trains'				
Pairwise comparison matrix				
	Bombardier	Siemens	Hitachi	Alstom
Bombardier	1.0000	5.0000	6.0000	3.0000
Siemens	0.2000	1.0000	3.0000	0.2000
Hitachi	0.1667	0.3333	1.0000	0.1667
Alstom	0.3333	5.0000	6.0000	1.0000

Figure 110 – Criteria 6 – Resulting Matrix

Table 15 – Criteria 6 – Priorities

Criteria 6	**Weight**
Bombardier	0.5371
Siemens	0.1011
Hitachi	0.0535
Alstom	0.3083

4.9. Calculating the priorities of the Criteria with respect to the Objective:

However, before the results of each criterion's analysis were combined, the criteria were compared with respect to the objective. This was completed using the same procedure, yet due to there being six criteria, which have to be compared in pairs, in all combinations; there were 15 pairwise comparisons. These comparisons have been conducted using the same methodology and are also supported in a qualitative manor (in note form). The reason behind this Pairwise Comparison is that the criteria are not equally important as factors for choosing the right manufacturer. Certain factors are of higher precedence than others. The Pairwise Comparisons using the fundamental scale was the fairest method of weighting these criteria. The comparisons are shown below:

Table 16 – Criteria with respect to Objective: 'Identifying the most suitable manufacturer for the High Speed Trains of HS2' Pairwise Comparisons

VHS Train in Operation (≥320kmph)	3	**Experience in HS sector**	1	Having VHS Trains currently in operation demonstrates reliability and successful implementation of VHS rail, which raises confidence in manufacturer's ability to deliver the 225-250mph trains for HS2. Experience in normal HS is also important but to a lesser degree than experience in VHS.
VHS Train in Operation (≥320kmph)	3	**Application in HS1**	1	Similar reasons as above. Application in HS1 demonstrates effective use of HS on British Infrastructure, however, trains for HS2 are planned to operate at much higher speeds than HS1 currently.
VHS Train in Operation (≥320kmph)	2	**UK Factory Location**	1	UK Factory Location is important, as will govern the job creation induced by manufacturing the rolling stock. Also the maintenance to ensure the HS trains run effectively and in case of breakdown. However, the experience with VHS will suggest more accurate initial design thus manufacture is slightly more important.
VHS Train in Operation (≥320kmph)	2	**Size and strength of company**	1	The size and strength of the company governs how much resources can be invested into the project after the initial HS2 £9.2bn contract. This includes opening manufacturing factories as well as dealing with setbacks etc.. However the ability and experience with VHS is still the more critical to ensure quality manufacture of the HS2 rolling stock.
VHS Train in Operation (≥320kmph)	3	**Traction of VHS Trains**	1	The traction of the VHS trains is important as it determines the adaptability of the trains to run using different traction systems and as outlined, some of the HS2 trains will need to run on the conventional infrastructure as well as the HS2 network. Nonetheless, the actual performance and reliability is more important than the adaptability of the trains.
Experience in HS sector	3	**Application in HS1**	1	Experience in HS sector demonstrates extensive knowledge and application of High Speed, which is necessary for the creation of the HS2 rolling stock. The application in HS1 is only a specific case of HS. Therefore less important.
Experience in HS sector	1	**UK Factory Location**	1	Experience in HS also includes geographical application across the world, which demonstrates implementation of HS rolling stock in a variety of situations. UK Factory location is equally important as demonstrates capability to implement HS in the UK and promotes the project's ability for job creation.
Experience in HS sector	2	**Size and strength of company**	1	The size and strength of a company is important, however, the contract for £9.2bn is substantial enough to not necessitate too much from the company themselves. Experience shows an extensive portfolio of HS application and will also enable better use of resources from previous understanding.
Experience in HS sector	2	**Traction of VHS Trains**	1	Experience in HS, for the same reason as experience with VHS, more important than the adaptability of the VHS trains of the manufacturer for the successful creation of HS2's rolling stock. However the technical capabilities available are also important.
Application in HS1	1	**UK Factory Location**	3	UK location is more important than Application in HS1. Though HS1 demonstrates successful UK implementation of HS it is not essential, HS2 is a much bigger project and UK locations are required to maintain/create the rolling stock. It also promotes job creation which, having an application in HS1, does not.
Application in HS1	1	**Size and strength of company**	3	Size and strength of company provides a good measure of the company's ability to take on such a large strategic project; whilst the application in HS1 does not determine the future capability and is only a specific instance of experience, unlike HS and VHS.

