Supporting Information - Reusing steel and aluminium components at end of product life

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This supporting information contains 136 pages, 29 tables and 2 figures.
The supporting information has been divided into three sections, the first analysing the end use of steel and aluminium using a mixture of top down and bottom up analyses, the second presenting a catalogue of product design descriptions for the main end use products identified, and section 3 presents analysis of the potential component reuse of each product in the catalogue.

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1. Identifying the main end use products

In 2008, approximately 1330Mte of liquid steel (S1) and 73Mte of liquid aluminium (S2) were produced globally. Average forming yields are taken as 86% for steel (S3) and 73% for aluminium (S2). Sector specific fabrication yields from the intermediate goods to finished products were taken from Hatayama et al (2010) (ref. S4) for steel and IAI (2008a) (ref. S2) for aluminium. From liquid metal to final goods, these yields equate to 75% and 61% for steel and aluminium respectively, implying a top-down estimate of 1,040Mte of steel products and 45Mte of aluminium products entered the global stock in 2008. These top-down estimates are summarised in Tables S1 and S2.

Table S1: Top down estimates of steel end use

Sector	Intermediate (%)	Fabrication yield (%)	End use (%)
Construction	50	94	52
Automotive	12	81	11
Other transport	3	81	3
Mechanical machinery	14	86	13
Metal products	14	95	15
Electrical equipment	3	81	3
Domestic appliances	4	95	4
1330Mte liquid production	1160Mte intermediate products		1040Mte end use products

Table S2: Top down estimates of aluminium end use

Sector	Intermediate (%)	Fabrication yield (%)	End use (%)
Construction	22	90	24
Transport (Auto & light truck)	17	84	18
Transport (truck, bus, marine, rail)	9	80	9
Other transport (Aerospace etc.)	1	60	Negligible
Machinery & equipment	8	75	7
Packaging – cans	8	75	7
Packaging - foil	7	75	6
Consumer durables	7	80	7
Electrical – cable	8	90	9
Electrical – other	5	80	5
Other (ex. destructive uses)	4	80	4
Other (inc. destructive uses)	4	80	4
73Mte liquid metal production	53Mte intermediate products		45Mte end use products

The analysis in this paper coordinates these top-down sector breakdowns with bottom-up calculations, improving the resolution of the end use to specific products (For example: splitting transport into cars and ships etc.). The bottom-up analysis also allows us to check the relative significance of certain products and components.

Bottom-up studies, by their nature, use a wide range of sources and can involve numerous assumptions and scaling. Care has been taken to use reliable data, and extensive comments on the assumptions and shortcomings of the methods are given. The total amount of steel and aluminium made each year varies. However, a bench mark is needed to reference the results. The benchmark year chosen here is 2008, and so wherever possible 2008 data has been used. However, data from other years has sometimes been used, and interpolated where possible.

The trade organisations use different product group definitions. To simplify clustering of products across both metals, this paper uses 4 groups:

1. Transport

2. Construction (including buildings and infrastructure)

3. Industrial Equipment (including mechanical and electrical equipment)

4. Metal Products (containing packaging, consumer durables and miscellaneous metal goods)

Where possible, bottom-up analysis has been performed by the authors. However, this study also uses a steel breakdown for construction derived using complementary top-down and bottom-up analysis by Moynihan and Allwood (2012) (ref. S5). Where it has not been possible to derive directly a bottom-up value for aluminium consumption this analysis uses aluminium product stock data for China and Connecticut collected by Wang and Graedel (2010) (ref. S6) and Recalde et al (2008) (ref. S7) respectively. The aluminium stock data is used to derive production data and then compare the significance of certain products. Even though the data is regional, the relative scale of product metal use is taken as indicative of worldwide consumption. For a saturated/stable stock of products, the production rate must equal replacement demand, given by equation 1.

$$Demand_{rep} = \frac{Current\_stock}{Av.\_life} \qquad (1)$$

A stable level of stock is a reasonable assumption in developed nations, and equation 1 is therefore used to estimate the annual consumption breakdown for Connecticut directly from a single years stock data. Product lifetimes presented in S6 are used for the analysis of the Connecticut data.

For increasing levels of stock, the total demand is equal to the sum of the replacement and new demand. From one year to the next, the new demand is equal to the difference in overall stock levels. Equations 2 to 4 present calculations for demand in year X.

$$Demand_X = Demand_{newX} + Demand_{repX} \qquad (2)$$

$$Demand_{newX} = Stock_X - Stock_{(X-1)} \qquad (3)$$

$$Demand_{repX} = \frac{Stock_{X0}}{Av.\_life} \qquad (4)$$

Where X is the year of interest, and X_0 is the year of initial data. The assumptions of equation 4 are that the stock was stable before year X_0 and that the lifetimes of the products are greater than $X\text{-}X_0$. For rapidly developing China, stock for both

2000 and 2005 is presented by S6. Figure S1 presents Chinese aluminium production from 1995 to 2005 (S2).

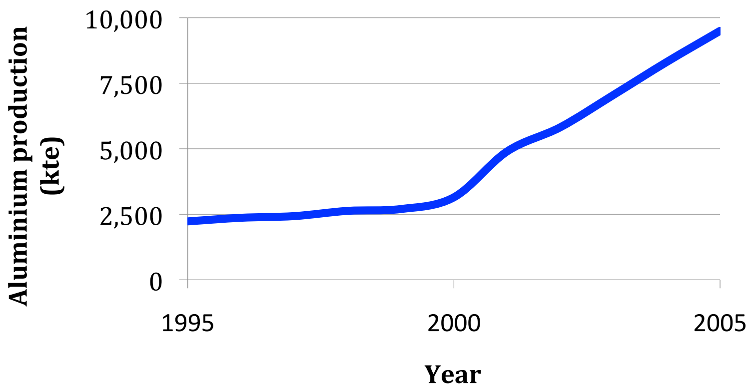


Figure S1: Historic data on Chinese aluminium production

Production was relatively stable before 2000, therefore a relatively stable stock before 2000 is a reasonable assumption. An example of the analysis for China is shown below for the transport sector:

Wang and Graedel (2010) (ref. S6) provide product specific stock data for Chinese transport in 2000 and 2005. By assuming a constant growth of stock between 2000 and 2005, the stock for the in between years can be estimated, as shown in Table S3.

Table S3: Derived Chinese transport stocks

	Stock (Wang et al, 2010) 2000 (Gg)	Stock				Stock (Wang et al, 2010) 2005 (Gg)	Annual Growth Factor
		2001 (Gg)	2002 (Gg)	2003 (Gg)	2004 (Gg)		
Transportation	**1754**	**2033**	**2356**	**2731**	**3166**	**3669**	**1.16**
Motor Vehicles	1430	1678	1969	2311	2712	3183	1.17
Passenger Vehicles	*522*	*650*	*809*	*1008*	*1255*	*1563*	*1.25*
Freight Transport Vehicles	*232*	*249*	*267*	*287*	*308*	*330*	*1.07*
Special Use Vehicles	*17*	*20*	*23*	*27*	*32*	*37*	*1.17*
Trailers	*29*	*32*	*35*	*39*	*43*	*48*	*1.11*
Agricultural Tractors and Vehicles	*66*	*81*	*101*	*124*	*153*	*189*	*1.23*
Motorcycles	*453*	*521*	*599*	*688*	*791*	*909*	*1.15*
Others	*40*	*19*	*9*	*4*	*2*	*1*	*0.48*
Military Vehicles	*44*	*46*	*49*	*51*	*54*	*57*	*1.05*
Police Vehicles	*28*	*31*	*35*	*39*	*44*	*49*	*1.12*
Bicycles	149	166	185	206	229	255	1.11
Air and Aerospace	45	48	50	53	56	59	1.06
Civil Aircraft	*23*	*25*	*28*	*30*	*33*	*36*	*1.09*
Military Aircraft	*22*	*22*	*22*	*23*	*23*	*23*	*1.01*
Marine and Freshwater	30	31	32	32	33	34	1.03
Motor Transport Vessels	*13*	*14*	*14*	*15*	*16*	*17*	*1.06*
Barges	*0*	*0*	*0*	*0*	*0*	*0*	*0.00*
Motor Fishing Vessels	*16*	*16*	*16*	*16*	*16*	*16*	*1.00*
Military Vessels	*1*	*1*	*1*	*1*	*1*	*1*	*1.00*
Railroad and Subway	66	71	76	81	87	93	1.07
Locomotives	*23*	*24*	*24*	*25*	*25*	*26*	*1.02*
Passenger Cars	*22*	*22*	*23*	*23*	*24*	*24*	*1.02*
Special Freight Cars	*21*	*24*	*27*	*31*	*35*	*40*	*1.14*
Subway Vehicles	*1*	*1*	*2*	*2*	*2*	*3*	*1.25*
Cargo Container	34	36	38	40	43	45	1.06

By considering the new demand and replacement demand, using equations 2 to 4, the consumption breakdown for the year 2005 for transport can be obtained, as shown in the last column of Table S4.

Table S4: New and replacement demand for aluminium in Chinese transport

	2001 (Gg)		2002 (Gg)		2003 (Gg)		2004 (Gg)		2005 (Gg)		
	New demand	+ 2000 replacement demand	New demand	+ 2000 replacement demand	New demand	+ 2000 replacement demand	New demand	+ 2000 replacement demand	New demand	+ 2000 replacement demand	2005 Fraction
Transportation	**245**	**367**	**306**	**428**	**373**	**494**	**449**	**571**	**540**	**662**	**100%**
Motor Vehicles	*219*	*314*	*277*	*373*	*341*	*436*	*414*	*509*	*501*	*597*	*90%*
Passenger Vehicles	*128*	*163*	*159*	*194*	*199*	*233*	*247*	*282*	*308*	*343*	*52%*
Freight Transport Vehicles	*17*	*32*	*18*	*34*	*20*	*35*	*21*	*36*	*22*	*38*	*6%*
Special Use Vehicles	*3*	*4*	*3*	*4*	*4*	*5*	*5*	*6*	*5*	*6*	*1%*
Trailers	*3*	*5*	*3*	*5*	*4*	*6*	*4*	*6*	*5*	*7*	*1%*
Agricultural Tractors and Vehicles	*15*	*20*	*19*	*23*	*24*	*28*	*29*	*33*	*36*	*40*	*6%*
Motorcycles	*68*	*98*	*78*	*108*	*89*	*120*	*103*	*133*	*118*	*148*	*22%*
Others	*-21*	*-18*	*-10*	*-7*	*-5*	*-2*	*-2*	*0*	*-1*	*2*	*0%*
Military Vehicles	*2*	*5*	*2*	*5*	*3*	*6*	*3*	*6*	*3*	*6*	*1%*
Police Vehicles	*3*	*5*	*4*	*6*	*4*	*6*	*5*	*7*	*5*	*7*	*1%*
Bicycles	17	36	19	37	21	40	23	42	26	45	7%
Air and Aerospace	2	4	3	4	3	5	3	5	3	5	1%
Civil Aircraft	*2*	*3*	*2*	*3*	*3*	*3*	*3*	*4*	*3*	*4*	*1%*
Military Aircraft	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0%*
Marine and Freshwater	1	2	1	2	1	2	1	2	1	2	0%
Motor Transport Vessels	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0%*
Barges	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0%*
Motor Fishing Vessels	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0%*
Military Vessels	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0%*
Railroad and Subway	4	7	5	7	5	8	6	8	6	9	1%
Locomotives	*1*	*1*	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	*0%*
Passenger Cars	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0%*
Special Freight Cars	*3*	*4*	*3*	*4*	*4*	*5*	*4*	*5*	*5*	*6*	*1%*
Subway Vehicles	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*1*	*1*	*1*	*0%*
Cargo Container	2	4	2	4	2	4	2	5	2	5	1%

Determining which analysis (China or Connecticut) to use for the various sector breakdowns is a result of local exaggerations of certain metal uses. For example, Chinese aluminium use in transport is much lower than the worldwide average. Typically, aluminium use in passenger cars is dominated by cast engines and, by a growing amount in the developed world, the body structure. The high cost of aluminium may prevent it being so prevalent in developing markets such as China where a cast iron engine block and steel sheet body structure are more likely to be used, accounting for the reduced relative use.

Figure S2 compares the overall breakdown of the two production mixes derived from the stock data against the IAI (2008a) (ref. S2) in Table S2.

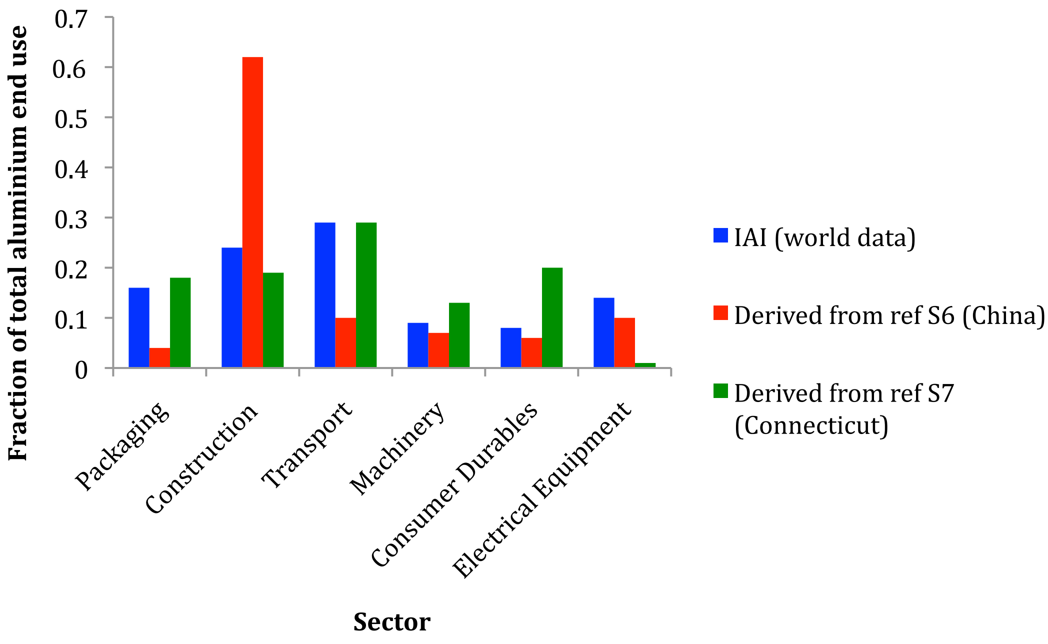


Figure S2: Comparison of world (S2) and stock analyses (S6 and S7) for aluminium end use

Connecticut most closely resembles worldwide production data for 'packaging', 'construction' and 'transport', whereas Chinese data most closely resembles worldwide data for 'machinery', 'consumer durables' and 'electrical equipment'. For a given sector, the stock analysis with the closest fraction to the world will be used if necessary.

1.1 Transport

The top-down estimates for transport end use are 146Mte of steel and 12Mte of aluminium per annum. The sector encompasses automotive, rail, aerospace and shipping vehicles. The following bottom-up study derives the relative importance of these products.

Automotive

For road vehicles, the OICA (2007) (ref. S8) provides production statistics and the following definitions:

- **Passenger cars** are motor vehicles with at least four wheels, used for the transport of passengers, and comprising no more than eight seats in addition to the driver's seat.
- **Light trucks** are motor vehicles with at least four wheels, used for the carriage of goods. Mass given in tons (metric tons) is used as a limit be-

tween light commercial vehicles and heavy trucks. The limit varies between nations, but is between 3.5 and 7 tons.

- **Heavy trucks** are vehicles intended for the carriage of goods, and are heavier than the limit for light trucks (varying between 3.5 and 7 tons).
- **Buses and coaches** are used for the transport of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass over the limit (ranging from 3.5 to 7 tons) of light commercial vehicles.

In 2008, approximately 53 million passenger cars were manufactured worldwide. Over 65% of these were manufactured in North America, Europe and Japan (see Table S5).

Table S5: Three region production of passenger cars

Region	Total Production (2008)
North America	6210000
Europe	18400000
Japan	9920000

Table S6 presents worldwide commercial vehicle production.

Table S6: Worldwide commercial vehicle production

Vehicle Type	Total Worldwide Production (2008)
Light Commercial	13600000
Heavy Trucks	3590000
Heavy buses and coaches	703000
Total	17800000

Aluminium in passenger cars

The average aluminium content in European, North American and Japanese cars is presented in Bertram et al (2009) (ref. S9) and shown in Table S7.

Table S7: Average aluminium content in passenger cars

	North America	Europe	Japan
Average Aluminium Content (kg)	145	118	114

Scaling the average aluminium contents of Table S7 by the production figures presented in Table S5, a three region average was taken as the worldwide aluminium content average of passenger cars in 2008, equivalent to 121.5kg. With over 65% of the worlds passenger cars produced in these three regions this is considered a reasonable assumption. Multiplying by the total passenger car production market gives a total of **6.4Mte** of aluminium being used in passenger cars in 2008.

Aluminium in light trucks

Light Vehicle Weight on the Rise (2007) (ref. S10) is a US department of energy publication, showing the average mass of light trucks in the US in 2006 is 4,712lbs, equivalent to 2,142kg. There are differences between the aluminium use in passenger cars and light trucks – a greater proportion of engine blocks are cast iron in light trucks, rather than aluminium, but a greater amount of bodywork and supporting framework are aluminium sheet and extrusions: providing a lightweight construction allowing a greater payload as well as corrosion resistance. Therefore, it has been assumed that the same percentage of total mass is aluminium in light trucks as in passenger cars (8.4%), implying that **2.5Mte** of aluminium is used in light trucks in 2008. Classing passenger trucks and light trucks together gives a total of 9**Mte** of aluminium.

Aluminium in heavy trucks

Heavy trucks are defined as over the light commercial vehicle limit, which varies between nations from 3.5 to 7te total weight. Assuming a weight of 5.6te (S11) and the same aluminium proportional composition as passenger cars (as explained for light trucks above) gives the total aluminium use entering service in heavy trucks in 2008 as **1.7Mte**.

Aluminium in heavy buses and coaches

Heavy buses and coaches range in mass from 3.5 – 7 tes. Assuming a value of 4Mte (S11), and an aluminium composition the same as the passenger car (as explained above for light trucks), then **0.2Mte** is used here.

Grouping heavy truck and heavy buses and coaches together under the banner of 'heavy trucks' gives a total aluminium dedication of **1.9Mte** in 2008.

Steel in passenger cars, light and heavy trucks, buses and coaches

The average passenger car has a mass of 1440kg, of which 960kg is steel (S12). This is consistent with data received from a leading UK car manufacturer. Therefore, we take the average composition of passenger cars as 66.7% steel. Multiplying by the total worldwide passenger car production implies a total of **50Mte** of steel used in passenger cars in 2008. Assuming the same composition for light trucks, heavy trucks and buses gives Table S8.

Table S8: End use of steel and aluminium in automotive applications in 2008

Vehicle type	Aluminium (Mte - %)	Steel (Mte - %)
Cars & light trucks	*8.9 – 20%*	*70 – 7%*
Cars	6.4 – 14%	51 – 5%
Light trucks	2.5 – 6%	19 – 2%
Heavy trucks & buses	*1.9 – 4%*	*15 – 1%*
Heavy trucks	1.7 – 4%	13 – 1%
Heavy buses	0.2 - Negligible	1.9 - Negligible

Aerospace

Aeroplanes are predominantly made from aluminium, with 66% of the A380 airframe aluminium (S13). The top-down estimate is 0.2Mte of end use aluminium (S2), less than 0.5% of the total end use aluminium, and therefore not a significant end user of the metal. To check the validity of the end use figure a bottom-up study is conducted below using data from Boeing and Airbus, the two major worldwide aerospace manufacturers. Tables S9 and S10 present the orders received in 2009 for each type of aircraft, and the corresponding mass of aluminium.

Table S9: Boeing commercial Aircraft Orders for 2009 (ref. S14)

Type	737	747	767	777	787	Total
Number	197	5	7	30	24	263
Max. take-off Mass (kg)*	78200	397000	204000	300000	204000	1180000
Al. per plane (te)**	15	75	39	57	39	224
Total Al. (te)	2910	375	270	1700	926	**6180**

- *Maximum take-off weights taken from ref. S15
- **The mass of aluminium in the 747 is taken from ref. S13. The other types are scaled using maximum take-off weight as a scaling factor.
- The mass of the 787 has been taken to be same as 767

Table S10: Airbus 2009 Orders (ref. S16)

Type	A318/A319/ A320/A321	A330/A340 /A350	A380	Total
Number	228	78	4	310
Empty mass (lb)	92400	284400	608400	
Empty mass (kg)	42000	129273	276545	
Engine Spec.	2 CFM56-5	4 CFM56-5C4	4 Trent 900s	
Engine Mass (kg)	3990	3990	6271	
Total Engine Mass (kg)	7980	15960	25084	
Airframe mass (kg)	34020	113313	251461	
Al. per plane (te)*	22.5	75	166	
Total Al. (te)	5119	5833	664	**11617**

*Table S10 assumes 66% of the airframes are aluminium.