Application in HS1	1	**Traction of VHS Trains**	2	The Traction of the VHS trains of current manufacturers shows the technical capability available for the VHS trains of HS2, this is more important than the specific experience of HS in HS1
UK Factory Location	1	**Size and strength of company**	1	These are both current measures of the future capability of the company. UK factory location promotes job creation, however the size and strength of company demonstrates an ability to make large personal resource investments in the UK, for example, setting up new factories. Therefore, both equally important.
UK Factory Location	2	**Traction of VHS Trains**	1	The amenities to ensure successful rolling stock production in the UK and the job creation possible through UK factory location are more important than the technical traction adaptability of the rolling stock.
Size and strength of company	2	**Traction of VHS Trains**	1	The manufacturer's size and strength is a more important capability than the technical adaptability of the traction. This is due to the size and strength of the company, possibly determining the creation of HS2's rolling stock being successful, whilst, the Traction is a characteristic of the trains produced and is not as essential.

CRITERIA with respect to Objective

Criteria being assessed: 'Criteria with respect to the Objective'

Pairwise comparison matrix

	VHS Train in Operation	Experience in HS sector	Application in HS1	UK Factory Location	Size and strength of company	Traction of VHS Trains
VHS Train in Operation	1.0000	3.0000	3.0000	2.0000	2.0000	3.0000
Experience in HS sector	0.3333	1.0000	3.0000	1.0000	2.0000	2.0000
Application in HS1	0.3333	0.3333	1.0000	0.3333	0.3333	0.5000
UK Factory Location	0.5000	1.0000	3.0000	1.0000	1.0000	2.0000
Size and strength of company	0.5000	0.5000	3.0000	1.0000	1.0000	2.0000
Traction of VHS Trains	0.3333	0.5000	2.0000	0.5000	0.5000	1.0000

Figure 11 – Criteria with respect to the Objective – Resulting Matrix

Table 17 – Priorities of Criteria with respect to the Objective

	Weight	Weight percentage
VHS Train in Operation	0.3267	**32.67%**
Experience in HS sector	0.1876	**18.76%**
Application in HS1	0.0633	**6.33%**
UK Factory Location	0.1712	**17.12%**
Sustainability of company	0.1560	**15.60%**
Traction of VHS Trains	0.0951	**9.51%**

The graphical breakdown of the criteria's priorities with respect to the Objective is shown in *Figure 122*. It is clear from the completed Pairwise Comparison, involving all criteria, that the 'VHS Train in Operation' is most critical criteria whilst the 'Application in HS1' is the least. Once all judgments have been completed and all priorities synthesised, the final priorities for each manufacturer were calculated and hence, a final decision, based on all judgments and analysis, has been made.

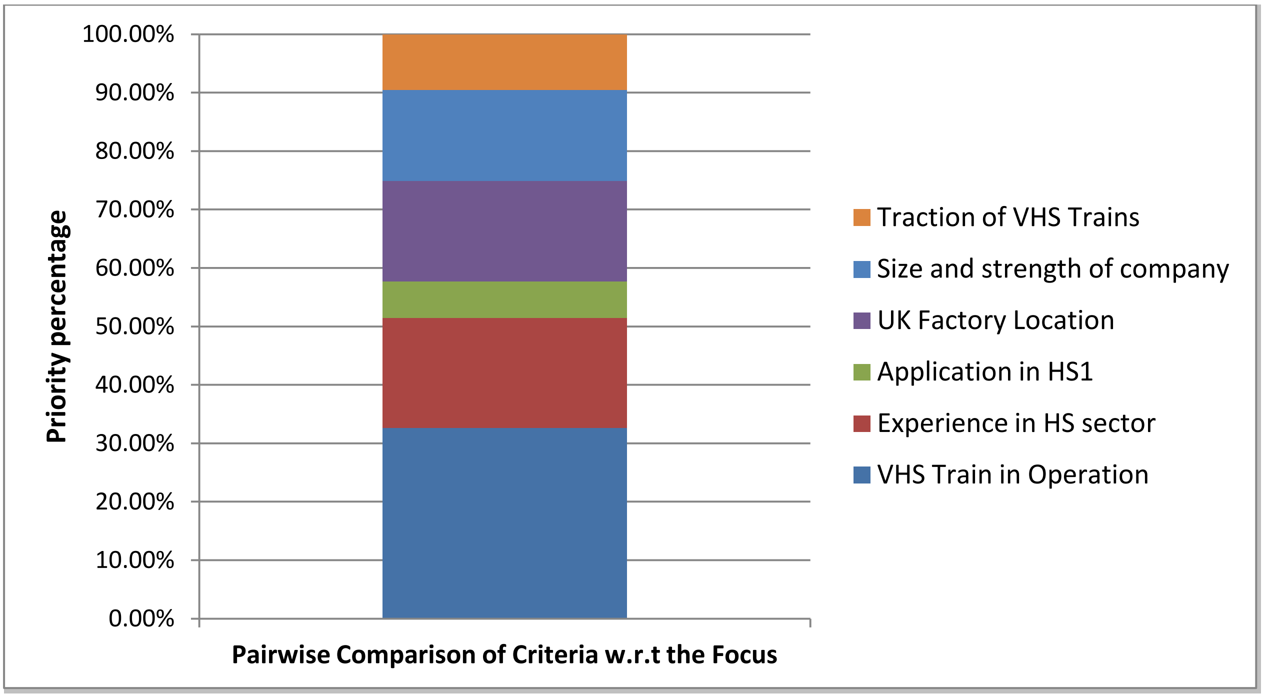


Figure 12 – Graph showing the breakdown of priorities of the Criteria with respect to the Objective

4.10. ***Calculation of Final Priorities and Results:***

Table 18, displaying all of the results created, can be seen below. The priority of the Criteria with respect to the Objective was multiplied by the priority of each Manufacturer with respect to each criterion. The sum of these totals for each manufacturer was then calculated, which then produced the final priorities for each manufacturer. See the equation below. Therefore, the recommended manufacturer for the rolling stock of HS2 was the manufacturer with the highest value, according to the Analytic Hierarchy Process method administered.

Table 18 – Table of all Priorities: Final Priority for each manufacturer, $Y = \sum_{i=1}^{6} A_{x_i} B_{x_i} = \sum C_y$

Criterion (x)	Criteria priority	y (Alternative)	A (Priorities of Manufacturers w.r.t Criteria)	B (Criteria Priority)	C (Final Priorities) (A*B)
1. Very High Speed Train in Operation (≥320kmph)	0.3267	Bombardier	0.0938	0.3267	0.0307
		Siemens	0.2063	0.3267	0.0674
		Hitachi	0.0602	0.3267	0.0197
		Alstom	0.6396	0.3267	0.2089
2. Experience in High Speed sector	0.1876	Bombardier	0.1759	0.1876	0.0330
		Siemens	0.0606	0.1876	0.0114
		Hitachi	0.2497	0.1876	0.0468
		Alstom	0.5139	0.1876	0.0964
3. Application in High Speed One	0.0633	Bombardier	0.0463	0.0633	0.0029
		Siemens	0.1105	0.0633	0.0070
		Hitachi	0.4927	0.0633	0.0312
		Alstom	0.3506	0.0633	0.0222
4. UK Factory Location	0.1712	Bombardier	0.5984	0.1712	0.1025
		Siemens	0.1123	0.1712	0.0192
		Hitachi	0.0824	0.1712	0.0141
		Alstom	0.2069	0.1712	0.0354
5. Size and strength of company	0.1560	Bombardier	0.0433	0.1560	0.0068
		Siemens	0.4965	0.1560	0.0775
		Hitachi	0.3628	0.1560	0.0566
		Alstom	0.0974	0.1560	0.0152
6. Traction of Very High Speed Trains	0.0951	Bombardier	0.5371	0.0951	0.0511
		Siemens	0.1011	0.0951	0.0096
		Hitachi	0.0535	0.0951	0.0051
		Alstom	0.3083	0.0951	0.0293

4.11. Final Priorities:

Table 19 – Final Priorities of Manufacturers

Final Priorities of Manufacturers	
Bombardier	**0.2269**
Siemens	**0.1921**
Hitachi	**0.1735**
Alstom	**0.4075**

Table 19 depicts the final calculated priorities for the manufacturers. The most suitable manufacturer being Alstom, based on the AHP analysis conducted.