In total, it is estimated only 0.02Mte of aluminium entered service in 2009 in commercial aircraft. For the IAI figure to be correct, there would have to be over 10 times the mass of aluminium entering commercial aircraft entering military and domestic planes. Therefore, 0.2Mte is an upper bound, and the aluminium entering aerospace is definitely less than the 1% of end use limit needed to be included in the catalogue.

Rolling stock

Aluminium sheet and extrusions are commonly used in modern freight and passenger rail carriages. This allows greater maximum speeds for express trains, decreased accelerating force requirements for commuter trains, and higher payloads for freight trains. Analysis on the aluminium stock of Connecticut found only a negligible use of aluminium in rail applications. Similarly, only 1% of alu-

minium produced for Chinese transport is used in rail transport. Therefore, rolling stock can be dismissed as an insignificant user of aluminium.
Steel is also used extensively for freight and passenger carriages. However, if rolling stock is not a significant user of aluminium it will also not be a major user of steel (in overall percentage terms), as the total amount of steel produced is so much larger than aluminium (over 22 times).
National statistics from Japan endorse this - only 0.1% of domestic steel in Japan is used in rolling stock (S17).

Shipping

Ship plate is typically wide steel plate that is welded to form the hull of vessels. 1% of steel in the EU is used in shipbuilding (S18). However, the majority of the world's ships are not built in Europe, Table S11 showing the total gross tonnage (Gte) by region.

Table S11: Total Gross Tonnage production of Ships in 2008

Region	Ship building (10,000 Gte) (ref. S19)	Fraction of ship-building share	Total Steel production in region (Mte) (ref S1)
South Korea	1240	51%	52
China	840	34%	495
Europe	140	6%	175
Japan	90	4%	120
Rest of world	140	6%	509

Assuming a linear relationship between the gross tonnage and the amount of steel required in the ship-building industry allows a scaling factor of 0.0125Mte of steel per 10,000Gte to be derived from the Europe data. This implies a worldwide total of **31Mte**. Table 1 'Other transport' sector gives a total of 28Mte, though the fabrication yield of 81% assumed in table 1 is too low for shipbuilding (more like 95%).
Aluminium is used for yachts and the superstructure of cruise ships and passenger and car ferries. This is due to the high corrosion resistance and specific strength, allowing most of the ship to float above the water line. 16% of the aluminium used in transport in Connecticut is destined for marine applications.

Scaled to the world, this is equivalent to 4% of end use of aluminium overall. Connecticut is a state with an extensive sea border, so another bottom-up check has been performed: there have been approximately ten newly-built cruise ships every year since 2001, all at 100,000 tonnes or greater, indicating approximately 1Mte of aluminium used annually for cruise ships. Considering aluminium is also used for car and passenger ferries, a figure of 4%, indicating 1.8Mte, is reasonable.

Summary for transport

Table S12 presents the summary of the bottom-up analysis.

Table S12: Summary of transport breakdown bottom-up estimates

	Steel (Mte)	Aluminium (Mte)
Cars & light trucks	70	8.9
Heavy trucks & buses	15	1.9
Ships	31	1.8
Other (Rolling stock, aerospace etc.)	1	0.2
Total Bottom-up	117	12.8
Top-down estimates (Tables 1 and 2)	146	12.2

The top-down and bottom-up estimates are consistent for aluminium (less than 5% error). However, there is a discrepancy of 20% for steel, originating with the discrepancy for automobiles: The top-down estimate predicts 113Mte of steel going into automotive transport every year (Table 1). However, the assumed yield is a relatively high 81%, compared to the IAI's (2008a) 70% (S2). The fabrication of the steel bodywork on cars (accounting for over 30% of the mass) can have a yield as low as 50%, therefore the 81% yield is probably too high. A more realistic automotive yield of 60% reduces the total top-down estimate to 114Mte, a discrepancy with the bottom-up estimate of less than 2%. However, the bottom-up estimate does not account for any military production. Therefore, an average of the bottom-up and top-down analyses is taken at 131Mte, as shown in Table S13.

Table S13: Estimated breakdown for global transport end use

	Steel (Mte)	Aluminium (Mte)
Cars & light trucks	70	8.9
Heavy trucks & buses	15	1.9
Ships	31	1.8
Other (Military, rolling stock, aerospace etc.)	15	0.2
Total	131	12.8

1.2 Construction

The top-down estimates for construction are 540Mte of steel and 10.8Mte of aluminium per annum. The sector encompasses both buildings and infrastructure, with the following key products investigated:

- Structural steel
- Reinforcement steel
- Sheet (cladding, floor decking, sheet piling, cold formed sections)
- Tube (linepipe, structural, non-structural and conduits for air or gas flow)
- Rail track

These products all have relatively high fabrication yields therefore the absolute top-down estimates are likely to be accurate.

Steel

84Mte of heavy (39.5Mte) and light sections (44.4Mte) were produced worldwide in 2008 (S1). Assuming all heavy and light sections are used in construction, and the yield is approximately 94% (S4), a total of 79Mte of hot rolled sections were used in construction in 2008. Data on the split between buildings and infrastructure for the use of structural steel in the EU and USA is shown in Table S14.

Table S14: Average use of hot rolled structural sections in the UK and USA

	EU (S20)	USA (S21)	Total using EU split (Mte)
Buildings	76%	65%	58.5
Infrastructure	24%	35%	20.5

The EU is more representative of worldwide steel use in construction than the USA, and therefore the EU breakdown between buildings and infrastructure is used for sections. Moynihan and Allwood (2012) (ref. S5) in an investigation of steel use in construction, finding fabricated sections from welded plate account for steel equivalent to 5% of heavy sections. This is split 70:30 between buildings and infrastructure (ref. S5); the total use of structural steel increases to **61Mte for buildings** and **20Mte for infrastructure.** 10% of the mass of a steel framed construction is connections (nuts, bolts and fin plates), accounting for another 6Mte in buildings and 2Mte in infrastructure.

In 2008, 147Mte of reinforcing bar was directly produced as an intermediate product (S1). Contact with a major UK wire rod producer indicates that 50% of wire rod is also used as reinforcement steel: 0.17Mte of wire rod was used for reinforcement mesh in the UK in 2009 (S22), out of a total UK demand of 0.349Mte (S23). 149Mte of wire rod was produced globally in 2008 (S1), indicating a total of 221.5Mte of reinforcing steel. Assuming a 94% fabrication yield (S4), this is reduced to 208.21Mte entering use each year.

Data for the relative use of reinforcement steel in buildings and infrastructure was not found at an international, regional or even national level. Moynihan and Allwood (2012) (ref. S5) use cement use as a proxy for reinforcement bar, analysing data from the UK, USA and Turkey. A split of 53% in buildings and 47% in infrastructure was calculated. This assumes that the amount of reinforcing steel per tonne of concrete is consistent across buildings and infrastructure. This was not fully verified and may be a source of error.

19% of drawn wire products are also used in construction, as cables, fences and wire reinforcement (S35), adding another 14Mte. Assuming a split equal to the reinforcement bars, and a fabrication yield of 94% (S4), this implies wire in construction accounting for 7.5Mte in buildings and 6.5Mte in infrastructure.

Steel infrastructure components also include railway track, of which 10.33Mte was produced in 2008 (S1), assuming a 94% yield this reduces to 9.75Mte. Hillenbrand (2008) (ref. S24) presents the amount of large diameter pipe produced worldwide in 2006 as 15Mte. Moynihan and Allwood (2012) (ref. S5) find tube accounts for 11% of steel in construction, implying 60.1Mte, and presenting the breakdown between buildings and infrastructure for each tube type.

Table S15: Tube breakdown in construction

	Buildings (Mte)	Infrastructure (Mte)	Total (Mte)	Total (%)
Line pipe	0	18.5	18.5	31
Structural	11	4	15	25
Non-structural	9.5	10	19	32
Handrails	*4.5*	*2*	*6.5*	*11*
Fences	*4.5*	*2*	*6.5*	*11*
Street Furniture	*0*	*6.5*	*6.5*	*11*
Tubes for air/gas	7	0	7	12
Total	27	33	60	100

The linepipe estimate of 18.5Mte is reasonable, as the figure from (S24) does not include all linepipe diameters and production will have increased between 2006 and 2008.

In buildings, sheet is used for cold-formed sections, cladding, and metal decking for composite floors. Sheet is also used for sheet piling foundations in infrastructure. Given we have tonnages for the other products in construction we can perform a mass balance to find the amount of sheet.

Assuming we need 540Mte of steel entering construction, means we have a total deficit of 160Mte to be made up with sheet. Moynihan and Allwood (2012) (ref. S5) derive the following percentage breakdown for sheet use in construction, shown in the second column of Table S16, allowing a global end use total to be estimated.

Table S16: Breakdown of sheet products in construction

Sheet product	Breakdown (ref. S5)	Total	Sector use
Cladding/Roofing	13%	21Mte	Buildings
Decking	6%	10Mte	Buildings
Sheet piles	4%	6Mte	Infrastructure
Cold formed sections	76%	122Mte	Buildings
Total	100%	160Mte	N/A

Nb: Cold formed sections includes purlins, cold rolled lightweight sections for mezzanines and sheds, and plasterboard track.

Table S17 presents the summary of the construction end use breakdown.

Table S17: Steel use in construction

	Buildings (Mte)	Infrastructure (Mte)	Total (Mte)
Sections	61	20	81
Connections	6	2	8
Rebar	110	98	208
Drawn wire	7	7	14
Sheet	152	6	160
Tube	27	33	60
Rail track	0	10	10
Total	363Mte (67%)	176Mte (33%)	540Mte

Aluminium

Aluminium in construction accounts for 24% of the end use of aluminium (S2), corresponding to **10.8Mte** annually. The statistics on end use in the American construction market (S25) are shown in Table S18.

Table S18: Aluminium use in construction

	American Breakdown (S25) (%)	Scaled worldwide tonnages (Mte)	Shape
Windows & door frames	33	3.5	>85% extrusions
Curtain walls & facades	19	2	>90% extrusions
Cladding	23	2.5	All sheet and plate
Other (Mainly gutters and spouts)	25	2.5	Mainly sheet and plate

The aluminium products are used almost exclusively in buildings.

1.3 Industrial equipment

The top-down estimates are 31Mte of steel and 6.3Mte of aluminium per annum for electrical equipment, and 135Mte of steel and 3.2Mte of aluminium per annum for mechanical equipment.

Electrical equipment

Bottom-up analysis of Chinese and Connecticut stock data both indicate approximately 55% of aluminium used in industrial equipment is for electrical, not mechanical, applications. The stock analyses and discussions with the UKs National Grid have produced the following list of key products that have been investigated:

- Steel pylons
- Steel reinforced cables
- Transformers, busbars (and motors)
- Aluminium cables
- Conduits

For the aluminium applications, the bottom-up Chinese analysis of stock data can be used to assess relative scale. Here, electrical applications are dominated by aluminium wire, cable transmissions and distribution cables. Other uses recorded in the Chinese analysis include bus bars, transformers, and generation equipment.

The top-down analysis indicates **4Mte** of aluminium in cables. This leaves **2.3Mte** of aluminium used for conduits, busbars and in transformers. Typical aluminium conductor steel reinforcement cable (ACSR) has a cross-sectional area ratio, aluminium to steel, of about 4:1. With steel having a density 3 times that of aluminium, we can predict about **2.4Mte** of steel used as reinforcement in electrical transmission cables.

10.4Mte of electrical sheet and strip was produced in 2008 (S1). Assuming a yield of 81% (S4), 8.4Mte is used in transformers and motors. Considering this is just the electrical component of these devices it is reasonable to double this percentage to approximately 2% of total end use to include the structural and casing elements, equivalent to **17Mte**. This leaves **11.6Mte** per annum used for the other applications such as steel pylons and wire sheathing.

Mechanical machinery

'Mechanical machinery' is a difficult sector to breakdown further, therefore characteristic case studies have been used to extract the key lessons for the product descriptions. A product description on rolling mills has been produced, and interviews conducted with mechanical machinery design companies.

For aluminium, manufacturing equipment dominates mechanical machinery, rather than agricultural or construction equipment. The analyses based on the stocks of China and Connecticut indicate that manufacturing equipment accounts for over 90% of the aluminium destined for mechanical machinery; equipment in the chemical and petrochemical industries is dominant – approximately 45% of stock in machinery in the sector in both 2000 and 2005 in China. Aluminium is used due to its mechanical properties combined with its excellent corrosion resistance in the presence of aggressive chemicals.

Total European foil production in 2008 was 810kte, with 25% used in industrial applications, largely for heat exchangers (S26). Scaling to world demand using GDP (S27), implies a global demand of 0.7Mte. The fabrication yield is predicted to be between 75-80% for the production of the heat exchanger fins, and therefore a final end use of **0.55Mte** is estimated.

Summary for industrial equipment

Table S19 presents the summary of the bottom-up and top-down analysis.

Table S19: Summary of industrial equipment breakdown estimates

	Steel (Mte)	Aluminium (Mte)
Mechanical machinery	135	3 (0.5Mte in heat exchangers)
Electrical Equipment	31	6
Electrical cables	/	4
Transformers and motors	17	/
Transmission cable reinforcement	2.5	/
Other (steel pylons/wire sheathing etc.)	11.5	N/A
Other (transformers, busbars, conduits)	/	2
Total	166	9

1.4 Metal Products

'Metal Products' contains packaging, domestic appliances and many miscellaneous metal goods.

Grouping 'metal products' and 'domestic appliances', the steel top-down analysis estimates **187Mte** of 'metal products' each year.

Grouping 'domestic appliances', 'other' and 'consumer durables', the aluminium top-down analysis estimates **13Mte** of 'metal products' each year. Bottom-up studies are used to increase the resolution of the end use estimates and to check the validity of the top-down numbers.

Packaging

Foil

Aluminium packaging foil is used for household foil, semi-rigid containers and pouches. The top-down analysis details **2.7Mte** of end use packaging foil in 2008 (S2). This estimate has been cross-referenced with data from Alufoil (2011) (ref. S26), stating total european foil production at 810kte, with 75% used in packaging. Scaling to a world demand using GDP (S27), implies 2.1Mte of end use. Considering GDP to be a very approximate method of scaling it is considered that the IAI (2008a) (ref. S2) figure of 2.7Mte is reasonable and will be used.

Drinks cans

The top-down data estimates **3.2Mte** of aluminium being used in drinks cans each year. As a bottom-up verification and estimate of steel use in drinks cans, data collected by European Aluminium Foil Association (2011) (ref. S28) shows typical European annual consumption of 52.7 billion drinks cans. Steel and aluminium drinks cans have an average weight of 21.4 grams and 14 grams respectively (S29), with aluminium accounting for 75% of the market. Scaling to world figures using a GDP ratio implies 46 billion steel cans (**1Mte**) and 138 billion aluminium cans (2Mte) worldwide. Once again, considering the limitations of scaling with GDP, the top down figure of 3.2Mte for aluminium drinks cans is reasonable and will be used.

Aerosols

Typical empty steel aerosols weigh 113grams, and have a 85% market share, the rest being aluminium. In 2008, the UK used 1.25billion aerosols (S30). Scaling to the world using GDP (S31), implies 5 billion aluminium aerosol cans (**0.4Mte**) and 28 billion steel aerosol cans (**3.1Mte**) are produced each year worldwide.

Food cans

Food cans are made from tin plated steel, weighing approximately 58 grams each (S32). In 2008, the world produced approximately 100billion food cans (S33), corresponding to **5.8Mte** of steel.

Shipping containers (inc. barrels etc.)

4% of Japans domestic steel use, equivalent to 1.4Mte, is in making containers (S17). 8% of the world steel exports originate from Japan. Scaling container production with total steel exports provides a crude estimate of worldwide container production, equal to 17.5Mte. Considering a fabrication yield of 92% (S4), this is reduced to **16.1Mte** annually, 1.5% of all end use steel.

Consumer durables and domestic appliances

'Consumer durables' and 'domestic appliances' cover many of the large electrical items in the home and office. The top-down analysis estimates **28Mte** of steel and **3.2Mte** of aluminium per annum. Bottom-up studies are needed to improve the resolution to individual products. Analysis of the Chinese aluminium stock analysis reveals consumer durables are dominated by household, rather than commercial, products. In turn, household durables are dominated by three key products: fridge/freezers, washing machines and televisions. This is consistent with the Connecticut aluminium stock analysis. Truttmann and Rechberger (2006) (ref. S34) present the typical material breakdown of these products, shown in Table S20.

Table S20: Steel and aluminium breakdown of household durables

	Refrigerator	Washing Machine	Television
Steel (and iron) (%)	47	51	17
Aluminium (%)	2	3	2
Average Weight (kg)	50	75	30

Fridge/Freezers account for 16% of aluminium consumer durable production in China, scaling to **0.51Mte** worldwide. Table S20 allows estimation of the total steel use in these products worldwide: the mass of steel is a factor of (47/2) greater than that of aluminium for refrigerators, equating to **12.45Mte**. Washing machines account for 17% of aluminium consumer durable production in China, scaling to **0.54Mte** worldwide. Table S20 allows estimation of the total steel use in these products worldwide: the mass of steel is a factor of (51/3) greater than that of aluminium for refrigerators, equating to **7.82Mte**. Televisions account for 13% of aluminium consumer durable production in China, scaling to 0.42Mte worldwide, less than the 1% of end use needed to justify an individual description in the product catalogue. Table S20 allows estimation of the total steel use in these products worldwide: the mass of steel is a factor of (17/2) greater than that of aluminium for televisions, equating to **2.55Mte**. This is also less than 1% of steel end use products.

Drawn steel wire products

74.5Mte of wire rod was drawn into wire in 2008. A leading wire producer provides the following end use breakdown of their products (S35).

Table S21: Percentage breakdown of drawn steel wire use

Sector	Breakdown
Metal products (wire binders, springs etc.)	4%
Agriculture (Barbed wire fences)	8%
Energy sector	21%
Basic materials (mining etc. – wire ropes)	4%
Automotive	36%
Construction (reinforcement, fences etc.)	19%

Grouping agriculture, metal products and basic material use together implies 16% of drawn wire use, equating to **20Mte.**

Other steel goods (inc. other packaging)

A mass balance on the 'metal product' sector implies **113Mte** of other steel products. This includes a multitude of products from chairs and filing cabinets to cooking equipment and other packaging.

Aluminium lithographic plate

A lithographic plate is used to repeatedly print images and text. The total world market volume grew from 390kte in 2002 to 414kt in 2004 (S36). Continuing this annual growth rate of just over 3%, indicates a worldwide demand of **0.47Mte** in 2008. This estimate is consistent with company specific figures from Novelis: a third of aluminium production is in rolled products, of which Novelis is a global leader. Just 3% of Novelis' rolled products are lithographic plate, implying approximately 1% (0.45Mte) of total aluminium production per year is dedicated to lithographic plate.

Aluminium deoxidation of steel

Aluminium (98% purity) is a very effective deoxidant of molten steel. It reacts with the dissolved oxygen to form aluminium oxide. Depending on the level of deoxidation, and hence the carbon and oxygen content, the resulting steel ingots range from fully killed, through semi-killed and capped to rimmed steel. On average approximately 1kg of aluminium is required to deoxidate every tonne of steel (S37). Although there are other methods of deoxidation, such as by vacuum or diffusion, aluminium is the dominant deoxidation method. 1Kg of aluminium for every tonne of the 1330Mte of molten steel produced in 2008 implies **1.3Mte** of aluminium was needed to deoxidise the steel.

Summary for metal products

Table S22 presents the summary of the analyses on metal products.

Table S22: Summary of 'metal products' breakdown estimates

	Steel (Mte)	Aluminium (Mte)
Packaging	26	6.5
Shipping containers	16	/
Foil	/	2.5
Drinks cans	1	3
Aerosols	3	0.5
Food cans	6	/
Domestic Appliances	28	3
Fridges	12.5	0.5
Washing machines	8	0.5
TV	2.5	0.5
Other	5	2
Other (inc. packaging)	113	/
Wire products*	20	/
Lithographic plate	/	0.5
Steel Deox.	/	1.5
Other (powder metallurgy – paint, pigments etc.)	/	1.5
Total	187	13

*Barbed wire in agriculture, wire ropes in the mining sector, wire binders, bottle tops springs etc.

Tables S23 and S24 present the steel and aluminium intensive products identified in section 1.