5. Analysis and Evaluation of results:

Overall, Alstom's final priority (0.4075) was almost double the second highest priority of Bombardier (0.2269). This demonstrates a clear dominance and hence the recommended choice. However, Alstom was not superior in regards to all of the criteria; it was highest in only 2 criteria which Bombardier happens to be also. How then is there such a vast margin of supremacy for Alstom? From Table 18 it is clear Alstom are superior in terms of experience in Very High Speed by a significant margin. Alstom's priority = 0.6396 with the second highest being Siemens priority (0.2063), which leaves a 0.4333 difference between the two, a very substantial lead to Alstom. This is coupled with 'Experience in High Speed sector' where Alstom is also the superior manufacturer with a 0.5139 priority, compared to second highest Hitachi (0.2497), a margin of 0.2642. These are the two criteria which also happen to have the highest priority weightings, with respect to the Objective, from the Pairwise Comparisons of all the criteria. Hence, being the most important criteria according to the comparisons. Therefore, this exaggerates these superior margins more so. This demonstrates that, though Alstom is not the superior manufacturer across all criteria, it is the best manufacturer with respect to the two most important criteria. However, to identify how much of Alstom's superiority is due to the priorities of the criteria, two graphs have been created. A graph of the final priorities of each manufacturer including the priority for each criterion (see *Figure 13*) and a graph of the final priorities for the manufacturers excluding the priority for each criterion (see *Figure 14*), have been created and aligned for comparison.

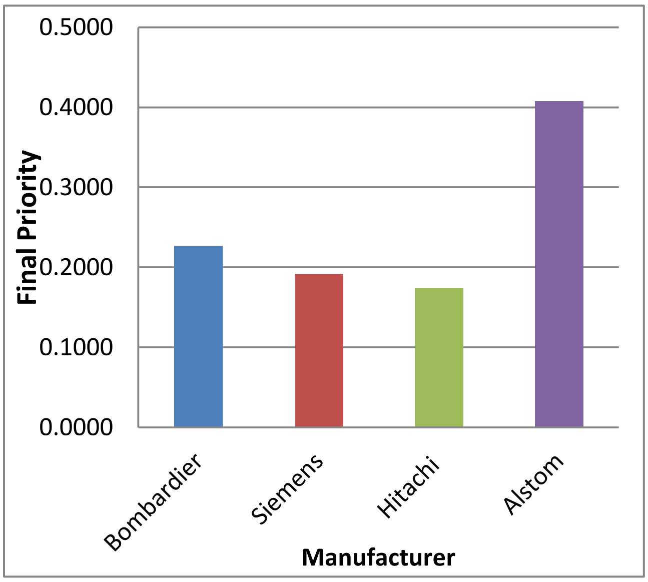


Figure 13 - Graph showing the Final Priorities of Manufacturers (Full AHP analysis)

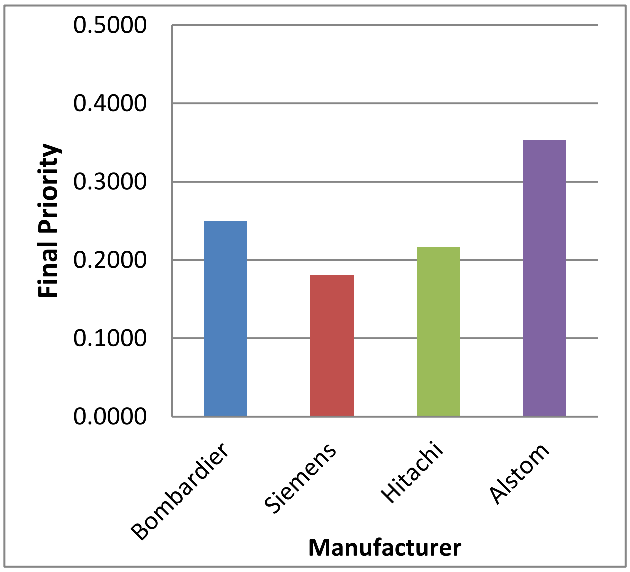


Figure 14 - Graph showing the Final Priorities of Manufacturers (Criteria Weighted equally)

Figure 14 clearly shows that if the criteria are weighted equally (excluding the criteria priorities) that Alstom is still significantly ahead of the other manufacturers with Bombardier still in second place. However, there is a substantial difference between Hitachi and Siemens. The reason for this is Hitachi has the highest priority (0.4927) for 'Application in HS1'; however, from the Pairwise Comparisons of the criteria, this was deemed the least important. Therefore when the priorities of the criteria are ignored, this criterion has a greater input than when the full AHP analysis is applied. Nonetheless this still demonstrates that Alstom is clearly ahead in terms of the accumulated individual priorities (excluding the criteria priorities) as well as after the full AHP analysis has been applied (including the criteria priorities, see *Figure 13*). This further backs up Alstom as the conclusive recommended manufacturer.