1.5 Steel and aluminium end use products

Table S23: Steel end-use products (2008). Breakdown rounded to nearest Mte

Steel	End-use per annum	
	Mte	Fraction
Transport	131	13%
Cars and light trucks	70	7%
Heavy trucks and buses	15	1%
Ships	31	3%
Other (rolling stock, aero, military)	15	1%
Construction	540	53%
Buildings	364	36%
Structural Steel	*61*	*6%*
Connections	*6*	*1%*
Reinforcement steel	*110*	*11%*
Sheet	*152*	*15%*
Drawn wire	*8*	*1%*
Tube	*27*	*3%*
Infrastructure	176	17%
Structural Steel	*20*	*2%*
Connections	*2*	*0%*
Reinforcement steel	*98*	*10%*
Sheet – sheet piling	*6*	*1%*
Rails	*10*	*1%*
Drawn wire	*7*	*1%*
Tube	*32*	*3%*
Industrial Equipment	166	16%
Mechanical Machinery	135	13%
Electrical Machinery	31	3%
Motors and Transformers	17	2%
Other (pylons, cables, sheathing)	14	1%
Metal products	187	18%
Packaging	26	3%
Consumer durables	28	3%
Wire products	20	2%
Other goods (inc. other packaging)	113	11%
Total	1024	100%

Table S24: Aluminium end-use products (2008). Breakdown rounded to nearest 0.5Mte

Aluminium	End-use per annum	
	Mte	Fraction
Transport	13	28%
Cars and light trucks	9	20%
Heavy trucks and buses	2	4%
Marine	2	4%
Other (eg. Aerospace)	0.5	0%
Construction	11	24%
Window and door frames	4	8%
Curtain walls and Facades	2	5%
Cladding	2.5	5%
Other (gutter, spouts etc,)	2.5	6%
Industrial Equipment	9.5	21%
Mechanical machinery	3	7%
Manufacturing equip	3	7%
Electrical	6.5	14%
Cables	4	9%
Other (busbars)	2.5	5%
Metal products	12	26%
Packaging	6.5	14%
Domestic Appliances	3	7%
Other Con. Durables	1.5	4%
Litho plate	0.5	1%
Deox of steel	1.5	3%
Other – powder metallurgy etc.	0.5	1%
Total	45	100%

2. Catalogue of product design descriptions

2.1 Transport

(1) Steel use in Cars (Mass ≈ 960kg (2001); Production ≈ 51Mte/yr, 5% Total)

Mass of whole vehicle is 1440kg

Product Function: Safe and swift road transportation of passengers

Constraints: Energy absorption for crash worthiness; stable dynamic handling; aesthetics and minimum mass is desirable

Mass Breakdown of Car Components[1]

Component	2010 Conventional IC Car (kg of steel/iron)
Body Structure and Panels	272
Drivetrain	222
Suspension	112
Wheels and Tires	43 (40)
Closures	54
Other	257
Total Steel/iron Mass of Car	960

130kg of iron and 830kg of steel

Body Structure and Panels

Design Criteria: Energy Dissipation (limiting) for crash worthiness; strength to withstand 'in-service' loadings (longitudinal braking forces, lateral cornering forces, vertical forces from bumps and forces from mild impacts); stiffness to prevent 'oil-canning' deflections

Material[2]*:* Cold rolled steel and hot dip galvanized (HDG) product. There is currently a relatively small price difference between HDG and uncoated, lowering demand for uncoated products. Up to 50% of the structure of a modern car will be made from high strength steels (>300MPa)[8].

Nb: The use of stainless steels is growing at 6% annually (the cost differential between stainless and carbon steel continuously reducing)[2]

Mass: The kinetic energy of the vehicle is proportional to vehicle mass, and therefore decreases with any light weighting. However, crumple zones are required to dissipate the energy and demand material. Accurate modelling of crash loadings and energy dissipation is required to effectively reduce the mass without compromising safety.

Coating: Often HDG, the zinc coating providing both a physical barrier and sacrificial corrosion protection[2].

Process: Cold rolled sheet is slit, and stamped, producing profiled sections which may be welded together to form the frame of the vehicle.

Drivetrain

The drive train consists of the components that generate power and transfer it to the vehicle wheels. It includes the engine, transmission, drive shaft and any differentials. This description focuses on the engine block and transmission.

Engine block

The high specific strength of aluminium has led to its use as a material for engine blocks. However, steel is stronger and is desirable for use in powerful diesel engines with higher pressures and temperatures[3]. The engine block is an expensive component and is critical to the successful operation of the vehicle.

Design Criteria: Strength (limiting) to resist forces exerted by the pistons and crank shaft; wear resistance; low thermal expansion; corrosion resistance; low density; good castability and machinability; durability. The engine block must also provide mountings for the other engine components, including the cylinder head, crankcase, engine mounts, drive housing and engine ancillaries.

Material: Compacted graphite cast iron or gray cast iron

Mass: The mass of an 8 cylinder, 4-stroke engine is approximately 100kg. Light weighting may compromise the durability, and reuse and remanufacture potential of the engine[4]. The use of higher strength steels would allow a lighter engine block to be produced. A switch to aluminium or magnesium will also achieve light weighting, but it must be ensured these materials can withstand the high stresses induced by the diesel engine.

Process: The melt is cast in either sand or lost foam casting. After solidification, the engine block is machined, the mounting holes drilled and cylinders bored.

Current Reuse[3]: Engines are routinely remanufactured; a value of $5.2billion placed on engine remanufacture within Europe. A shared platform across brands and companies also facilitates reuse, with the same engine often being used by several OEMs. When repairing grey cast steel engine blocks, the cylinders are re-bored and liners 'slip-fitted' into the cylinders.

Current Material Yield: 50% estimated

Transmission (gears)

The engine produces power at a very high angular velocity. The transmission system converts this power to a higher torque and lower angular velocity, corresponding to the angular velocity of the wheels. Different gears are engaged to provide different combinations of desired torque and angular velocity.

Design Criteria: Strength (limiting) against root bending failure; stiffness to provide consistent contact; corrosion and fatigue resistance

Material: Medium carbon steel

Process[4]: Gear blanks are primarily produced using sand casting. These blanks are then machined to produce the gear teeth. Shell castings can produce nearer net shape castings, requiring significantly less machining. Many automotive spur and helical gears are also produced using gear rolling, though this process limits the minimum number of teeth on the gear, typically to 18. Current research suggests powder metallurgy (P/M) gears have the capacity to replace solid steel gears in small car transmissions.

Nb: Automatic gearboxes (popular in North America) are considerably heavier than manual gearboxes.

Suspension

The suspension provides ride comfort to the passengers and minimizes dynamic tire force fluctuations.

Design Considerations: Maximum steady state lateral acceleration; roll stiffness; ride frequencies; lateral load and roll moment distribution; and ride heights at various states of load

Material: Cold rolled, high strength steel strip[5]

Air springs are lighter and less stiff than leaf springs; providing superior ride comfort. They can also be inflated or deflated to produce the desired ride height. The stiffness of an air spring, k, is directly proportional to the load, m. The natural frequency is given by $\sqrt{(k/m)}$. Therefore, the natural frequency is independent of the load; optimal performance can be guaranteed throughout operation. In contrast, conventional springs are tuned to a particular load, making for poor performance under sub-optimal loading.

Hydraulic shock absorbers are dampers that extend and compress depending on the motion. Forcing oil through an orifice dissipates energy. This is a very effective damper when working properly. However, hydraulic dampers suffer from leakage as they wear (an environmental and performance problem), and cavitation: dissolved air comes out of solution, creating a dead band in force generation as the pressure created on the compression stroke must first compress the air before providing energy loss.

Light weighting: Higher strength steels would allow light weighting[6]

Wheels

Design Criteria: Strength (limiting) to transfer longitudinal, lateral and vertical loadings; stiffness to minimize deflections during cornering; fatigue and corrosion resistance

*Material***:** Hot rolled carbon-manganese steel (highly formable)[5]

Coatings: The wheels must be painted to avoid corrosion and/or hidden with wheel covers.

Process: The wheels are typically pressed from sheet metal, and then welded together (often leaving unsightly bumps).

Current Reuse: Reuse is hampered by uncertainty of corrosion and fatigue degradation.

Light weighting: Substitute materials, such as aluminium or magnesium may be used to reduce weight, but are more expensive

Current Material Yield: 80% estimated

Tire

The steel content of tyres is approximately 15% of total mass[7]. For a passenger car tyre at 21lbs (11kg), this equates to 1.65kg per tyre.

Design Constraints: Strength (limiting) and good bonding with the rubber tire compound

Construction: Radial or cross-ply wire mesh construction

Current reuse: Negligible. Tire retreading satisfies a small and decreasing market for passenger car tires. However, the tires can be retreaded up to 10 times[8].

Light weighting: The use of higher strength steel would allow less steel to be used[6]

Closures

Closures consist of items such as the doors, boot lid and bonnet.

Design Constraints: Stiffness (often limiting) to prevent 'tin-canning' effect; aesthetics and low mass is desirable. Nb: Closures are increasing used as part of the crash structure.

Material: Cold rolled steel and hot dip galvanized (HDG) product.

Mass: Light weighting of the body structure must consider the high levels of energy dissipation required for crash worthiness. Closures are increasingly being used as part of the crash structure for side impacts.

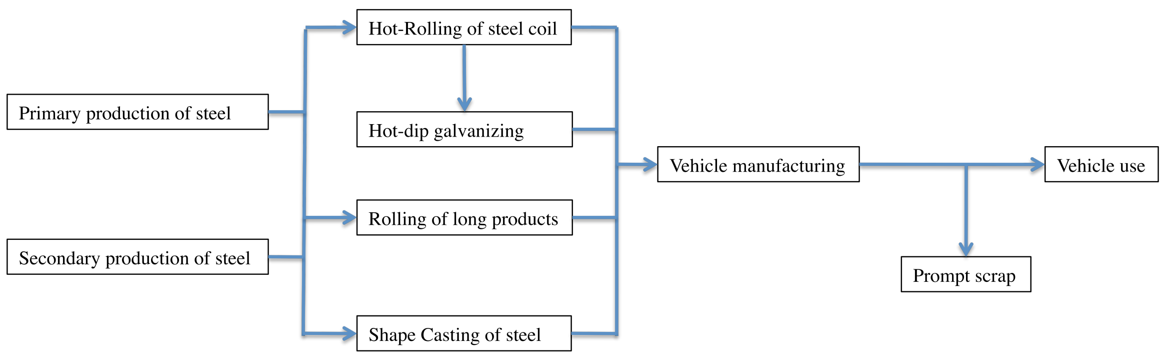
Coating: Often HDG, providing both a physical barrier and sacrificial corrosion protection.

Process: Cold rolled galvanized strip is trimmed, and closure blanks formed (approximately 5-10% material loss). Tailor welded blanks are often produced: different grades and gauges are welded to provide a more optimum material distribution, resulting in a lighter blank. The emissions benefits are nullified by the extra welding required. The blanks are then formed into the final shape in a press shop, where a series of presses shape and cut the metal. The material yield loss is up to 50%.

Abbey steel, a family run business in Stevenage, has for 30 years, bought, trimmed and re-sold around 10,000 tonnes per year of these cut outs. Manufacturers of small components including filing cabinets, electrical connectors and shelving use them for non-critical parts.

Significant yield improvements could be made if yield was addressed from a whole supply chain perspective.

Process Supply Chain[2]



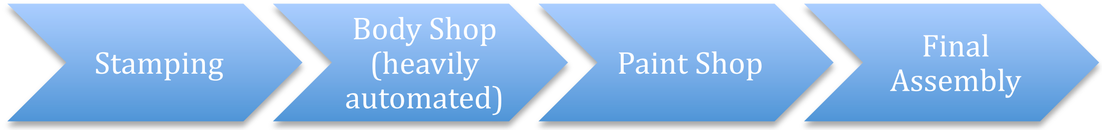
Car manufacturing process supply chain

The schematic above presents the various process stages. Nb: Scrap is produced along all the process routes, and not just at the vehicle manufacturing stage.

The figure opposite presents the various companies involved in production:

Original Equipment Manufacturers (OEMs) assemble the vehicle, and tend to keep distinguishing features of the car, such as the BIW and closures, in-house.

(The process steps within the assembly shop are shown in the flow chart below). The steel manufacturer can supply directly to the OEM, or to tier one and lower suppliers. Tier one suppliers deal directly with the OEM, whereas the lower tier supply components and/or provide support to the first tier. There are many thousands of sub-suppliers to the relatively large Tier Ones and OEMs.



Historical Development[2]

The automotive market has traditionally used mild steels of relatively low strength and high formability. However, demand for high strength steels (tensile strength > 300MPa) has grown rapidly in recent years. These are currently used in vehicle wheels, side impact bars, car suspension and clutch parts, but the trend is for their use to be extended, for instance in body panels. They allow down gauging, and hence light weighting. Future challenges are to develop high strength, highly ductile and weldable steels.

Light weighting

Absolute light weighting is a key strategy for the automotive industry to meet European emission targets of 95grams CO2/km by 2020. It is typically thought within the industry that this will demand vehicles of less than 1000kg. Due to their high specific strength, aluminium and carbon fibre composites are competitive substitute materials.

A rule of thumb within the industry, is that a 6-8% fuel saving can be realized for every 10% weight reduction.

References:

[1] Induced from numbers taken from: World Steel Auto. 2010. Future Steel Vehicle. Online: http://www.worldautosteel.org/uploaded/FSV_Executive_Summary.pdf

Last accessed 20 July 2010.

[2] Automotive Sheet Atlas. 2004. Automotive atlas – Section 1: Trends and Requirements of the Automotive Industry. Corus

[3] Dong H. Plenary lecture: Current Status of Engine Remanufacturing in the UK. 4th International Conference on Maintenance, 22-26 November 2008, Hainan, China, Publication Code: 56852

[4] Davis JR, Chapter 6: Casting, Forming and Forging. 2005. Gears Materials, Properties, and Manufacture. ASM International

[5] Automotive Sheet Atlas. 2004. Automotive atlas – Section 6: Application of automotive strip steels. Corus

[6] Lightweighting and life cycle impacts. 2010. Presentation at Wellmet2050 Workshop on Cross-sector Light weighting, 16th November 2010. Tata Steel.

[7] Rubber Manufacturers Association
Available Online:
http://www.rma.org/scrap_tyres/scrap_tyre_markets/scrap_tyre_characteristics/
Last Accessed: 7th December 2010

[8] Ferrer G. 1997. The economics of tire remanufacturing. Resources, Conservation and Recycling. Vol. 19, pgs. 221-255

[9] Automotive Sheet Atlas. 2004. Automotive atlas – Section 7: Future requirements. Corus

(2) Aluminium use in Cars (Mass of Al. ≈ 122kg; Production ≈ 8.9Mte/yr, 20% Total)

Mass of typical automobile: 1440kg

Product Function: Safe and swift road transportation of passengers

Constraints: Energy absorption for crash worthiness, stable dynamic handling, aesthetics and minimum mass is desirable. A design life of 10 years is typical

The predominant material used in automobiles remains steel. However, aluminium is increasingly used in automobiles due to its high specific strength, aesthetic appearance and corrosion resistance. The light weighting benefits offer either superior fuel economy or greater utilization for the same weight: increased size and gadgetry. Absolute light weighting is a possible strategy for the automotive industry to meet European emission targets of 95grams CO2/kg by 2020[1]. It is typically thought within the industry that this will demand vehicles of less than 1000kg[1]. A rule of thumb within the industry, is that a 6-8% fuel saving can be realized for every 10% weight reduction[2].

The average mass of aluminium in new cars is 118kg in Europe, and this is set to increase further as emissions legislation drives further light weighting[3].

Nb: Carbon fibre reinforced composites are also emerging as competing materials.

Average Aluminium Mass in Cars (2006)[3]

Component	2006 European Average Aluminium Content (kg/Car)
Engine Block	40.3
Transmission Casing	16.3
Chassis, Suspension and Steering	12.5
Wheels	17.7
Heat Exchanger	12.3
Other Components	19
Total	117.7

Other aluminium components include closures, body and IP beams, heat shields and bumper beams.[3]

Engine Block

An engine block houses the pistons and associated mechanical components of a multi-cylinder internal combustion engine. It is typically placed at the front of the vehicle, under the bonnet.

Dimensions: Determined by the number and orientation of the cylinders

Design Requirements: Strength (limiting) to resist forces exerted by the pistons and crank shaft; wear resistance; low thermal expansion; corrosion resistance; low density; good castability and machinability; durability. The engine block must also provide mountings for the other engine components, including the cylinder head, crankcase, engine mounts, drive housing and engine ancillaries.

Material: Casting aluminium alloy AA356[4], with a typical ultimate tensile strength of 245MPa, yield stress of 215MPa, and fatigue strength of 60MPa[5]

Substitute Material: Aluminium has increasingly replaced the market for steel blocks. However, magnesium, which is lighter than both, is now being used in low volumes.

Coatings: Coatings are typically applied to the interior of the cylinders: plasma spray coatings, typically based on metallic, carbide containing, ceramic or composite materials. These coatings increase wear resistance, and have been found to decrease the coefficient of friction, increasing fuel efficiency.

Mass: The average mass of an 8 cylinder, 4-stroke engine block is approximately 40kg. There is a continual drive to lightweight engine blocks. However, subsequent durability concerns directly conflict with the reuse potential of the engine.

Process: Molten aluminium (typically produced from recycling of old scrap) is cast in either sand or lost foam casting. After solidification, the engine block is machined, the mounting holes drilled and cylinders bored.

Current Reuse[6]: Engines are routinely remanufactured; a value of $5.2billion placed on engine remanufacture within Europe. A shared platform across brands and companies also facilitates reuse, with the same engine often being used by several OEMs. The development of advanced surface technologies such as spraying, cladding and thermo chemical treatments are slowly overcoming the quality and fatigue issues associated with remanufactured engines. When repairing the cylinders, they are re-bored and aluminium liners inserted by a shrinking process.

Current Material Yield: 50% (estimated)

Transmission Casings

A transmission casing conceals the interior parts of the gearing and clutch mchanism. Aluminium enclosures work well with aluminium heat sink parts to remove and dissipate heat from components.

Design Criteria[7]*:* Stiffness (limitting) to maintain correct alignment of the gear mesh. High thermal conductivity (dissiplating heat from internal components)

Material[4]: Casting aluminium alloy A380 [10] is typically used

Mass[7]: The current mass of an aluminum transmission casing is approximately 16kg. Mass reduction is complicated by the high stiffness demanded for gear mesh alignment. Such alignment is critical for long life, efficient tranmission and low noise. FEA models are being developed to model the vibratory and bearing forces to optomise the casing design.

Process: Molten aluminium (typically produced from recycling of old scrap) is die cast. On solidification, the part is machined for mounting as appropriate.

Current Reuse: Transmission casings are sometimes reused as part of drive train.

Chassis, suspension and steering

These elements are made predominantly from castings, but forgings extrusions and sheets are also used. The suspension provides ride comfort and minimizes vertical dynamic tyre forces.

Mass: Approximately 12.5kg of aluminium per car in such components

<u>Aluminium suspension arms</u>

Material[3]: Aluminium alloy AA6053 is often used

Process: The suspension arms are produced using open die forging (shaping of heated metal parts between a top die attached to a ram and a bottom die attached to a hammer anvil or press bed).

Current Reuse: The aluminium suspension arms are sometimes reused and chassis elements (wings etc.) may be reused if the car has been taken off the road early due to a crash.

Wheels

Design Requirements: Strength (critical under worst loading), stiffness to minimize deflections under vertical and lateral loads, minimum mass, aesthetic (bold designs)

Material[3]: Aluminium casting alloy, A356, is typically used

Coatings[8]: Solvent or acrylic based clear powder coatings, providing both gloss and surface protection against chipping and scratching

Mass: The mass of a typical aluminium alloy wheel is approximately 12kg. A forged aluminium wheel is stronger than a cast wheel, and therefore requires less material. Forged wheels can be up to 20% lighter than cast wheels and are becoming more popular.

Process: The majority of aluminium wheels are cast using either gravity sand casting or low-pressure sand casting (eliminating any trapped gas within the mould). Wheels are also forged, using heat and pressure to deform a slug of metal. Forging results in a radial grain structure that is extremely strong, but is constructed from 2-3 pieces welded or bolted together. Some wheels are produced from extruded billets (telephone pole sized cylinder), which are sliced and machined to produce the final shape.

Nb: Magnesium wheels, which are lighter than both steel and aluminium, are now being produced.

Current Reuse: Reuse is hampered by uncertainty of fatigue degradation. Currently, wheels cannot be legally reused on another vehicle.

Heat Exchanger

The use of aluminium heat exchangers is particularly desirable in automobiles due to their low mass.

Body in White (BIW)

Aluminium use in BIW is small across the entire market. However, since the introduction of the Jaguar XJ, the first car to incorporate a BIW from sheet based aluminium (causing a weight saving of 100-150kg)[1] greater use of aluminium in BIWs is likely. Typically, 5xxx series alloys (AA5052/AA5182/AA5754)[3] are used on the interior, and 6xxx series on the exterior (AA6009/6010/6022 and AA6111)[3]. Any aluminium extrusions used in the bodywork are typically AA6063. A material yield of approximately 50% is typical for such construction from sheet.

Economics The material accounts for approximately 5% of the cost of the car sale value (this includes materials other than aluminium)

References

[1] Wellmet2050 Workshop on Cross-sector Light weighting, 16th November

2010. Tata Steel.

[2] Automotive Sheet Atlas. 2004. Automotive atlas – Section 7: Future requirements. Corus

[3] Bertram M, Buxmann K and Furrer P. 2009. Analysis of Greenhouse Gas Emissions Related to Aluminum Transport Applications. *Earth and Environmental Science*. Volume 14, Supplement 1 pgs 62-69.

[4] Aluminum Processes and Materials. 2012
Aluminium in Transportation – The Aluminium Association
Online: http://aluminumintransportation.org/main/aluminum-processes-and-materials/aluminum-processes-and-materials
Last Accessed: 5th February 2012

[5] Anonymous, "Aluminum Cylinder Block for General Motors Truck/SUV engines," A Design Study in Aluminum Casings, pp. 1-31.

[6] Dong H. Plenary lecture: Current Status of Engine Remanufacturing in the UK. 4th International Conference on Maintenance, 22-26 November 2008, Hainan, China, Publication Code: 56852

[7] Harris O, Douglas M, James B, Woolley A and Lack L. Predicting the Effects of Transmission Housing Flexibility and
Bearing Stiffness on Gear Mesh Misalignment and Transmission
Error. Available online:
http://www.mscsoftware.com/support/library/conf/auto00/p01500.pdf

[8] Paper entitled "The Wheel of the Future: Innovative Coating Technologies in the Aluminum Wheels Industry" by Heiko Schneider and Dieter Marquardt presented at PCE 2004 in Hannover, Germany on 22-23 Apr 2004. Bound copies of the conference papers available from the organizers, Vincentz Verlag, Schiffgraben 43, 30175 Hannover, Germany. Tel: +49 511 9910 025. Fax: +49 511 9910 029

(3) Steel and aluminium use in Trucks (Steel / Al. ≈ 15 / 1.9Mte/yr, 1 / 4% Total)

Product Function: Safe and swift road transportation of freight (or people in the case of buses)

Constraints: Energy absorption for crash worthiness; maximized volume and freight mass capacity.

The weight distribution is typically about 7te for the tractor unit and 12te for the trailer.
The description of the 5 steel intensive components in the automobile (body structure and panels, drivetrain, suspension, wheels and tires, and closures) are all intensive steel components for trucks also. Two variations on the descriptions for the automobile must be noted:

- The strength of steel makes it almost exclusively used in the powerful diesel truck engines, and often transmission housings will be cast iron rather than aluminium
- Retreading of truck tires is much more common than passenger tires

Trucks use steel for strength and durability, aluminium for lightweight and corrosion resistance, polished stainless steel for bright finishes, and moulded plastics for complex shapes.

Frame rails and cross members are usually formed from high-tensile steel. Suspension components, axles, engine mounts are also made from steel. Some are cast and some are welded.

The cab structure and outer skin may be made from steel or aluminium. If steel is used the metal is coated with one or more layers of corrosion barriers such as zinc. Front bumper may be stamped and drawn from steel or aluminium.

Most fuel tankers and silo semi-trailers are made entirely of aluminium, and aluminium is frequently used for vans, tipping and self-discharging bodies. Without aluminium, the average articulated vehicle would be 800kg heavier

Manufacturing process

Future developments

Longer vehicles (double trailers) can improve fuel efficiency up to 40%. Most trucks are volume limited, but for mass limited vehicles (bricks, steel, fuel etc.), materials with a higher specific stiffness (aluminium and composites) are often used for construction.

There is also significant potential to save fuel and reduce fleet sizes by coordinating return journeys so that trucks never travel empty.

Current life expectancy from production to disposal

Tractor: 5-10 years (wear of drivetrain; Increasing regulations on emissions can cause obsolescence of tractor units). Greatest wear does not necessarily relate to mileage, as urban drive-cycles, with greater braking, steering and varying engine temperatures can cause the greatest wear.

Trailer: 10-15 years often due to run-down bodywork that prevents viable re-furbishment.

Current reuse

Large component and sub-assembly reuse is much more prevalent than in the passenger car market, with both refurbishment and reuse strategies being applied.

For specialised heavy trucks, with expensive bodywork, the engine and cab may be replaced (the price of the body work far exceeds that of the drivetrain and cab).

Commonality and standardisation between cabs and drivetrains (engines and gear boxes) has helped facilitate reuse. In the past, even small truck components (opposed to sub- assemblies) were reused, such as truck axles etc.

UK trucks at EOL are often used for spare parts for trucks in the developing world.

Bodybuilders 'and' chassis engineers who can convert/build new truck bodies cover two large sections of the reuse market. For example, converting 4 axle standard trucks to 6 axle tippers, or shortening and lengthening of wheelbase. Another example would be converting a delivery van to a recovery vehicle.

References

[1] Aluminium in Commercial Vehicles, European aluminium association. 2006
Online: http://aluminumintransportation.org/main/commercial-vehicle/case-studies
Last Accessed: June 2011

[2] Aluminium in trucks, trailers and Factsheet. 2006
Online: http://aluminumintransportation.org/main/commercial-vehicle/case-studies
Last Accessed: June 2011

(4) Steel Ship (Production≈31Mte/yr, 3% Total)

The majority of the words ships (by tonnage) are of the following varieties[1]: container, cruise, diversified, tanker, dry bulk, and offshore. The top 20 public shipping companies in the world own a combined fleet mass of 472Mte distributed between over 9000 ships[1]. The mass of a typical Very Large Crude Carrier (VLCC) is 30-36 thousand tonnes[1].

Dimensions are typically constrained by economical feasibility and the maximum geometry permitted by the likely sea route (for example: 32.2m widths and 12 m drafts are the upper limits determined by the panama canal, and a maximum height of 40m above waterline is determined by bridges in New York and San Francisco)[2].

The majority of the steel is in the hull, formed from welded steel plates attached to a framework of sections comprised of steel bars (flat, channel, tee and angle)[2]. The description below concentrates on the most used component, steel ship plate.

Ship Plate

Design Constraints: Dimensional consistency and flatness[3], a good combination of high strength, toughness, and weldability[4].
Dimensions[3]: Thickness of 6-20mm, tending thinner. The width is as wide as possible, with demand a main driver for 5m plate rolling mills

Material: Steel for hull construction is usually mild steel containing 0.15 to 0.23 percent carbon and a reasonably high manganese content[2]. Both sulphur and phosphorous in the steel are kept to a minimum (<0.05%); higher quantities are particularly detrimental to welding[2]. In highly stressed regions of large tankers, container ships and bulk carriers use high tensile steels[2]. Though weldability and fatigue endurance are concerns. Other alloying elements may include boron, copper, and nickel[4].

Coatings: Paints and coatings are often used to prevent ships rusting. Alternatively, cathodic protection on ships is often implemented using galvanic anodes attached to the hull.

Process supply chain of predominant material (Ship Plate)

Steel ship plate is currently only produced from ore, not recycled steel[2]. After the production of the steel, the challenge is to roll the steel thin and flat at maximum width[3]. Thermo-mechanically controlled rolling (TMCR) produces high strength and low temperature properties[5].

Reasons for End of Life[2]

Deterioration of the ship with age causes more costly and frequent repairs, ultimately the ship is no longer a viable commercial option. Given a favourable scrap price as well, the owner will scrap the ship for demolition, typically in the Far East. Technical obsolescence can also cause the relatively quick scrapping of vessel categories, such as multi deck ships in the late 1960s made obsolete by containerization.

Economics[1] The material accounts for approximately 60% of the total shipbuilding cost, labour 40%. Approximately $150billion was directly invested in shipping in 2007. Many banks and financial institutions value ships at their scrap value after a certain age. A relatively small number of companies own the majority of the worlds shipping. For example, five companies own 55% of the worlds cruise ships. Classification societies (such as Lloyds Register in London) provide assurance to the underwriter against the maritime risk. Approximately 10 large classification societies exist.

Historical development of metal and energy use Airlines cut passenger ships in the 1950s. Aluminium is now commonly used for cruise ships, as the higher specific strength allows a greater height above the water line for a given draft.

Current Reuse[6] One of the largest examples of metallic reuse results from ship dismantling in India. Approximately 50% of the world's discarded ships are broken in India, the majority in Alang, Gujarat. Tilwankar et al's (2008) analysis finds the ship breaking industry contributes 10- 15% of India's steel demand in 2008. Up to 80% of the steel recovered from the vessels is in the form of re-rollable ferrous sheets. These percentages imply reuse of ship plate provided up to 12% of India's steel demand in 2008. The steel is converted (without melting) into flattened plates, bars and rods that are used in the construction sector, offering a 66% emissions saving on conventional recycling.

Current Life Expectancy from Production to Disposal[1] 25-35 years. . In 2007, 216 vessels scrapped, average of 27 years for tankers and 32 years for dry cargo vessels (wide spread in each case). There are a few examples of vessels scrapped after 60 or 70 years.

References

[1] Stopford, Martin. 2009. Maritime Economics. 3rd Edition.

[2] Eyres, EJ. 2007. Ship Construction. 6th Edition.

[3] Bhooplapur P, Champion N, Lee J and Kriechmair J. 2010. Plate Mill Technology for Energy Sector Applications. South East Asia Iron and Steel Institute (SEAISI)

[4] 2008. High Performance Steel Plates for Shipbuilding Applications
Kyung-Keun Um, Sang-Ho Kim, Ki-Bong Kang, Young-Hwan Park and Ohjoon Kwon
Technical Research Laboratories, POSCO
Pohang, Kyungbuk, Korea

[5] Shipbuilding Steels: Part Two. Key to Metals.
Online:
http://www.keytometals.com/page.aspx?ID=CheckArticle&site=kts&NM=290
Last Accessed: 14th January 2011

[6] Tilwankar AT, Mahindrakar AB and Asolekar SR. 2008. Steel Recycling Resulting from Ship Dismantling in India: Implications for Green house gas emissions, *Second International Conference on 'Dismantling of Obsolete Vessels'*, University of Glasgow and Strathclyde, UK

(5) Aluminium Aircraft (Production ≈ 0.2Mte/yr, negligible Total)

This product description concentrates on the primary components of an aircraft structure: the fuselage, wing, empennage and supporting structure. Aircraft structures must be lightweight, durable and damage tolerant[1]. Aluminium, with its high specific strength and relatively low cost, lends itself to such an application. Polymer matrix composites are now being exploited in high-performance military aircraft, but wrought aluminium alloys remain the predominant material in the fuselage and wings of commercial airliners[2], typically 80% of the airframe being aluminium by weight[3].

The direction of net loads typically changes between in-flight and taxiing scenarios. It should be noted that in-flight loads are typically higher[2].

Wing

The wing acts as a beam, transmitting the lift forces during flight to the central fuselage.

Design Constraints: Bending and torsional stiffness is required to prevent both aileron reversal (adverse twisting of the wing during rolling) and flutter (high frequency oscillation of the wing)[4]. Strength is needed to carry the loadings (lift, thrust and weight of the engines and fuel)[4]. Corrosion resistance is also required[2].

Construction: The wing is a continuous structure from tip to tip[4]. The wing acts as a 'torsional box'[4], constructed from spars (forming the sides of the 'box'), ribs, stringers and wing skin panels[2]. Extrusions are used as wing stringers[2]. Plate, in the range 25-50mm, is used for wing covers[2]. The high strength 7xxx series alloys used in the wing contain zinc and copper. The copper makes it difficult to weld, therefore the structure is riveted together[3]. Further development of friction stir welding may change this in the future.

Materials: The upper wing skin demands high compressive strength; AA7055, AA7449 or AA7150 typically used[1]. The lower wing skin must possess tensile strength, fracture toughness and resistance to fatigue crack growth; AA2024 typically used[5]. High strength 7xxx series alloys (such as AA7075) are used for the wing spars.

Coatings: Structural aircraft components are often anodized to further increase their corrosion resistance[2].

Fuselage

The fuselage acts as a thin-walled pressure vessel in bending and torsion[4].

Design Constraints: Strength to resist internal cabin pressure (0.795bar – 2000m effective altitude)[4]; stiffness to resist loads imparted by wing lift; fatigue crack growth; fracture toughness and corrosion resistance. Fracture toughness is typically the limiting design consideration[2].

Material: The fuselage skin must exhibit high tensile strength and fracture toughness[6]. AA2024 is the most widely used material for fuselage skin, though AA7475 is also sometimes used[6]. High strength 7xxx series alloys (such as AA7075) are used for the internal frames, stringers and stiffeners.

Construction: Semi-monocoque structure, made up of a skin to carry shear loads and cabin pressure, longitudinal stringers to carry longitudinal tension and compression loads, circumferential frames to maintain shape and distribute loads, and bulkheads to carry concentrated loads[2]. Sheet and plate in the range of 1-10mm is used for fuselage skin[2]. Extrusions are used as fuselage stringers[2].

Coatings: Same as the wing

Empennage (Tail of the Plane)

The horizontal and vertical stabilizers act as an upside down and vertical wing respectively, with very similar design considerations, and the same materials used.

Design Constraints: Both upper and lower surfaces are critical in compression due to bending; stiffness is the limiting design criterion[2].

Construction and coatings: Same as the wing

Supporting Structures

The supporting structures include the attachments of the wings to the fuselage, and the landing gear to the wings and fuselage.

Design Constraints: Designed for strength, fatigue and fracture toughness[2].

Coatings: Same as the wing

Process supply chain

Machining of components such as wing spars, stiffeners, ribs and landing gear offers optimal final shapes and lightweight design[5]. However, the yield for this process results in 'buy-to-fly' ratios as high as 30; only 3% of the material purchased ends up in the plane structure[5]. Near-net casting of the aluminium ingots would improve this yield. Alternatively, further optimization and yield improvement may be realized with rapid manufacturing additive techniques.

Economics

Reducing aircraft mass allows greater payloads to be carried, or alternatively fuel savings to be made. Therefore, light weighting has been continually pursued over the years. Direct operating costs are becoming increasingly important with the rise in jet fuel over the last decade[6]. Recent estimates include $300/kg weight saving potential over the life of the aircraft in 2004[7] compared to 1500euros/kg in 2007[6].

Historical development of metal and energy use

Aluminium alloys have been used for the structural components of aircraft since 1930[2]. The advent of precipitation hardening and methods for increasing corrosion resistance (anodizing and cladding) in the 1920s prompted its use.

Current Reuse: Negligible

Current Life Expectancy: 25 years (used 250days/year and a range of

2x8000km/day)[6]

Current Mass and Material Yield: The empty mass of the A380 is 276.8te[4]. Light weighting of 10-30% is readily available with the use of CFRP compared to an aluminium baseline[6]. For machined structural components, the material yield can be as low as 3%[5].

References

[1] Alumatter Case Study: Aerospace
Available Online:
http://aluminium.matter.org.uk/content/html/eng/default.asp?catid=154&pageid=2144416895
Last Accessed: 24th November 2010

[2] Starke Jr E and Staley J. 1996. Application of modern aluminum alloys to aircraft. Prog Aerospace Sci Vol. 32, pgs 131-172

[3] The Aluminum Association: Aluminum in Aircraft
Online:http://www.aluminum.org/Content/NavigationMenu/TheIndustry/TransportationMarket/Aircraft/default.htm
Last Accessed: 23rd November 2010

[4] Guest S. 2006. Cambridge University Engineering Department, Long Vacation Part1A-Part1B Airbus A380-800: a structural design case study

[5] Dornfield D. 2010. Green Manufacturing – Degrees of Perfection.
Available Online: http://green-manufacturing.blogspot.com/2010/07/degrees-of-perfection.html
Last Accessed: 23rd November 2010

[6] Kaufmann M, Zenkert D and Wennhage P. 2009. Integrated cost/weight optimization of aircraft structures. Structural Multidisc Optim

[7] Curran R, Raghunathon S and Price M. 2004. Review of aerospace engineering cost modelling: the genetic causal approach. Prog Aerosp Sci 40(8): 487-53

2.2 Construction

(6) Steel Sections (Production ≈ 96Mte/yr, 9% Total)

Steel sections are used as both beams and columns in the construction industry, as well as in large machinery applications. Beams are usually referred to as I-sections and columns as H-sections (note that some structural sections are tubes).

The section may be considered as consisting of flange and web components:

Sections are very effective at carry web plane bending and compression, but the open section is poor in torsion.

Dimensions Typically, the flange thickness will be greater than the web thickness.

Overall Design When a structural engineer is choosing a beam or column, the strength requirement is typically checked first. For beams of significant length, however, the stiffness will likely be the limiting criteria. The maximum permissible central deflection of a structural beam under live loading with brittle finishes is L/360 (where L is the length of the beam) and L/200 for non-brittle finishes, as specified by British Standards[1].

Hot rolled sections typically come in standard sizes, know as universal beams (UBs) and universal columns (UCs). UBs are designed such that flange buckling can typically be assumed not to occur, and the full moment capacity of the beam may be realized when assessing ultimate limit states. This assumption requires the beam to be in a low shear state, defined as shear<0.6*shear capacity and the plastic moment capacity<1.2*elastic moment capacity[2].

Web

Design Constraints: Strength to resist shear forces; corrosion and fire resistance; the web depth, in combination with flange width and thickness, should provide sufficient web plane bending stiffness (realizing a central deflection less than L/360).

Material[3]: Structural steels contain small amounts of the useful alloying elements, carbon (0.17%) and manganese (1.4%). Sulphur (0.04%) and phosphorus (0.04%) are harmful elements present in the steel; their levels are closely controlled. In the UK, structural steels are designated by a code such as "S275-JR" where the 2nd to 4th characters present the material yield strength in MPa, and the last 2 characters represent fracture toughness properties. The ultimate strength of S235 sections is a minimum of 430MPa.

Coatings: Coatings provide fire protection to the steel. If not encased within brickwork or concrete, the beam is typically coated with intumescent paint. Alternatively, it is covered with mineral wool boards or coated with cementitious sprays. Coatings may also be used to increase corrosion resistance (intumescent paint and sprays offer some corrosion protection*).

Flanges

Design Constraints: Strength and geometry to resist web plane bending moment, and provide sufficient web plane bending stiffness (realizing a central deflection less than L/360); slenderness ratio constraint (b/2t<18, where b is the breadth and t the thickness of the flange) preventing local buckling[2]. The flange width and thickness may also be sized to allow attachment of secondary beams and services.

Material: As for the web

Coatings: As for the web

Process chain of predominant material

For sections of non-standard sizes, some steel fabricators will cut and weld appropriate plates to create the desired shape. However, the majority of sections are mass-produced as shown in the schematic above.

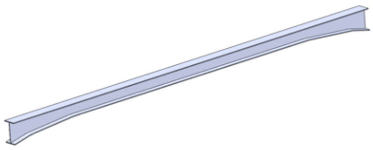
Blooms are continuously cast and then cut when the centre has solidified. The blooms are then reheated and hot rolled at approximately 1200°C. Multiple passes through reverse rollers are required. Little work hardening is imparted during rolling because the temperature is sufficient for the steel to self-anneal. The rolling acts to transform the cross-section, align grains and reduce porosity.

Direct hot rolling after continuous casting could conserve some of the energy already invested in heating the material. However, it is important that the centre of the bloom has solidified before hot rolling commences. Additionally, without removal of cut blooms to a rolling shed, multiple series-aligned rollers would be needed to reduce the cross-section.

Tata Steel Europe is exploring nearer-net shape casting of I-beam blooms, reducing the mechanical work necessary to create the cross-section. This may also allow the removal of intermediate reheating during rolling.

Economics A steel portal frame typically accounts for 15% of the total structural cost of a warehouse[4]. The frame usually accounts for 10-15% of the cost of a typical multi-storey building[*].

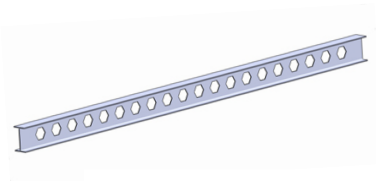
Historical development of metal and energy use The first sections produced in the 19th century consisted of riveted plates, forming the web and flanges. In the mid-20th century, rolled sectional joists (RSJs), with tapered flange thicknesses, were used. However, British and European standards now refer to standard section universal beams (UBs) and universal columns (UCs), produced with parallel inner flange faces.



Fabsec™ Beam

Significant Variations from Design

The shear force and bending moment requirements of a beam typically demand only 2/3 of the material currently used. By varying the cross section of the beam along its length, considerable material savings could be made. Fabsec beams (shown opposite) are manufactured by welding flange and web plates to produce a beam that may have tapered sections, forming nearer optimal beams (it should be noted that the majority of fabsec beams produced do not have tapered sections). Fabsec beams offer a potential weight saving of 14-18%, depending on end loading conditions[5].