To explore the results further, the breakdown of the full AHP final priorities has been presented graphically to express more clearly how much each criteria is responsible for the overall final priorities. See *Figure 15*

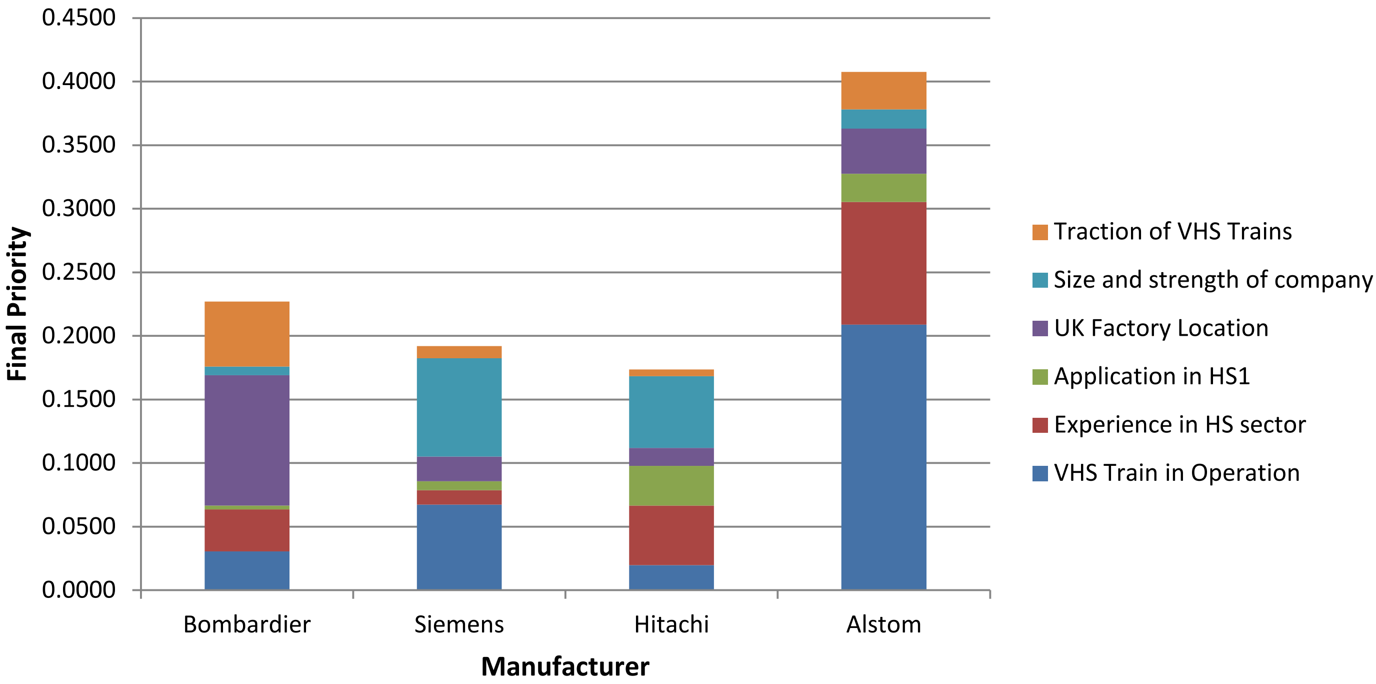


Figure 15 – Graph showing breakdown of Final Priorities, regarding the critieria, for each Manufacturer

This graph shows the 'VHS Train in operation' criteria about doubled Alstom's overall priority and is of greater value than both Hitachi's and Siemen's overall priority by itself. This seems excessive. The reason for this is Alstom has much more experience manufacturing and implementing VHS Trains than any of the other manufacturers. The TGV Réseau (Alstom) has been in operation since 1993 when the earliest implementation by the other manufacturers was in 2000 being the ICE 3 Class 403/406. However, these trains were produced by a Bombardier-Siemens consortium; hence why they share the value and cannot individually claim the manufacture of the ICE 3 Class 403/406. After this Siemens is the only manufacturer to have produced itself a VHS Train that has had experience in operation (Velaro D), however, it has only been in operation since 2011. This is in comparison to Alstom, who have successfully manufactured and implemented several VHS Trains since 1993 (see manufacturer profiles for full list) and currently the Alstom AGV has the world Rail speed record on conventional rail of 574.8kmph (357mph), (BBC News, 2007). However it is not just the judgments which are responsible for the large priority value. The results from the

Pairwise Comparison of all the criteria showed the highest priority criteria was the 'VHS Trains in operation' therefore it's importance being valued higher than the other criteria also exaggerated the overall priority value of Alstom which, as mentioned earlier, was already the highest by a significant margin.