Cellular Beam

Fabsec beam production is relatively small; the logistical issues of additional cutting, welding etc uneconomical in most cases.

Cellular beams (shown opposite) are standard universal beams, produced with cells cut out of the web at regular intervals to reduce weight. These beams offer a weight saving of up to 22%[5], and integration of services within the web depth of the beam. However, the material yield loss increases.

Current Reuse: There is minimal reuse of hot rolled steel sections. The limited activity centres on cascading reuse, with larger sections reused in the shoring and bracing industries[6]. In certain high fatigue loading cases, such as bridges and offshore structures, direct reuse may not be applicable.

Current Life Expectancy: Typically determined by the life expectancy of the construction, rather than of the steel section. Building life expectancies are typically 40-60years. The life of a steel section is often extended through building/infrastructure adaption and upgrade[6].

References

[1] British Standard: 5950 Part 1. Section 2.5.4. Table 8

[2] Handbook of Structural Steelwork, 4th Edition, BCSA, SCI, 2007

[3] Structural Steel
Online: http://www.steelstrip.co.uk/structural_steels.htm
Last Accessed: 26th October 2010

[4] Warehouse Guidance. 2010. Target Zero: Guidance on the design and construction of sustainable, low carbon warehouse buildings. Corus, BCSA, Cyril Sweett, SCI, Prologis

[5] Design Optimisation Case Study: Structural Beams. Mark Carruth, 2010

[6] Gorgolewski M, Straka V, Edmonds J and Sergio C. 2006. Facilitating Greater Reuse and Recycling of Structural Steel in the Construction and Demolition Process, *Canada Institute of Steel Construction*

[*] Tata Steel Europe

(7) Steel Reinforcing Bar (Production ≈ 210Mte/yr, 21% Total)

Reinforcing bars, commonly known as rebars, are placed within concrete (often as a cage) to increase the strength (both tensile and compressive) and stiffness of concrete components. Reinforcement can be pre-stressed, to induce a compressive force in the concrete. This prevents the concrete entering tension in bending and cracking. Reinforcement bars can be used both within poured in-situ concrete, and in pre-cast concrete.

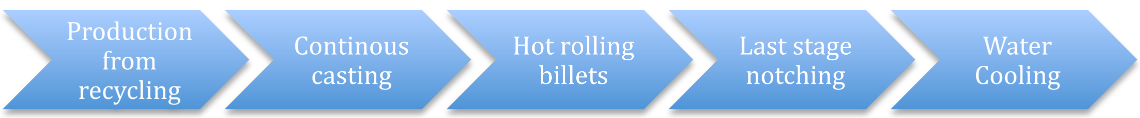
A minimum concrete covering is required for fire protection. The concrete also provides an alkaline environment, preventing corrosion. Too little surrounding concrete can cause an increase in rust, leading to more cracks and ultimately structural failure.

Design Constraints: High tensile yield strength (typically greater than 400MPa), high ductility, good bonding to the concrete, and similar coefficient of thermal expansion.

Material: Typically unfinished tempered low carbon manganese steel.

Coatings: Reinforcement bars are sometimes covered with a corrosion resistant coating, especially when under a marine environment. These bars are typically hot dip galvanized or covered in an epoxy based coating[1]. Nb: in non aggressive environments the rebar may be left at the construction site to rust on purpose to provide a better bonding surface for the concrete.

Process supply chain of predominant material



In the UK, production of reinforcing bar is predominantly from scrap. The molten steel is continuously cast into billets, which are then allowed to cool. The rolling of reinforcement bars is often remote to the casting facility. The billets are reheated to 1150°C, and hot rolled through several rolling stands to achieved the desired reduction in cross-section[2]. The last stage contains notches in the rollers that cut into the reinforcing bar to produce the ribs, which assist in bonding the steel to the concrete[2]. The bars are then water quenched, producing a ductile core and a temper martensite finish on the surface, improving strength[2].

Steel companies have investigated various methods of producing high strength rebar. The predominant method is currently a post rolling quench treatment (as described above). This is combined with microalloying (additions of vanadium and niobium) to produce extra high strength rebar (yield strength of above 600MPa). Current research is focusing on fine grain rebars, increasing strength and toughness with minimal ductility pay-off. Welding of such rebars, however, may cause problems with an increased grain size in the heat affected zone, causing a weakness.

Chinese Rebar (annual production approaching 100Mte)[1]

In developed countries, rebars typically have a yield strength of 400MPa and above. The Chinese domestic market, however, is dominated by grade 2 rebars with a yield strength of 335Mpa. Grade 2 rebars account for 60% of all products and applications in China. The mass of rebar China requires annually could be reduced by 14% if the strength were upgraded from grade 2 (335MPa) to grade 3 (400MPa), with a further 10% possible saving with an upgrade from grade 3 to grade 4 (500MPa).

Economics The rebar accounts for about 12.5% of the shell cost (WellMet2050 estimate)

Historical development of metal and energy use There has been a 40% increase[3] (using 2008 figures) in world crude steel production destined for reinforcement bar since 1998, indicating the growth of this sector. High strength reinforcing bars have been developed in the last 40 years, and welding rebar has existed since the 1970s.

Current Reuse: There is currently a negligible market for reclaimed reinforced concrete slabs, and extraction of the steel from the concrete after use is not currently possible. However, research at the High Power RF Faraday Partnership[4] has investigated the use of microwaves to heat the water within the concrete, causing cracking and ultimate disintegration. It is possible that this may allow reclamation of the rebar.

Current Life Expectancy: Usually determined by the life expectancy of the building (typically 40-60years), rather than the capabilities of the concrete. Specific rebar failures are typically caused by corrosion, induced by loss of alkalinity due to carbonation of the concrete from the atmosphere; too high a water:cement ratio in the concrete; stray currents in the ground inducing corrosion, and preferential corrosion caused by dissimilar metal contact[5].

References

[1] Caifu Y. 2010. Development of high strength construction rebars. Proceedings of International Seminar on production and application of high strength seismic grade rebar containing vanadium.

[2] Celsa website
Production Process - The rod & bar mill - Rolling reinforcing bars
Online:
http://www.celsauk.com/ProductionProcess.mvc/TheRodAndbarMill?=RollingReinforcingBars
Last Accessed: 10th November 2010

[3] World Steel Association. 2008b. Steel Statistical Yearbook 2008. World Steel Association.

[4] Wace PF, Shute RA and Hamblin C. 1993. Microwave Demolition Toll for Mounting on Long Range Manipulator (EMIR). Elsevier Science Publications B.V.

[5] Verma B. Corrosion of Steel Reinforcements in Concrete. Department of Materials and Metallurgical Engineering. Indian Institute of Technology, Kanpur.
Online:
http://www.contrib.andrew.cmu.edu/~neeravv/presentations/Neerav_Term%20paper.pdf
Last Accessed: 27th October 2010

[*] ***Celsa UK***

(8) Steel sheet in Construction (Production ≈ *160*Mte/yr, 1*6*% Total)

Steel sheet used in construction is dominated by purlins, roofing and cladding, panel systems and lintels[1]. These products are briefly discussed below.

Cold formed sections (122Mte)

Cold formed sections are predominantly purlins and structural channels for mezzanines and sheds. Purlins are horizontal structural members running the length of the building, and supporting a roof deck or wall cladding. They can also provide lateral stiffness to a portal frame. They are a common feature of portal frame construction.

Design Constraints: Structural performance (strength and stiffness). Typically, purlins will be stiffness limited[2]. Design is based on simple beam loading[2], with a maximum allowable deflection, L/200 for non-brittle finishes, as specified by British Standards[3]. The purlins must also display corrosion resistance to ensure desired life.

Material and Geometry: Cold formed low carbon steel. Long steel strips are formed into C or Z sections. Z sections are slightly weaker than C sections when laterally unrestrained. However, Z sections have a shear centre at the centroid of the section, and are therefore less likely to twist under self-weight. The lipped flanges of both types of section provide additional lateral torsional strength[2].

Construction[2]: The purlins are bolted onto cleats, which are welded onto columns or rafters. Purlins are typically vertically spaced every 2m, with spans of 4-5m.

Process: Cold formed through multiple rollers from steel strip. Each set of rollers (or stands) only perform an incremental part of the bend. The production rate is a function of the thickness of the strip and the amount of bending required.

Mass: Typically anywhere between 1.5 and 15kg/m, though larger purlins are possible[4]. Purlins represent a relatively small amount of the total mass of a typical steel framed building.

Economics[5]: Z- sections are slightly more expensive (approximately 4%) than C sections. Despite accounting for little of the steel mass in a building, the time taken to erect the purlins can be considerable, and have a disproportionate economic and time impact on the completion of the project.

Current Reuse: Negligible. Even during deconstruction and reuse projects, purlins are often damaged and need to be replaced[6].

Current Lifetime: Usually determined by the life expectancy of the building. Building life expectancies are typically 40-60 years.

Roofing, decking and Cladding (31Mte)

Steel provides strong and durable cladding. However, a disadvantage is that steel is a good thermal conductor. Additionally, there is the potential for bimetallic corrosion with poor fastener design.

Design: Strength and stiffness considerations for environmental loadings; durable; lightweight and portable

Material: Stainless steels are often used (greater than 11% of the mass of the steel is chromium)

Coating: Often galvanized if not stainless

Current Life Expectancy: Most warranties are for 25-50 years.

Current Reuse: Negligible. Even in cases of portal frame relocation, cladding is often not reused as changing thermal and fire standards mean cladding older than ten years is unlikely to meet modern codes.

Sheet piling (6Mte)

4% of sheet piling in infrastructure is currently reused by relocation (S41). Given greater economic incentive and better workmanship to ensure easy extraction, and it is assumed this could rise to 10%.

Panel Systems (negligible)

Suspended ceiling frames are common in modern non-residential construction. They consist of a grid of interlocking upside down ‘T’ steel channels. Non-metallic panelling then spans the spaces between the channels. The suspended ceiling conceals a host of services and ducts above, as well as offering acoustic balance in the room below. They also allow the services to be easily accessed and adapted. A disadvantage is that they reduce the height of the room.

Design Constraints: Stiffness (limiting) to prevent sagging; strength, rigidity, cost

The grid is supported by wires screwed directly into the true ceiling.

Lintels (negligible)

A lintel is a horizontal beam used above a door, window, or fireplace opening. It usually bears the weight of the wall above the opening.

Design Constraints: Structural performance (strength and stiffness). Design is based on simple beam loading, with a maximum allowable deflection, L/200 or L/360 for non-brittle and brittle finishes respectively[3]. The lintels must also display corrosion resistance to ensure desired life.

References

[1] Ley J. 2003. An Environmental and Material Flow Analysis of the UK Steel Construction Sector. PhD Thesis. Cardiff University.

[2] McCormack. 2008. Structural Steel Design, Section 10.6. 4th Edition. Pearson Education Inc.

[3] British Standard: 5950 Part 1. Section 2.5.4. Table 8

[4] Sun Bow Roofing
Industrial, commercial and Residential: Purlins and Structural
Online: http://www.sunbow.com.au/purlins.htm
Last Accessed: 3rd November 2010

[5] Economics of Structural Steel Work Purlins. 2001. The Southern African Institute of Steel Construction (Johannesburg)
Online: http://www.scribd.com/doc/17372174/Economics-of-Structural-Steel-Work-Purlins
Last Accessed: 2nd November 2010

[6] Gorgolewski M. 2008. Designing with Reused Building Components: Some Challenges. Building Research and Information, 36:2, 175-188

(9) **Steel Line pipe** (Production ≈ 18Mte/yr, 2% Total)

This product description focuses on line pipe used in the energy sector. However, line pipe does have other infrastructure applications, many of which share similar design principles.

Design Considerations

Constraints: Strength typically governs over stiffness, required for the high stresses experienced during installation of both onshore and offshore linepipe[1]. Other requirements are for corrosion and fatigue resistance.

In-service Design Requirements[2]: The in-service pipeline requirements and capabilities are a function of the pressure (P), diameter (D), material yield stress (σ_y), and pipe wall thickness (t). Force equilibrium implies the following relationship:

$PD \propto \sigma_y t$

PD presents a measure of the fluid flow rate. An increased flow rate therefore requires an increase in pressure and/or pipe diameter, demanding an increase in material yield stress and/or wall thickness.

Location[2]: During installation of deep sea line pipe, the weight of the hanging 'string' is critical, promoting the use of thinner higher strength steels. In very cold environments, however, very high strength steels tend to embrittlement, therefore the trend is for thicker walls.

Dimension The diameter of the pipe is matched to standard sizes, the largest (longitudinal) welded pipes limited by the width of the largest (4.2m) plate mills[2]. The typical wall thickness of large diameter pipe is 15-35mm[2] (the thickness usually increased by 3-6mm for increased corrosion resistance)[3].

Construction Welded pipe is typically longitudinally welded. However, spiral welds allow larger diameters, as they are not restricted by the width of the plate mill.

Material[2] Steel is microalloyed, typically with niobium, though vanadium and titanium are also used. Nb: The role of solid solution hardening is limited by welding requirements.

Mass[3] A change in the installation method may allow significant mass savings. For a reference line pipe specification (24" outside diameter, 31.8mm wall thickness, σ_y = 550MPa, at a water depth of 2150m), initial studies have indicated potential mass savings of 9-28%, depending on corrosion and fatigue considerations.

Coatings[4] Polypropylene copolymers have recently been developed for line pipe coatings. External three layer polypropylene coating technology combines the good adhesion of epoxy resin with the mechanical properties of polypropylene.

Process supply chain of predominant material (for energy sector)[2]

Line pipe is constructed from plate, demanding a smooth/flat surface for welding. These plates may be produced in General Plate Mills (GPM), though Energy Sector-Specialized Plate Mills (ESPMs) also exist.

For the energy sector, plates undergo thermo-mechanically controlled rolling (TMCR), consisting of both primary and secondary rolling to obtain the desired metallurgy. Thick slabs are required to achieve a minimum strain level of 35% in primary rolling, maximizing austenite grain refinement. The process exploits recrystallization mechanisms and accelerated cooling to get fine grains, high strength and toughness.

Failure Modes[5] Corrosion is a primary cause of failure. The fluid in the pipeline is corrosive and may contain sand particles. The internal coating will be worn by abrasive corrosion. When the coating is penetrated, the steel pipe is exposed to the fluid and ultimately leads to leaking and shut down of the pipeline.

Economics[4] Orders for line pipe are usually very large, often in the hundreds of thousands of tonnes. In the case of the energy sector, there are potentially huge financial and social costs in the event of failure.

Historical development of metal and energy use In the past, furnace welding drew the pipe through a tapered section to form the seam, resulting in a seam strength much lower than that of the surrounding steel[6]. Advancements have included the tapering of the edges to increase welding area, and electric welding which heats only the required areas[6]. The strength of the seam is now consistent with the strength of the steel[6].

Bituminous materials were widely used as external pipeline coatings, but they soften at high temperatures, become brittle at low temperatures, and are easily damaged during handling and transport.

Future Requirements There are increasing challenges in extraction technology. Offshore, pipelines are likely to go to ever-greater depths, and onshore more extreme environments will be encountered.

Current Developments[2] The IMMPETUS research institute at the University of Sheffield is investigating near net-shape plate making, hot charging of plate slabs and the use of remelted scrap in high-integrity pipe stock. Other foreseeable developments include clad plate-rolling technology.

Current Reuse Negligible. Retrieval of the pipe is often difficult, and there are concerns about the integrity of reclaimed line pipe, such as the damage caused by corrosion and fatigue.

Current Life Expectancy from Production to Disposal[7] The design life, often limited by corrosion, is typically 20 years. However, approximately 40% of the world's line pipe network has reached its design life. Efforts are being continually applied to further extend the residual life.

References

[1] Liu M and Wang YW. 2008. Stress analysis of pipe lowering-in Process during construction. Proceedings of IPC2008, 6th International Pipeline Conference, Calagary, Alberta, Canada, September 29-October 3, 2008

[2] Bhooplapur P, Champion N, Lee J and Kriechmair J. 2010. Plate Mill Technology for Energy Sector Applications. South East Asia Iron and Steel Institute (SEAISI)

[3] Design Optimisation Case Study: Deep Sea Linepipe. Mark Carruth, 2010

[4] G.P. Guidetti, G.L. Rigosi, R. Marzola. The use of polypropylene in pipeline coatings. Progress in OrganicCoatings27 (1996)79-85

[5] Castanier B and Rausand M. 2006. Maintenance Optimization for subsea oil pipelines. International Journal of Pressure vessels and piping. Vol/ 83 pgs 236-243

[6] Pipeline Technology. Canadian Pipeline Energy Association
Available Online:
http://www.cepa.com/pipeline101.aspx?page_guid=A00C8B11-C336-4114-AE37-D5D3EC61F3E9
Last Accessed: 14th December 2010

[7] Cesar R.F. Azevedo *. Failure analysis of a crude oil pipeline. Engineering Failure Analysis 14 (2007) 978–994

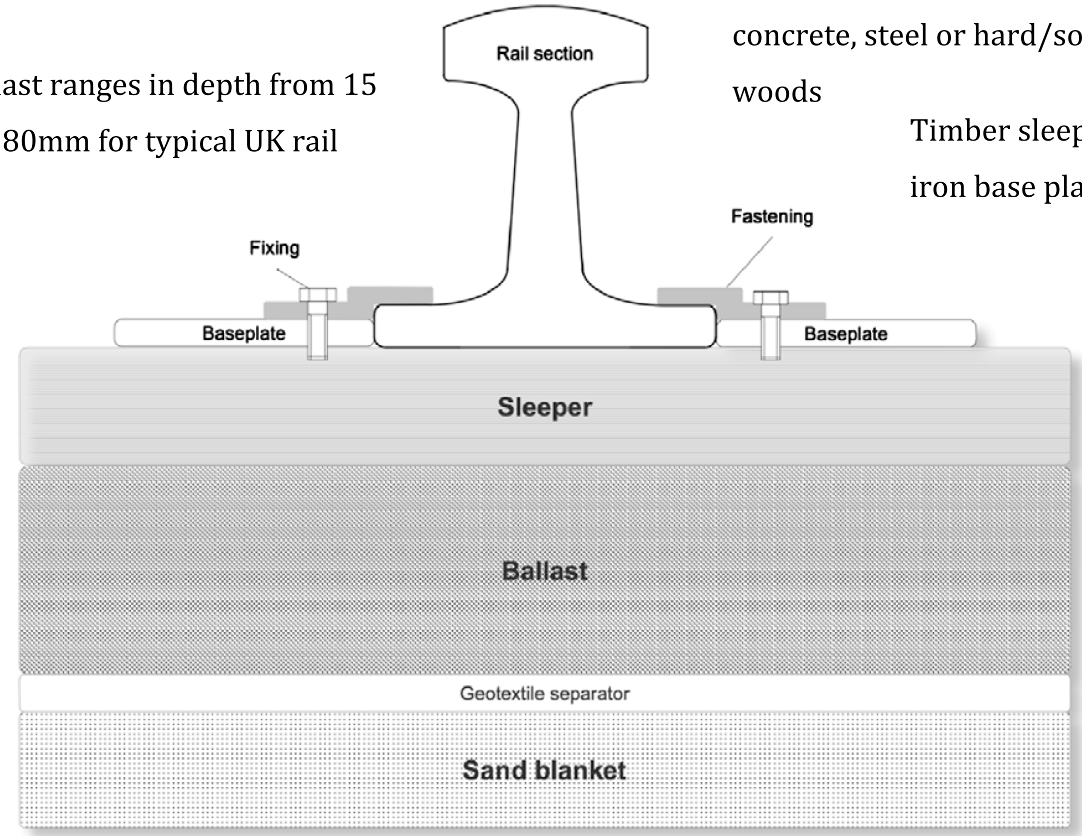
(10) Steel Rail Track (Mass ≈ 60kg/m; Production ≈ 9.75Mte/yr, 1% Total)

This product description concentrates on the most carbon intensive element of the rail systems, the metallic rail section

Sleepers are made from concrete, steel or hard/soft woods

Ballast ranges in depth from 15 to 280mm for typical UK rail

Timber sleepers require iron base plates



Schematic of typical rail track cross-section[1]

<u>Sleepers</u>

Concrete sleepers offer lower overall carbon emissions than timber or steel equivalents[1]. Timber sleepers require the use of carbon intensive iron base plates, greatly increasing the embodied emissions of this system.

Rail Section

The rail acts as beam supported by adjacent sleepers (typically spaced at 0.8m intervals).

Design Constraints: Strength (limiting) to withstand loading; wear resistance; crack resistance; fatigue resistance and corrosion resistance. In the UK loading is measured in Equivalent Million Gross Tonnes Per Annun (EMGTPA)[1]. Low loading track is classed as less than 10EMGTPA, and high loading track as over 60EMGTPA.

Material: Plain carbon-manganese pearlitic steel[2]. These steels have large elastic modulo, and high strength, ductility and wear resistance.

Maintenance: Rail grinding (in the UK performed approximately every 45EMGTs), tamping and stone blowing (aiding maintenance of vertical geometry of ballasted track and increasing the service life of the ballast)[1].

Reasons for Failure: Wear of railhead, foot corrosion, and crack propagation leading to RCF (rolling cycle fatigue)[1,2].

Process supply chain of predominant material (Steel Rail Section)

Pearlitic steel is hot rolled to form the flat bottom rail section. The rail steel can be produced using both primary and secondary production. Due to the critical fatigue loading endured, the melt is typically not deoxidized using aluminum (the resulting aluminates can create crack propagation sites)[3].

Hardness is desired to increase wear resistance. The hardness of pearlitic steels can be improved by controlling the cooling rate, producing a finer microstructure[2]. Often, premium rails produced using this method are used for high curvature applications, whereas standard naturally cooled rails will be used on straight sections of track[2]. The limited hardness of pearlitic steel has driven research on the use of harder bainitic steels. However, the in-use work hardening of the pearlitic steels results in greater wear resistance than the initially harder bainitic steels[2].

Economics Cost of rail in full track renewal accounts for less than 7%[4]

Historical development of metal use

Iron rails were introduced in the mid 1700s. In the 1830s, double-headed rails were invented, the advantage being that the rail could be turned over when the top surface had worn. However, anchorage of the rail caused damage to the bottom surface and the bullhead rail, which had a more substantial base, became more popular. By the late 1800s the flat bottom rail had developed into a form very similar to as used today.

Future Rail Track Designs

Future track designs include the embedded rail system, developed by Balfour Beatty. Literature also includes multi-headed rails (such as the double-headed and quadruple-headed rail)[1]. The embedded rail track reduces maintenance and accessory components, while the multi-headed systems offer life extension through rotation of the rail to present a new rail-wheel interface. A double-headed embedded rail could offer carbon savings of up to 40%[1].

A novel use of functional segregation is the capped railway system currently under development in Sweden[5]. Identification of the prominent failure mechanism of the rails has inspired replacement of the contact surface with a wear-resistant boron steel push-fit cap. Only 15% of the rail need be replaced when changing the rail, offering a total carbon saving of 92% (the rail also needing to be replaced less often due to the wear-resistant cap).

Current Reuse: The internal integrity of worn rails is established and any defects removed. Lengths of rail are welded together into long strings, and resupplied to the network for use in secondary, low loading, routes. Such cascading of rails was practiced in the UK until relatively recently, and is still practiced in Germany[4].

Current Life Expectancy: 13-38years[1]. Life cycle analyses indicate an 11% reduction in CO_2 impact for a 50% increase in rail section service life[1]. Provided railhead wear is not too close to the limit, rails are transposed with an adjacent rail, allowing the opposite rail head surface to be worn[4]. Large potential mass savings (25% estimate) are possible in European and USA trains, which would increase the service life of the rail track[6]. Nb: On some low loading track in the UK, rails from the 19th century are still in use.

Current Material Yield: >90%

References

[1] Milford R and Allwood J. 2009. Assessing the CO2 impact of current and future rail track in the UK. Transportation Research Part D 15, pgs 61-72

[2] Lee K and Polycarpou A. 2005. Wear of conventional pearlitic and improved bainitic rail steels. Wear, Vol. 259, pgs. 391-399

[3] Vinogradov S, Fetisov A and Zhuchkov V. Improving the Quality and Castability of Steel by improving the technology used for deoxidation during its treatment outside the furnace. Metallurgist. Vol 47. Nos 9-10, 2003

[4] Email: jay.jaiswal (Corus) 13th July 2010. "RE: WellMet2050: Cascading Reuse of mainline tracks on branch lines"

[5] Rerail. 2010. Change Track Towards a Less Resource-Demanding Future. *Rerail Track System*

[6] Rochard B and Schmid F. 2004. Benefits of low-mass trains for high speed rail operations. Proceedings of Institute of Civil Engineers: Transport. Vol 157, pgs 51-64

(11) **Aluminium Window Frames** (Mass ≈ 20kgs; Production ≈ 3.6Mte/yr, 8% Total)

Aluminium is strong, durable, and requires little maintenance. Aluminium window frames also allow architectural integrity to be maintained, their appearance often suiting both modern and listed buildings. A disadvantage of using aluminium in buildings is its high thermal conductivity. As such, thermal breaks (plastic pieces attached with resin) are required.

The window frame may be considered as interior and exterior frames (connected extrusions), separated by thermal breaks.

Interior and Exterior Frames

Design Constraints: Strength (security is typically governing), durability (a high life expectancy is necessary for economic pay-back[1]), ease of maintenance, energy efficiency, sound resistance, aesthetic appeal and ease of use (the window may be opened), corrosion and condensation resistance (avoid trapping moisture against the edge seal[1]).

Material: AA6060 or AA6063[2,*].
Mass: Light weighting of the frames would reduce the overall heat loss. However, security and sound considerations currently demand large strong frames.
Coatings[3]: The extrusions are either anodized, sealed with baked-on fluoropolymer paint, or powder coated[*]. Spray polyurethane foam is used in the cavities to improve thermal performance.

Process: Extrusions are used as the process allows the formation of any constant cross section. This allows the incorporation of draft excluders, thermal breaks, glazing beads, and grooves for connection. However, this also prevents any standardization in cross-section design[*]. The windows are fabricated remote to the building and then installed into the window opening using sealant and fasteners to make weather tight.

Construction: The window frames have a 'drained and ventilated' construction[1]. Any moisture should drain away under the action of gravity, avoiding condensation between the panes (see 'Predominant Failure Mode')[1].

Thermal Break

Due to the high thermal conductivity of aluminium, the interior and exterior frames must not form a bridge to allow heat loss. Therefore thermal breaks (made from plastic) are constructed between the two frames.

Predominant Failure Mode The predominant failure mode is condensation between the panes, sometimes the result of poor installation of the frames[1].

Process supply chain of predominant material (AA6060 or AA6063)

The aluminium is produced from primary and secondary production. The remelt is sweetened by virgin aluminium (up to 30% of the melt). The limitations on the quantity and type of scrap recycled are the controls of iron and manganese levels, thought to effect extrudability and corrosion resistance respectively[*]. Billets are produced, and the side of the frames directly extruded. The extrusions are typically anodized to improve their corrosion resistance. The trade of the extrusions is geographically widespread (as they can be transported easily)[4]. The window frames are then fabricated local to the final use location[4].

Economics[4] The aluminium material accounts for approximately 35% of the cost of manufacture and installation of the frames. Aluminium window frames are typically popular in the industrial and commercial buildings markets.

Historical development of metal and energy use

Aluminium window frames became popular with the advent of double glazing the 1960s. However, since the introduction of PVC frames, the market share of aluminium frames has decreased to less than 20%[5]. Other competitive window frame materials are hard and softwoods. Aluminium and timber composite windows are becoming more popular, with the use of durable aluminium on the exterior, and aesthetic timber on the interior.

Current Reuse: Negligible. Reuse of the frames is expensive; a deconstruction project recorded aluminium window frame removal (for reuse) requiring 0.54 man-hours each[6]. It is also difficult to deconstruct the frames without affecting the weather proofing in subsequent application[*]. Corrosion is not a problem, but the surface appearance of anodized or painted frames may change[*]. The lack of standardization also discourages reuse[*].

Current Life Expectancy from Production to Disposal: 20-30years[7]

Current Material Yield[8]: 75-80%

References

[1] Garvin S and Wilson J. 1998. Environmental Conditions in window frames with double-glazing units. Construction and buildings Materials. Vol. 12, pgs 289-302

[2] Alu-Select – Applications (AA6063)
Online:
http://aluminium.matter.org.uk/aluselect/01_applications.asp?AlloyID=24
Last Accessed: 23rd November 2010

[3] Whole Building Design: Building Envelope Design – Windows
Online: Http://www.wbdg.org/design/env_fenestration_win.php
Last Accessed: 23rd November 2010

[4] Holmes m. 1990. Material Substitution in the UK window industry, 1983-1987, Butterworth-Heinemann Ltd.

[5] Aluminum Extrusion
Online: http://aluminum-extrusion-blog.blogspot.com
Last Accessed: 23rd November 2010

[6] Nahb Research Centre. Deconstruction – Building Disassembly and Material Salvage: The Riverdale Case Study. Prepared for the US Environmental Agency, 1997

[7] Old House Web: Life Expectancy

Online: http://www.oldhouseweb.com/how-to-advice/life-expectancy.shtml

Last Accessed: 23rd November 2010

[8] WellMet2050 site visit to aluminium extrusion factory

[*] Innoval technology

(12) Aluminium Curtain Walling (Production ≈ 2.1Mte/yr, 5% Total)

A curtain wall is a building facade that protrudes from the buildings structural members, allowing light to penetrate deep into the interior of the building. The curtain wall is non-structural[1], and supports neither the roof nor floor loads of the building. The wind loads and dead load (weight) of the curtain wall is transferred to the building structure, typically at the floor line[2]. Curtain walls protect the building from the weather, and can be lightweight[1]. An aluminium frame is typically used to support the glazing, as aluminium has high specific strength, high corrosion resistance and aesthetic qualities.

A drawback of using aluminium is its high thermal conductivity, potentially causing significant heat loss from the building and causing condensation on the interior, accelerating corrosion. To decrease thermal conductivity, plastic thermal breaks (traditionally PVC[2]) separate the interior and exterior aluminium components.

The aluminium material forms a grid of mullions (vertical members) and transoms (horizontal members) supporting the glazing. The vertical spans typically correspond to the floor height[1]. The construction consists of the glass glazing, plastic thermal break, aluminium mullions, transoms, and aluminium pressure plates.

The curtain wall is supported either by hanging from the top or propping from the base[1].

Mullions

Design Criteria[1]: Stiffness (often governing) to prevent unacceptable glass deformations; weather resistance; strength against wind loads, dead loads (glazing weight) and maintenance loads.

Material[1]: Typically AA6063 T6 or AA6060 (conforming to BS1474 in the UK)

Coatings[1]: The extrusions are either anodized or painted using a polyester powder, providing additional corrosion resistance.

Process[1]: The mullions are produced through an extrusion process at 400-500C.

Extrusion allows a wide range of mullion depths and interior reinforcement to be created, providing sufficient strength and stiffness.

Transoms

The transoms design criteria are similar to those for the mullions. However, less material is required as they are individually supporting less dead load from the glazing. The material, coating and construction process is the same as for the mullions.

Aluminium Pressure Plate[1]

The pressure plate holds the glazing in place and allows drainage of moisture. Its material, coating and construction process is the same as for the mullions.

Process supply chain of predominant material (AA6060 or AA6063)

The aluminium is produced from primary and secondary production. The remelt is sweetened by virgin aluminum (up to 30% of the melt). The limitations on the quantity and type of scrap recycled are the controls of iron and manganese levels, thought to effect extrudability and corrosion resistance respectively[*]. Billets are produced, and the side of the frames directly extruded.

Economics Curtain wall facades are found mainly in commercial and institutional buildings. An American study found the cost of aluminium curtain walling (including the glass) to be approximately $38/sq foot[3]. This figure includes material and labour costs. The material cost is typically 30-35% of the cost of the curtain wall[4].

Historical development of metal and energy use Aluminum frame curtain walls have existed since the 1930s, and have been increasingly popular since WWII[2].

Current Reuse: Negligible. It is also difficult to deconstruct the sections without affecting the weather proofing in subsequent application[*]. Corrosion is not a problem, but the surface appearance of anodized or painted frames may change[*].

The lack of standardization also discourages reuse*.

Current Life Expectancy: 40 years[5]

Current Mass / Material Yield[6]: 75-80%

References

[1] Glazing – Facades: Curtain Walling. Saint-Gobain Glass.
Available Online: http://uk.saint-gobain glass.com/upload/files/curtain_walling.pdf
Last Accessed: 24th November 2010

[2] Vigener P and Brown M. 2010. Building Envelope Design Guide – Curtain Walls. Whole Building Design, a program of the National Institution of Building Sciences
Available Online: http://www.wbdg.org/design/env_fenestration_cw.php
Last Accessed: 24th November 2010

[3] 2008-2009 Cost Comparisons for Commercial Wall Systems. 2009. Capital Building Company.
Available Online:
http://www.gobricksoutheast.com/CostComparisons/WallCst3.pdf
Last Accessed: 24th November 2010

[4] Specialist Costs – Curtain Walling. 2005.
Available Online: http://www.building.co.uk/data/specialist-costs-curtain-walling/3054089.article
Last Accessed: 24th November 2010

[5] Typical Life Expectancy of Building Components. 2010. Cost Modelling Limited.
Available Online:
http://www.costmodelling.com/downloads/BuildingComponentLifeExpectancy.pdf
Last Accessed: 24th November 2010

[6] WellMet2050 site visit to aluminium extrusion company

[*] Innoval technology

(13) Aluminium Roofing and Cladding (Production ≈ 2.4Mte/yr, 5% Total)

Aluminium roofing and cladding construction ranges from single skins for agricultural sheds, to more sophisticated systems for commercial and industrial buildings[1].

Product Design Constraints[1]: Strength to withstand both positive (live and dead loads) and negative loading (suction); stiffness not to cause unsightly defections (and reservoirs of water under roof loading); thermal insulation to prevent excessive heat loss; durability and fire resistance.

Construction[2]: Cladding systems are typically assembled on-site, consisting of profiled aluminium liners and sandwiched insulation (typically mineral wool). Sinusoidal, trapezoidal and half round profiles are all used to increase the stiffness. Composite claddings are pre-assembled panels consisting of flat sheets and sandwiched core (typically polyisocyanurate - PIR). These panels are increasingly used, but are not as popular as built-up systems at present.

Profiled Aluminium Liners

Dimensions[1]: The width covered by profiled aluminium cladding sheets range up to 500mm, demanding a coil width of up to 700mm. The typical thickness of roof and wall weather sheets is 1.2mm. The thickness of the sheet is constant.

Design Constraints[1]: Structural integrity (dead loads and live loads, may be negative due to wind induced suction); safety in use; thermal performance; fire ratings and corrosion resistance.

Material[3]: 3xxx and 5xxx series alloys: AA3003/3103 and AA5005/5005A

Coatings[1]: The natural aluminium oxide is an acceptable durable finish, but not aesthetic. Therefore, coatings such as PVDF (a smooth 25μm thick flurocarbon) are used.

Fasteners[4]

The cladding is generally fastened to purlins or horizontal rails. The fasteners must resist shearing and popping loads, and have high corrosion resistance. To prevent preferential corrosion either aluminium rivets or stainless steel self-drilling and tapping screws are used.

Process supply chain of predominant material (1xxx and 3xxx profiled sheet)

The profiled sheet is formed through multiple rollers from aluminium strip. Each set of rollers (or stands) only perform an incremental part of the bend. The production rate is a function of the thickness of the strip and the amount of bending required.

Historical development of metal and energy use Metal wall cladding became popular in the 1970s. Heat loss regulations are becoming increasingly strict, with a maximum average 'U' value of $0.35W/m^2\,K$ now permitted for cladding in England and Wales[5].

Current Reuse: Negligible. Even in cases of portal frame relocation, cladding is often not reused as changing thermal and fire standards mean cladding older than ten years is unlikely to meet modern codes[6].

Current Life Expectancy from Production to Disposal: 40 years[7]

References

[1] Appropriate selection of metal thickness for use in walling and roofing applications. 2010. MCRMA Technical Paper No. 20. The Metal Cladding & Roofing Manufacturers Association Limited
Available Online: http://www.mcrma.co.uk/technical/t10.aspx
Last Accessed: 2nd December 2010

[2] Metal wall systems design guide. 2004. MCRMA Technical Paper No. 5. The Metal Cladding & Roofing Manufacturers Association Limited
Available Online: http://www.mcrma.co.uk/technical/t10.aspx
Last Accessed: 2nd December 2010

[3] AluSelect – Applications
Available Online:
http://aluminium.matter.org.uk/aluselect/01_applications.asp

Last Accessed: 2nd December 2010

[4] Fasteners for metal roof and wall cladding: design, detailing and installation guide. 2000. MCRMA Technical Paper No. 12. The metal cladding & roofing manufacturers association
Available Online: http://www.mcrma.co.uk/technical/t10.aspx
Last Accessed: 2nd December 2010

[5] Design guide for metal roofing and cladding to comply with energy requirements of UK building regulations (2006). 2007. MCRMA/EPIC Technical Paper No. 17. Engineered Panels in Construction (EPIC)/The metal cladding & roofing manufacturers association limited
Available Online: http://www.mcrma.co.uk/technical/t10.aspx
Last Accessed: 2nd December 2010

[6] WellMet2050 site visit to Portal Power

[7] Cost Modelling: Building component Life Expectancy
Available Online:
http://www.costmodelling.com/downloads/BuildingComponentLifeExpectancy.pdf
Last Accessed: 2nd December 2010

2.3 Industrial Equipment

(14) Steel Mechanical Machinery (Production≈135Mte/yr, 13% Total)

Table 1 presents a break down of intermediate steel products in mechanical machinery[1].

Table 1: Breakdown of Mechanical Machinery Components

Intermediate Product	%
Rail	1
Wire rod	1
Hot rolled bar	25
Plate	20
Hot rolled coil (HRC)	21
Cold rolled coil (CRC)	14
Welded tube	13
Seamless tube	2
Cast products	4

Overall Material Yield[1]: 80%

A wide range of products are included in this sector, it is therefore difficult to give full coverage. Instead, an example of large mechanical machinery, the rolling mill, is described in detail.

Rolling Mills

Rolling mills are large pieces of mechanical machinery used to transform the cross-section of steel ingots, plates and bars. Plate mills, for example, can be up to 1.5km long. Typical material composition figures for a plate mill are 5,000te of steel for mill equipment (27,000te over entire life), and 120,000te of concrete.

End of life and life extension

As is typical of mechanical machinery, failure is often physical. The product is used until it is beyond repair. Alternatively, the product may cease to be a useful business asset in the current location, and therefore it is shipped elsewhere (typically to a developing economy). Modular design and product upgrade are common elements of service in the industrial equipment sector, and modern designs consider future needs and upgrades, making ultimate failure likely to be physical[2]. This physical life is determined by the physical life of the housing, which can last for 100 years. Process obsolescence due to upstream processing is also possible – for example, continuous casting has reduced the amount of ingot casting that requires subsequent rolling.

Upgrades for rolling Mills

Steels are going towards higher strength, presenting challenges for the old plate mill. Upgrading the power, torque and load limits of the mill stand and ancillary process areas are now necessary. Common examples of the latter include post-rolling cooling, levelling and shear-line operations.

Current reuse

Currently negligible, however there is significant opportunity to reuse the work rolls by replacing the outer surface with a sleeve that can be replaced. This idea has been successfully trialled and recorded in [3].

References

[1] Cullen, J.M. and Allwood, J.M. 2012. Mapping the global flow of steel from steelmaking to end-use goods. To be submitted to Environmental Science and Technology, 2012.

[2] Bhooplapur, P, Brammer, MP, and Steeper, MJ. 2008. Upgrading existing plate mill for higher strength product. Institute of Materials, Minerals, and Mining, Ironmaking and Steelmaking. Vol 37. No 7. pgs 491-495

[3] Hajduk D, Pachlopnik R, Bembenek Z and Molinek B. 2010. Sleeved rolls: old idea, new possibilities. Ironmaking and Steelmaking, Vol 37, no 4

(15) **Steel Electrical Equipment** (Production ≈ 31Mte/yr, 3% Total)

The three predominant end uses of steel in electrical equipment are steel pylons, steel reinforced cables (ACSR) and transformers and motors. Other significant applications include quadrature boosters, helical steel tape for small coaxial cables and steel electrical conduits.

The importance of a continuously robust transmission network demands electrical equipment is typically maintained, rather than replaced, causing minimal disruption to the network[*].

Steel Pylons

There are currently over 37000 steel lattice pylons as part of the UK transmission network[1].

Dimensions[2]: Steel electricity pylons are typically 15 to 55m in height, though structures of over 300m exist. Spans between adjacent towers can be over 500m.

Design constraints[2]: Strength to support loadings (predominantly weight of conductors, but also ice; wind and temperature environmental loads); geometry and stiffness to maintain minimum spacing between the conductors and ground (the conductors typically carrying voltages of 275kV and 400kV in the UK), and corrosion resistance

Material and construction[2]: Cold formed, angled (typically L-section), galvanized steel. These sections are bolted together to form a lattice tower. The lattice towers generally consist of 4 tapered legs, such that they are widely spaced at the bottom, and closer at the top. The legs are connected by horizontal members and bracing. This is considered the most cost effective design. Foundations are typically formed from large diameter steel piles. Construction uses a climbing derrick or gin pole. Helicopters have been used in remote areas.