A final point, which reinforces the result of Alstom having the highest priority overall, is the fact it was not the lowest priority within any of the criteria. All other manufacturers were the weakest with regard to at least one criterion however, as demonstrated in Table 18, Alstom was not. To support this it is also worth mentioning that Hitachi, who had the lowest priority overall, was the weakest in terms of three criteria; more than any of the other manufacturers. Therefore, there is substantial basis for the final order of priority.

6. Findings and Manufacturer recommendation:

Based on the final calculated priorities produced from the AHP analysis, the order of recommendation for the most suitable manufacturer for the Trains of HS2 is as follows (Most suitable to least suitable): Alstom 1st followed by Bombardier 2nd, Siemens 3rd and Hitachi4th.

Therefore, based on this strategic analysis using Saaty's Analytic Hierarchy Process method, the most suitable manufacturer for the Trains of HS2 is Alstom. The last choice, and least recommended according to the analysis, is Hitachi.

7. Conclusion, Discussion and future application:

Application of the AHP model has been effective; the breaking down of, an initially inconceivable, strategic decision into simple pairwise comparisons and mathematically combining them to produce a single most recommended decision. In this case, a mathematically–justified final recommendation has been reached, incorporating a range of factors, variables and issues; for which company should be chosen to manufacture the High Speed Trains of HS2. Yet, there are still some weaknesses to the analysis which must be acknowledged. Firstly this contribution was, though as unbiased and factually based as possible, still subjective. It relied on one individual's judgements for each pairwise comparison. Even though Saaty's fundamental scale was adhered to the judgments remain subjective.

Therefore, to improve the validity of, and add more weight to the analysis, a sample of individuals should undertake all the pairwise comparisons and an average used for the priority synthesis, or by using the group of individuals to complete the pairwise comparisons together and agree on the judgments. This would prove effective, as there is broader knowledge available and discussion over judgments has been proven to improve validity of the final judgment. A study into the validity of AHP is a potential target for the future to improve the validity of the final priorities and hence final recommendation. A sample of individuals with relatively good HS2 knowledge should be used to complete the pairwise comparisons, still using the manufacturer profiles and fundamental scale to base the judgments upon.

Though such a complex decision has been broken down into simpler, smaller pairwise comparisons, this can still can be difficult to judge and involve many sub factors such as: what kind of viewpoint is being used eg) economic, cost effective, environmental etc.. In the case of this analysis, an overall viewpoint based on the stated primary objectives of the project was employed. However to improve the analysis further, the AHP analysis could be conducted from different strategic perspectives to demonstrate a broader analysis. This could reflect various scenarios and, hence, add more weight to the final decision for the most suitable manufacturer by showing a range of viewpoints have also been considered.

An option that could also be explored, from the outcome of this analysis, is that of a consortium. For the purpose of simplifying the analysis, the possibility of two manufacturers forming a strategic partnership was discounted. This allowed the manufacturers to be judged and assessed separately. However, now the analysis has been completed, an investigation into creating the optimum partnership could be conducted. For example Alstom is clearly best in terms of experience, in both the application of Very High Speed and the extensive portfolio of countries with High Speed Application. However, it does not have a manufacturing factory in the UK, which could catalyse job creation as targeted, to build the rolling stock. This could be addressed by identifying the manufacturer with the best 'UK Factory location' which happens to be Bombardier, by a significant margin. Bombardier also happen to be second highest priority overall which stands them in good stead. Therefore, this partnership could take advantage of Alstom's extensive experience and make the best possible use of Bombardier's UK manufacturing resources. Further, more detailed, investigation could be conducted by analysis of the results obtained or by using another AHP model to identify the optimum strategic consortium for the manufacture of the HS2 Rolling Stock.

Overall the analysis completed has formed a good basis and platform for further investigation and embellishment. The method can be improved and enhanced by being conducted using various strategic perspectives, coupled with judgments being made by a group of suitable individuals. A more advanced model can also be designed, incorporating more criteria and refining the current ones. By implementing these concepts, an effective strategic decision can be made and a recommendation, that will have substantial foundation, for which company should manufacture the High Speed Trains of HS2.

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