Mass: The UK National Grid L2 pylon for 400kV transmission (27,000 such pylons in the UK) has 12te of steel in the lattice and 0.4te in the foundations reinforcement[1]. Bad detailing can easily add 10% to the weight of the structure[3].

Bespoke tower design is uneconomic, however current UK regulations do allow the designer to reflect different environmental loadings by changing the length of spans in different parts of the country[2]. Globally, heavier sections than required are often used due to the limited production of the optimum cold-formed section in the region[3].

Coatings[2]: The steel is galvanized to prevent corrosion

Predominant mode of failure[*]: The pylons are maintained until replacement becomes economic. Corrosion undermines the integrity of the tower.

Historical development of metal use[2]: The UK National Grid L6 suspension tower (developed in 1960s) weighed 23.2tonnes. The L12 tower (developed circa 1980) weighed 15.8tonnes for the same capacity. Collaboration between electrical and structural engineers led to this weight saving of a third. Life extension of the pylons constructed in the 1950s for 275kV was intended when the pylons were designed so they could be operated at 400kV at some stage in the future.

Alternative Designs: Alternative designs, such as folded plate poles or gantries, are typically considered twice as expensive as the current steel lattice design[2]. A steel tower with tubular members would decrease aerodynamic loading, but the increased complication in connection design, and increased material cost, prevent these towers being popular. National Grid (UK) is considering the use of composite members for the cross-arms[*].

Current Reuse[*]: Due to the extensive maintenance on the towers, direct reuse of the towers is not possible due the lack of structural integrity at end of life.

Current Life Expectancy: 40 years

Economics: Putting cables underground prevents the aesthetic damage to the landscape of overhead lines. However, the laying of cables underground can be 4 to 10 times more expensive.

Aluminum Conductor – Steel Reinforced (ACSR): used as bare overhead power lines in long span, medium and high voltage lines

There are currently over 22,000 km of overhead cables in the UK[1].

Design constraints: High strength and low weight for the long span; high conductivity; flexibility to withstand deflections due to self-weight, and corrosion resistance

Material and construction[4]: Concentrically stranded aluminium wire (typically AA1350-H19) of one or more layers around a high strength coated steel, of single or stranded wire. The central steel core supports the weight of the transmission line while the aluminium is used for its conductive properties. ACSR cables are available in specific sizes and varying amounts of central steel and outer aluminium, achieving desired capacity and strength. The number of aluminium strands typically range from 3 to 100, and the number of steel wires from 1 to 20.

Coatings[4]*:* The core steel wires are usually galvanized, aluminium coated, or aluminium clad. Additional corrosion protection is available through the application of grease. The coating of the steel core typically accounts for 11-18% of the core weight.

Reasons for End of Life[*]*:* Greater power demands cause higher temperatures, in turn causing structural sag and efficiency problems, prompting replacement.

*Economics***:** Conductors represent 20 to 40% of the installed cost of a line[3]. The cost of overhead transmission lines is £1.4-1.8million/km for a 400kV double circuit line (this includes the installation cost)[5].

Current Reuse: Negligible. The cables have typically lost their mechanical strength on replacement and therefore are not reused (they would sag too much)[*].

Current Life Expectancy: 30 years

Transformers (and Motors)

There are currently over 1100 transformers as part of the UK transmission network[1]. The production of electrical steel was 10.5Mte in 2008 (nearly 1% of all steel produced)[6].

A transformer allows the voltage to be stepped up or down by altering the number of coils on the primary and secondary windings. Transformers are necessary for high voltage transmission of electricity across large distances (necessary for economic power transmission). They consist of a ferromagnetic core, winding coils, tank, insulation, bushings and tap changer[7]. For more details on the construction see reference [7].

Material: Electrical steel is an iron alloy with a silicon content up to 6.5% (increasing electrical resistivity and decreasing the eddy current losses). Manganese and aluminum can be added up to 0.5%.

Production: Winding a steel strip around a rectangular form and then bonding layers together – it is then cut in two to form two C sections. These are bound together with a steel strap, forming a laminated core. Laminations may be cut to the finished shape by a punch and die, or in smaller quantities may be cut by a laser.

Process supply chain of Electrical Steel[8]:

These electrical steels are manufactured in the form of cold rolled strips (thickness less than 2mm). Once stacked (laminated) these form the cores of transformers or the stator and rotor parts of electric motors.

Current energy intensive aspects of the process include the very high slab-reheating temperature and very long manufacturing process. The high slab reheating temperature (1400C) is currently necessary to secure fine precipitates as inhibitors. Thin strip casting of electrical steels is a possibility, but the precise control of operating parameters has so far prevented production.

Economics: The cost of a transformer is £0.8-2.2million for a 90-240MVA rating[5].

Current Reuse: When a transformer fails, the tank and 60% of the transformer may be reused, however this incurs very high disassembly and transportation costs[*].

Current Life Expectancy: 40 years, though a transformer working at full capacity will last only 20 years[*].

References

[1] G. P. Harrison, E. J. McLean, S. Karamanlis and L. F. Ochoa, 'Life cycle assessment of the transmission system in Great Britain', Energy Policy, 38 (7), July 2010, 3622-3631.

[2] Lomas C. 1993. Transmission Tower Development in the UK. National Grid Company. Engineering Structures. Vol 15. No.4

[3] F. Adam, J. Bradbury, W.R. Charman, G. Orawski, M.J. Vanner. 1984. Overhead lines—some aspects of design and construction. IEE Proceedings, Vol. 131, Pt. C, No. 5

[4] IEEE TP&C Winter Meeting, 2006. Bare overhead transmission conductors: selection and application.
Online: http://ieee-tpc.org/ieee_tutorials/Thrash_OvhdCondApplications.pdf
Last Accessed: 25th October 2010

[5] ODIS document on National Grids website
Online: http://www.nationalgrid.com/NR/rdonlyres/CC4994A2-83C5-4990-9E0C-F8CE04DCA588/43378/Appendices2010_Final.pdf
Last Accessed: 23rd December 2010

[6] World Steel Association. 2008b. Steel Statistical Yearbook 2008. World Steel Association.

[7] Franzén A and Karlsson S. 2007. Failure Modes and Effects Analysis of

Transformers. Royal Institute of Technology, Sweden School of Electrical Engineering, Stockholm

[8] Zhaosuo Xia, Yonglin Kang, Quanli Wang, 2008. Developments in the production of grain-orientated electrical steel. Journal of magnetism and magnetic material. Vol. 320, pgs 3229-3233

[*] National Grid (UK)

(16) Aluminium Electric Cables (Production ≈ 4Mte/yr, 9% Total)

Dimensions Individual aluminium strand diameters typically range from ∅5-20mm. Individual steel core wire diameters typically range from ∅1-5mm.
The two predominant types of electrical aluminium cable are shown above. Aluminum conductors are used widely in overhead electrical transmission and distribution. Transmission lines conduct high voltage power from a generating source to substations, and distribution lines from these substations to individual homes and businesses. There are currently over 22,000 km of overhead cables in the UK[1]. Aluminum was briefly used as a conductor in household wiring, but is no longer used due to household fires linked with improper installations.

Aluminum Conductor – Steel Reinforced (ACSR): used as bare overhead power lines in long span, medium and high voltage lines[2]

Design constraints: High strength and low weight for the long span, high conductivity, flexibility to withstand deflections due to self-weight, and corrosion resistance

Material and construction[2]: Concentrically stranded aluminium wire (typically AA1350-H19) of one or more layers around a high strength coated steel, of single or stranded wire. The central steel core supports the weight of the transmission line while the aluminium is used for its conductive properties. ACSR cables are available in specific sizes and varying amounts of central steel and outer aluminium, achieving desired capacity and strength. The number of aluminium strands typically range from 3 to 100, and the number of steel wires from 1 to 20.

Coatings[2]: The core wires are usually galvanized, aluminium coated, or aluminium clad. Additional corrosion protection is available through the application of grease. The coating of the steel core typically accounts for 11-18% of the core weight.

All Aluminum Conductor (AAC): used as bare overhead power lines for short spans where maximum current transfer is required[2]

Design Constraints: Moderate strength and low weight for short spans, good conductivity, flexibility to withstand deflections due to self-weight, and corrosion resistance

Material and construction[2]: Concentrically stranded aluminium wire (typically AA1350-H19) of multiple layers. The alloy provides good conductivity, equivalent to 61.2% IACS (61.2% of the conductivity of annealed copper).

Other Aluminum Cables

Other transmission cable varieties include the use of AA6201-T81 aluminium alloy, used as the main conductor or support, depending on the design[2].

Trap wire construction (where the strands have trapezoidal cross-sections) developed in the early 1990s, allows a smaller cross-sectional area of cable for a given conductivity[2]. This decreases environmental loadings on the cable.

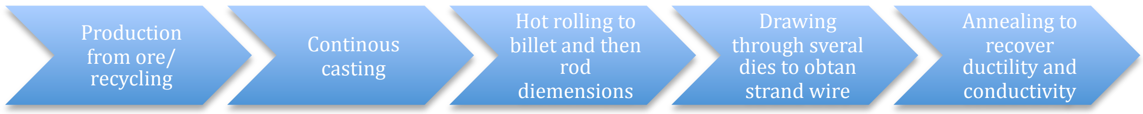
ACCC (aluminium conductor composite core) overhead lines were developed recently. The steel core is replaced with a pultruded carbon and glass composite. This allows a greater cross-section of aluminium for a given diameter (increasing conductivity); improves sag resistance caused by high loading induced high temperatures; allows greater spans between supporting pylons, and prevents bi-metallic corrosion.

Aluminum vs. Copper Conductors[4]

The use of aluminium, instead of copper, is predominantly because of lower overall cost (the rising cost of copper in the 1960s and 1970s prompted the switch from copper to aluminium). Additionally, aluminium cables weigh less than copper. This is despite the conductors needing to be larger due to the higher electrical resistivity of aluminium (the conductivity of annealed copper being 100% IACS).

Reasons for End of Life[*]: The importance of a continuously robust transmission network demands electrical equipment is typically maintained, rather than replaced, causing minimal disruption to the network. However, greater power demands cause higher temperatures, in turn causing structural sag and efficiency problems, prompting replacement.

Process supply chain of predominant material (Pure aluminium or 1xxx series alloy)



Economics: Conductors represent 20 to 40% of the installed cost of a line[3]. The cost of overhead transmission lines is £1.4-1.8million/km for a 400kV double circuit line (this includes the installation cost)[5].

Current Reuse*: Negligible. The cables have typically lost their mechanical strength on replacement and therefore are not reused (they would sag too much)*.

Current Life Expectancy 30 years

References

[1] G. P. Harrison, E. J. McLean, S. Karamanlis and L. F. Ochoa, 'Life cycle assessment of the transmission system in Great Britain', Energy Policy, 38 (7), July 2010, 3622- 3631.

[2] IEEE TP&C Winter Meeting, 2006. Bare overhead transmission conductors: selection and application.
Online: http://ieee-tpc.org/ieee_tutorials/Thrash_OvhdCondApplications.pdf
Last Accessed: 25th October 2010

[3] Adam F, Bradbury J, Charman W, Orawski G, and Vanner M. 1984. Overhead lines—some aspects of design and construction. IEE Proceedings, Vol. 131, Pt. C, No. 5

[4] International Aluminum Institute
Online: http://www.world-aluminium.org/?pg=About%20Aluminium/Applications%20and%20Products/Electricity
Last Accessed: 25th October 2010

[5] ODIS document on National Grids website Online: http://www.nationalgrid.com/NR/rdonlyres/CC4994A2-83C5-4990-9E0C- F8CE04DCA588/43378/Appendices2010_Final.pdfLast Accessed:

23rd December 2010

[*]   National Grid (UK)

(17) Aluminium Electrical (Other) (Production ≈ 2.3Mte/yr, 5% Total)

The majority of aluminium used in electrical applications is in cables. However, aluminium is also used in electrical conduits, bus bars and aluminium armor and sheathing.

Aluminium Electrical Conduits

Electrical conduits protect wiring from physical and corrosive damage. In applications where lightweight, non-magnetic or highly corrosion resistant conduits are required, they are made from aluminium.

Design Constraints: Strength and stiffness to protect electrical wiring, (high corrosion resistance, lightweight, non-magnetic)

Material[1]: examples found include AA6063 – T1 temper

Process[1]: Many aluminium conduits are extruded tubes

Considerations: Due to preferential corrosion, it is necessary to ensure all connections are of a material known to be compatible with aluminium

Aluminium Bus Bars

Aluminium bus bars conduct high voltage electricity within a switchboard, distribution board, or sub-station. Bus bars can carry very large currents, and distribute the current to multiple devices.

Design Constraints: High conductivity, corrosion resistance (particularly within sub-stations)

Material: The 1xxx series of aluminium alloys have a high electrical conductivity. Bus bars are often made from AA1350. Aluminium is often chosen above copper due to lower cost and weight

Geometry: Aluminium bus bars tend to be either flat strips or hollow tubes, allowing efficient dissipation of heat. Also, in high current applications smaller thicknesses are more efficient due to the skin effect[2]. Bus bar tubes can be as small as $10mm^2$ in cross sectional area, but in substations tubes of 50mm diameter (1960mm^2 cross sectional area) are common.

Aluminium Sheathing

Cables within buildings may contain many insulated conductors in an overall jacket, with protective aluminium armor. For smaller coaxial wires, aluminium sheathing is used to protect the wires.

Design Constraints: Strength and stiffness to protect electrical wiring, high corrosion resistance

Material[3]: AA5056 (commonly referred to as Alclad 5056).

Process: Jacketing is performed by passing the wire through an extruder; the aluminium sheathing is extruded around the wire.

References

[1] Republic Conduit - Aluminum Rigid Conduit
Online: http://www.republic-conduit.com/default/Download/Aluminum%20Rigid%20Electrical%20Steel%20Conduit.pdf
Last Accessed: 25th October

[2] Walter A. Elmore. 2004. *Protective Relaying Theory and Applications*. Marcel Dekker Inc.
Google Books. Online: http://books.google.co.uk/books?id=1Jqhpd-rhoUC&pg=PA411&lpg=PA411&dq=Walter+A.+Elmore.+Protective+Relaying+Theory+and+Applications.+Marcel+Dekker+Inc.&source=bl&ots=m9Tqnqvswj&sig=7X5HPFbMWVrlfc5eEoZbCsaBdSs&hl=en&ei=jwnLTMbkAZS7jAfs2KnPCg&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBkQ6AEwAA
Last Accessed: 25th October 2010

[3] HM Wire International
Online: http://www.hmwire.com/aluminum_alloys.html
Last Accessed: 25th October 2010

[*] National Grid (UK)

2.4 Metal Products

(18) Steel Packaging Products (Production ≈ 26Mte/yr, 3% Total)

Steel packaging applications range from drink and processed food to aerosols, confectionary and software. This product description focuses on the two predominant applications: processed food and aerosol cans. It is estimated 7Mte of steel is used in food cans and 3Mte in aerosol cans annually. The steel is usually tinplated; tin is non-toxic, good for seam welding and provides mild corrosion resistance to the steel, protecting the steel from being corroded by the atmosphere or food. Nb: Due to the high cost of tinplate, other corrosion resistant steel alloys and metallic coatings have been developed, such as electrolytic chromium/chromium oxide coated steel (ECCS), commonly known as tin-free steel[1].

Food Can (Mass ≈ 58 grams*; 6Mte/yr)

Dimensions and Construction

The can is typically a 3-piece construction, consisting of a welded can body, and two circular ends that are mechanically fastened with a double seam.

Can Body

Design Constraints: Hoop strength to withstand high positive (2-2.5bar) and negative (1-1.5bar) pressures at different stages of food thermal sterilization (retorting) process; axial strength during filling, handling and storage; provision of an inert surface against the food stuffs, and an impenetrable barrier against oxygen and bacteria.

*Dimension**: A rectangular strip of approximately 0.17mm thick tinplated steel is folded and seam welded to form the can body (typically 73mm diameter and 115mm height).

Typical Free Variables: To meet the strength requirements, the designer typically varies the thickness of the material, the hardness of the material and the amount of beading[2].

Material: The material is typically double-reduced tinplate, with a coating of between 1 and 12 grams of tin per square meter[1].

Beading[2,]:* The retorting process (post-filling and sealing) causes the can to experience negative pressures of 1-1.5 bar. Circumferential beads resist implosion of the can. These beads, however, decrease the axial strength of the can, effecting filling, handling and storage. There are typically 19 beads of varying depth (0.3-0.4mm) at a 3mm pitch over 54mm of the wall height. Variations in bead depth and pitch have been the subject of many studies.

Coatings: The body is often lined with a polymer based lacquer[2].

Process[1]: Steel strip is cut into large sheets. Lacquer is applied to the sides destined to become internal surfaces. The lacquered sheets are dried in an oven, and slit into smaller sheets. Each small sheet is rolled into a cylinder. High resistance (electric current) welding of the seam forms the body, and the inside surface of the weld is sprayed with lacquer. The can ends are flanged outwards, ready to accept the end pieces. After attachment of one end, the cans are given circumferential beads, increasing the strength against implosion. A final pressure tester is used to reject any cans with pinholes or fractures. The cans are then palletized and dispatched to the filling plant.

Material Yield[*]: 97% within the can making plant

<u>Can Lid and Base</u>

Design Constraints: Bending strength to withstand high positive (2-2.5bar) and negative (1-1.5bar) pressures at different stages of food thermal sterilization (retorting) process; to withstand high positive and negative pressures at the different stages of food thermal processing; provision of an inert surface against the foodstuffs, and an impenetrable barrier against oxygen and bacteria.

Dimension[*]: A circular lid of 0.21mm thick tinplated steel of 73mm diameter.

Material: The material is typically tinplate steel (often not double reduced)[2], with a coating of between 1 and 12 grams of tin per square meter[1].

Coatings: The end pieces are often lined with a polymer based coating

Process:* Circular blanks are cut from tinplate strip, press formed, curled and then lined with a seaming compound. The lid ends are double seamed around the end of the can body.

Material Yield:* 85% within the can making plant

Economics

The steel material accounts for 70-75% of the cost of can production*. Previous studies have predicted a 13% mass saving in the end pieces will give a 3-4% saving in the total cost of the end pieces[3].

Historical development of metal and energy use

The thickness of the can body and ends has decreased by around 40% and 18% respectively in the last 20 years[2]. This has been possible through the use of double-reduced steels and can body wall beading[2].

Current Reuse: Negligible. Some projects are investigating unwinding the double seam rim to allow refilling, resealing and resale[4].

Current Life Expectancy from Production to Disposal: Shelf life can be up to 3 years

Current Material Yield: 93% within the can making plant

Current Energy Requirement: 1.4kg of CO_2 is released in making 1kg of tinplate[5]. 53% of the energy is needed to produce the steel[6], and 28% needed for conversion of the slab into a tinplate sheet[6]. The remaining energy is associated with the other alloys required[6].

Aerosol Can (Mass ≈ 113gms; 3.1Mte/yr)[7]

Dimensions and Construction

Aerosol cans come in a range of sizes, typically with a diameter of 42-65mm, and a height of up to 300mm*. They are produced via 3-piece construction: the circular ends (one with a small hole for the valve) are mechanically joined to the welded body using double seams. The aerosol is then filled with liquid, and the valve crimped to the can. A propellant (in the form of liquefied or compressed gas) is forced under pressure through the valve and into the can. The pressurized can is immersed in warm water at 50°C to check for leaks. The valve actuator and dust cap are then added.

Aerosol Body

Design Constraints: Hoop strength to withstand internal pressure (15 bar in the EU)[*], and interior and exterior corrosion resistance.

Material and Geometry: The material is typically double reduced tin-plated steel[8]. The thickness of the steel ranges from 0.17mm to 0.23mm[1].

Process[8,9]: Steel strip is cut into small rectangular blanks that are rolled to form a cylinder. High resistance (electric current) welding of the seam forms the body.

Material Yield[*]: 97% within the aerosol making plant

Aerosol Lid and Base

Design Constraints: Hoop strength to withstand internal pressure (15 bar in the EU)[*], and interior and exterior corrosion resistance.

Material and Geometry: Tin-plated steel (not necessarily double reduced)[8]. T-3, T-4 or T-5 tempers[8]. The material is softer and more ductile than the can body. The metal is typically 0.3 - 0.35mm thick[*].

Process[*]: Circular blanks are cut from tinplate strip, press formed, curled and then lined with a seaming compound. The lid ends are double seamed around the end of the aerosol body.

Material Yield[*]: 85% within the aerosol making plant

Noted Failure Modes[8] Internal/external corrosion, overheating and mechanical abuse causing puncturing

Economics: The steel material accounts for 70-75% of the cost of aerosol production[*]. Aluminium is often used for more expensive, aesthetic, brands[8].

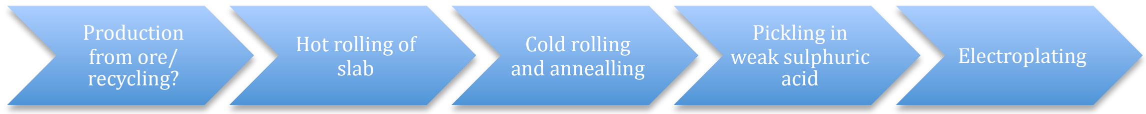
Current Reuse: Negligible. Reuse of the can may require redesign of the lid and valve to allow removal and refilling. Refilling the aerosol through the valve may be possible through temperature induced pressure changes and suction.

Current Life Expectancy*: < 2 years

Current Material Yield: 94% within the aerosol making plant

Current Energy Requirement: 1.4kg of CO_2 is released in making 1kg of tinplate[5]. 53% of the energy is needed to produce the steel[6], and 28% needed for conversion of the slab into a tinplate sheet[6]. The remaining energy is associated with the other alloys required[6].

Process supply chain of predominant steel packaging material (Tinplate)[6]



Tinplate is steel with a thin layer of tin on both sides. It is produced remote to the steel making facility. Slabs are hot rolled to a smaller gauge, before cold rolling to final steel thickness. Double reduced tinplate steel endures a further cold rolling step after annealing, work hardening the material to an increased yield strength. The steel coils are pickled in weak sulphuric acid to clean the surfaces, before being rinsed and stored in water ready to be tinned. Zinc chloride is used to dry the plate, before a coating of tin is applied via electrolysis. A coating of between 1 and 12 grams of tin per square meter of steel is applied.

Historically, the tin coating was applied by hot dipping steel strips (not coil) into a bath of molten tin, resulting in coatings of up to 15grams per square meter[1]. Electroplating allows much greater control and thinner layers of tin to be applied.

References

[1] Metal Packaging Manufacturers Association
Online: http://www.mpma.org.uk/pages/pv.asp?p=mpma1&fsize=0
Last Accessed: 8th November 2010

[2] Pocas MFF. 2003. Recent Developments in Can Design. Canning. Galley: Article No. 0161
Online:
http://www.esb.ucp.pt/twt/embalagem/MyFiles/biblioteca/publicacoes/0161a.pdf
Last Accessed: 8th November 2010

[3] WRAP Report. 2007. Reducing weight, reducing cost: light weighting can ends

[4] Reusa-can: Environmentally friendly refurbished cans
Online: http://www.reusacan.com/
Last Accessed: 20th July 2010

[5] LCI Data for Steel Products. 2010. Report produced for Rachel Milford (WellMet2050). Data provided by Peter Hodgson (Tata Steel Europe). World Steel Organization

[6] Boustead I and Hancock. 1981. Energy and Raw Materials Requirements for Tinplate Production in the UK. Resources and Conservation. Vol. 6. Pgs 29-45

[7] Aerosol Cans
Online: http://egov.oregon.gov/ODOT/HWY/OOM/EMSdoc/Q4A.pdf
Last Accessed: 9th November 2010

[8] Daehn R and Blum J. 2004. Failure Analysis of Three-Piece Steel Aerosol Cans. ASM International, Vol. 4(4), pgs 58-67

[9] How Aerosols are Filled
Online: http://www.yorks.karoo.net/aerosol/link3.htm
Last Accessed: 15th December 2010

[*] Crown Cork and Seal

(19) Aluminium Beverage Can (Mass≈14grams; Production≈3.2Mte/yr, 7% Total)

Dimensions[1] Typically (330-500) ml, ∅(52-65) mm; for soft drinks and beers; global

The can consists of a drawn can body and base attached to a can lid riveted to the tab. It is not unusual to find cans in which the opening on the lid fractures, and the bottom dome and lid bulge at nearly the same pressure (typically 100-115psi)[2]

Can body and base

Design constraints[1,2]*:* Strength to resist internal pressure (>90psi); Ductility and texture to allow drawing and wall ironing process; Axial strength to withstand the vertical loads imparted by filling, seaming and stacking; An inert internal surface for product contact (health and safety); External print capability (a near 100% surface for brand decoration and consumer information).

Material: Internally coated AA3004/AA3104/3204 H19 (containing both magnesium and manganese)

Mass: Accounts for approximately 80% of the total empty mass of the can

Coatings: The majority of internal coatings are epoxy-based lacquers[3] (approximately 120mg per can[1])

Process[2]*:* Circular blanks are punched from wide aluminium coil (generating a yield loss of approximately 20%). The base and body are formed from a single blank by DWI (drawing and wall ironing). The base is domed to resist internal pressure, and the top edge of the body trimmed to remove ears, then necked and flanged. The can then undergoes washing, lacquering and printing.

Can lid

Design Constraints[2]*:* Strength to withstand internal pressure (>90psi); Stiffness to prevent excessive deflections; Provision of an inert surface for product contact (health and safety)

Material: Coated AA5182-H48/H49 (containing more magnesium and less manganese than the can body material, increasing strength).

Mass: The (relatively thick) lid accounts for approximately 20% of the total mass of the empty can

Coatings: Similar to those for the "Can body and base"

Process[1]: Circular blanks are punched from wide, pre-lacquered aluminium coil. The drinking aperture is scored, a bubble is drawn from the lid to provide tab location, and then tab attachment is achieved by riveting. The lid is seamed to the body after filling to provide an hermetic seal; seaming consists of two roll forming stages that clinch a rubber compound (on the lid) between tight lid and body curls.

Tab[1] Separate Piece of Metal (AA5182, i.e. same as end).

Scored opening[1,2] Controls the load that is needed to open the drinking aperture by the consumer (but also prevents premature opening/leakage).

Process supply chain of predominant material (Can body/base AA3004/AA3104/AA3204 H19)[2]

Elements of the supply chain are geographically widespread, preventing the use of heat developed in one process in subsequent stages. Wide strip coil is hot and cold rolled from 30" thick ingots. Casting aluminium in thinner slabs has been investigated, but due to the faster cooling and reduced rolling reduction, the desired textures (for easy DWI and low earing) have been difficult to achieve. Suggestions from the literature include altering the cooling rate and the composition of the alloy.

Economics[1,4] The aluminium material accounts for approximately 75% of the cost of the can.

Historical development of metal and energy use The industry has continually focused on light weighting due to the large economic incentive to reduce cost. The mass has reduced by 30% from the 1960s. In recent times, the mass has decreased from 16.55gms in 1992 to 14.7grms in 2005[5].

Current Reuse[1] Negligible. The can design would need to be strengthened against accidental crushing/damage. A key consideration would be removal and re-attachment of the end - double seaming may have to be replaced. Coating removal and relacquering would not be necessary, but a returned can would need to be washed thoroughly to remove debris, then washed with a fluid to deactivate remnant microbes, then rinsed in water. The internal coating would survive (it is already designed to survive such treatment).

Current Life Expectancy from Production to Disposal[2] < 6weeks

Current Mass / Material Yield[4] 14grams / up to 80%

Current Embodied Energy[2] 2.3MJ in the aluminium in one can

References

[1] Crown Cork and Seal

[2] Hosford WF and Duncan JL. 1994. The Aluminum Beverage Can. Scientific American

[3] Protective and Decorative Coatings. Metal Packaging Manufacturers Association
Online: http://www.mpma.org.uk/pages/pv.asp?p=mpma15&fsize=0
Last Accessed: 20th November 2010

[4] WellMet2050 Site Visit

[5] The Aluminum Can Group – Facts
Online: http://www.aluminium-cans.com.au/Facts.html
Last Accessed: 20th November 2010

(20) Aluminium Packaging – Other (Foil) (Production ≈ 2.7Mte/yr, 6% Total)

Dimensions Aluminium sheets with a thickness below 200μm are described as foils[1]. Household foils have a gauge of 9 to 25μm, whereas container foils are typically 37.5 to 200μm thick[2].

Significant packaging applications of aluminium foil include household foils, foil pouches and semi-rigid containers.

Household foil

Design constraints: Flexibility (low stiffness in all out of plane directions) to allow wrapping around foodstuffs, provision of an inert surface against food (for relatively short time period < 1 week), and an impermeable barrier to light, oxygen and odours

Material: Typically uncoated AA8011-O

Mass: Very high area covered to mass ratio ≈ 46 grams/m^2

Process: With the sheet foil at the required gauge (9-25μm), lengths of several meters are cut, coiled and packaged for sale. See "Sheet foil process supply chain" below.

Foil pouch

Design constraints: Provision of an inert decorative surface against food/liquid (for relatively long time period > 1week), and impermeable barrier to light, oxygen and bacteria. High thermal conductivity (allowing heating of internal foodstuffs).

Material: Typically, laminated 1xxx and 8xxx series

Mass: Very high area covered to mass ratio - good for transportation (≈68 grams/ m^2)

Coatings: The lamination provides an inert surface, but decreases recyclability of the pouch.

Process[3]*:* The process differs from beverage can production, as foil pouches are filled and sealed immediately after production. The process uses roll-fed laminated foil as the input, and produces the pouch via one of three methods: vertical forming where a continuous cylinder is formed and seamed as the foil is unwound; horizontal forming requiring a seam on both sides; and mandrel forming (for less flexible films) where the pouch is shaped round a mandrel, before being filled.

Semi-rigid packaging

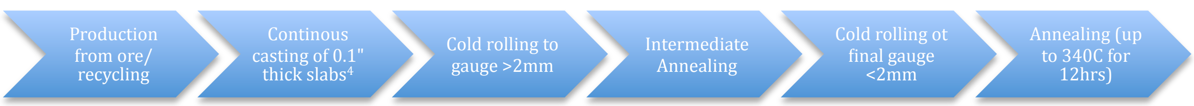
Design constraints: Semi-rigid stiffness in out of plane directions. Provision of inert surface against food/liquid, an impermeable barrier to light, oxygen and bacteria, high thermal conductivity to allow heating. Microwavable packaging is preferable.

Material: Manganese bearing 3xxx series alloys are predominant, though 1xxx and 8xxx series are also used

Mass: Very high area covered to mass ratio - good for transportation (≈500grams/ m^2)

Process: Semi-rigid containers are produced using a mould press line (70pcs/min production rate is typically for a single machine). Yield losses occur during the pressing stage, dependant on the container being produced.

Sheet foil process supply chain



Coils are typically cast using twin roll casting technology (TRC), producing aluminium strips 1350-2129mm wide, and several millimetres thick. Cold rolling in the break-mill reduces the thickness to 200-260μm. The 'foil-stock' is then transported to foil mills and undergoes further cold rolling to final thickness.

To restore ductility to the work hardened foil, the strip is intermediately annealed. A final anneal is required after cold rolling to final gauge. This may require a temperature of up to 340C for up to 12hours. Any remaining lubricant will be burnt off during the final anneal.

Rolling of foil gauge from thick ingots is still practiced, but cold rolling of thin continuously cast slabs is now the preferred method, requiring much less energy. For final gauge thicknesses of less than 25μm[5], two pieces are rolled together, producing a matt and bright side. This prevents tearing of the foil and allows a larger roller gap to be used[2]. The thickness of the foil is controlled using radiation feedback: beta radiation is passed through the foil and the intensity recorded by a sensor on the other side, determining foil thickness and informing roll gap adjustment.

A major problem with packaging foil production is the development of pinholes and strip breaks[6]. Foil stock properties and impurities are the main causes of such imperfections. Also, TRC results in higher cooling rates at the surface (in contact with the water cooled rollers), causing finer grain sizes than in the core, and a heterogeneous distribution of particles. Control of the microstructure through further processing is therefore required to prevent pinholes and strip breaks.

Economics Processing cost from TRC strips is significantly lower than from the thicker traditional DC castings[5].

Historical development of metal and energy use Aluminium household foil replaced tin foil in the mid-20th century.

Current Reuse: Negligible

Current Life Expectancy from Production to Disposal: <6weeks

Current Material Yield Loss[7]: 15%

References

[1] European Aluminum Foils Association
Online: http://www.alufoil.org/front_content.php
Last Accessed: 26th October 2010

[2] Foil. Aluminum Association (USA)
Online:
http://www.aluminum.org/Content/NavigationMenu/TheIndustry/Foil/

default.htm
Last Accessed: 26th October 2010

[3] Aluminumfoils.com
Converting Materials and Methods
Online: http://www.aluminumfoils.com/converting-materials/bag-pouch-envelope.html
Last Accessed: 25th October 2010

[4] Hosford W and Duncan J. 1994. The Aluminum Beverage Can. Scientific American

[5] Robertson G. 2006. 2nd ed. Food Packaging, Principles and Practice: Chapter 7 Metal Packaging Materials., Boca Raton, FL, Taylor & Francis Group: ISBN 0-8493-3775-5.

[6] Keles O and Dundar M. 2007. Aluminum foil: Its typical quality problems and their causes. Journal of Materials Processing Technology. Vol. 186, Issues 1-3, pgs. 125-137

[7] WellMet2050 site visit to aluminium foil producer

(21) Steel and aluminium Consumer Durables (Steel / Al. ≈ 28 / 3.2Mte/yr, 3% / 7% Total)

The majority of steel and aluminium within consumer durables is in household white goods (accounting for 70% of the aluminium), rather than commercial appliances[1].

The mass of steel and aluminium in white goods is predominantly accounted for by fridges/freezers and washing machines.

Refrigerator (Steel / Aluminium = 12.5 / 0.5Mte/yr)

A refrigerator combines two fundamental sub-assemblies:

- A thermally insulated box
- A heat pump

Dimensions: Typically 140-180cms tall, and 60-90cms wide and deep.

Design Constraints: Keep foodstuffs at a low temperature

Overall Mass: On average, 50kg, of which 47% is steel and iron and 2% is aluminium[3].

Exterior cabinet and door

Relatively few refrigerators have aluminium panelling

Design constraints: Delineating/protective of interior mechanism, aesthetic appeal, corrosion resistance

CRS Material[6]*:* Steel is typically used, however if aluminium is used, AA3003 and AA3103 are common sheet materials used as fridge/freezer linings. AA5754, AA34004 and AA3105 are also used.

Process: Multiple Die pressings create the panelling shape. These parts are either welded or clinched together

Interior cabinet or liner

The interior cabinet is often a polymer not a sheet metal. However, aluminium versions do exist. In this case, the specification is the same as for the exterior cabinet, with a layer of insulation placed between the two metal sheets to minimize heat loss.

Cooling system

The cooling system incorporates an aluminium fin and tube heat exchanger and a steel (70% by mass) compressor and expander.

Fins

Design Constraints[4]*:* High heat conductivity, large surface area, corrosion resistance (exposed to many fluids – refrigerants and coolants internally and salt and water externally).

Material[4]*:* Coated AA1060 or AA3004

Coatings[4]: Cladding alloy of AA4343/4045/7072/5052. The zinc content in the alloy is carefully controlled to prevent galvanic corrosion

Yield: Approximately 80%

Process[4]: The fins are cut from sheet material

Tubes

Design Constraints[4]*:* High heat conductivity, large surface area, corrosion resistance (exposed to many fluids – refrigerants and coolants internally and salt and water externally).

Material[4]: Drawn (AA1050, 1197, 3003, 3102); extruded (AA1050, 3003, 5059, 6101). Extrusion and drawing are highly optimized and easily customized for the production of complex thin-walled profiles

Coatings[4]: Same as for “Fins”.

Yield: 75-80%

Process[4]: The tubes are either extruded or drawn

Construction[4]: Traditionally, mechanical joints are used to join the tubes and fins by “expanding the tubes to the fins”. For heat exchangers with aluminium fins and tubes, the joints may be created in a single thermal brazing process. During brazing, all parts of the heat exchanger are placed in a furnace and heated to 600°C. The clad alloys of the brazing sheets melt and seal the joints on cooling.

Copper vs. Aluminum[4]

The use of aluminium, instead of copper, is predominantly because of lower overall cost.

Compressor

Design constraint: Must increase the pressure of the refrigerant. Corrosion resistance

Materials: Cast iron shell, motor, and piping

Mass: 10-14kg

Current reuse: Refrigerator compressors are routinely removed before the refrigerator is shredded for scrap. These compressors are then sold for reuse in the developing world.

Historical development of metal and energy use

The mass production of fridges and freezers started in the 1920s. General developments have included a drive towards greater electrical efficiency, changing refrigerant, better insulation and greater separation between the fridge and freezer compartments.

Current Reuse: Negligible. Reuse is currently restrained to small-scale charity or commercial operations exporting end of life appliances/compressors to the developing world.

Current Life Expectancy from Production to Disposal: 6 years. The E- SCOPE survey found 1/3 of discarded appliances are functional, and of those that are broken, a 1/3 are classified as in need of repair, distinct from broken beyond repair[5]. Due to the lower use phase emission of new white goods, a 50% life extension typically only results in an energy saving of approximately 12%[3].

Washing machine (Steel / Aluminium = 7.8 / 0.5Mte/yr)

The main sub-assemblies are the shell, motor, transmission, pump, and spin and washer tubs. Aluminum components are the shell panelling on expensive machines and the die cast components incorporating the mechanism (transmission housing, end shields for the motor, and pulley and hubs).

Worldwide, washing machines divide into two distinct types: the top-loader and the front-loader, which are dominant in the US and European market respectively[5]. No stooping is required for the top loader, and the mechanism is less susceptible to the shaft bending moment experienced in the front-loader. The front loader, however, is a better design for fitted kitchens.

Dimensions: Typically 850mm tall, and 595-600mm wide (the depth varies considerably)

Overall Mass[3]: On average 75kg, of which 51% is steel and iron and 3% is aluminium

Shell panelling

Relatively few washing machines have aluminium panelling

Design Constraints: Delineating/protective of interior mechanism, aesthetic appeal, corrosion resistance

Material[6]: If aluminium, AA5754 is a common sheet alloy of medium strength used for appliance bodywork. Also, AA3404 and AA3105 are also used.

Process: Cold rolled aluminium is pressed multiple times to form the correct shape. These parts are either welded or clinched together.

Transmission housings

Design Constraints: Stiffness (limitting) to maintain correct alignment of the gear mesh.

Material: AA380 or AA384

Process: Cast aluminium is formed into the rough shape in a die-casting machine. The resulting shape is then machined to create a smooth finish and drill holes etc.

Motor connected to the agitator through the transmission.

Nab: The spin tub is made from stainless steel or steel designed for a porcelain coating.

Historical development of metal and energy use

The mass production of washing machines started in 1930s. General developments have included a drive towards superior vibration isolation; higher drum speeds; less water usage; and increased electronic control.

Current Reuse: Negligible

Current Life Expectancy from Production to Disposal: 10-15 years

Historical development of metal and energy use

The mass production of washing machines started in 1930s. General developments have included a drive towards superior vibration isolation; higher drum speeds; less water usage; and increased electronic control.

Current Reuse: Negligible

References

[1] Jinlong Wang, Thomas E Graedal. 2010. Aluminium in-use Stocks in China: a bottom-up Study Journal of Materials Cycles Waste Management. 12:66–82

[2] Allwood, JM, Cullen, JM, Carruth, MA, Milford, RL, Patel ACH, Moynihan M, Cooper DR, and McBrien, M. 2011. Going on a metal diet. WellMet2050 Emissions by 2050. Environmental science & technology, 44(6), 1888-1894.

[3] Truttmann N and Rechberger H. 2006. Contribution to Resource Conservation by Reuse of Electrical and Electronic Household Appliances. Resources, Conservation and Recycling 48, 2006, 249-262

[4] Alumatter. Case Study – Heat Exchanger
Available Online:
http://aluminium.matter.org.uk/content/html/eng/default.asp?catid=166&pageid=2144416524
Last Accessed: 24th November 2010

[5] Cooper T. 2005. Slower Consumption: Reflections on Product Life Spans and the "Throwaway Society"

[6] Aluselect: Applications
Available Online:
http://aluminium.matter.org.uk/aluselect/01_applications.asp
Last Accessed: 20the January 2011

(22) Aluminium Deoxidation of Steel (Production ≈ 1.4Mte/yr, 3% Total)

The main sources of oxygen in steel are from oxygen blowing in the Basic Oxygen Furnace (BOF), oxidizing slags, atmospheric oxygen dissolving in the liquid steel during pouring operation, and rusted and wet scrap.

The solubility of oxygen in molten steel is 0.23% (at 1700°C), dropping during solidification to 0.003% in solid steel. The oxygen liberated oxidizes steel components (C, Fe, alloying elements), forming gas pores (blow holes) and non-metallic inclusions entrapped within the ingot, adversely effecting the steel quality. In all steel making processes, except the acid silicon reducing process, deoxidation is required. Deoxidizing processes include:

- deoxidation by metallic deoxidizers (aluminium, manganese or ferrosilicon)
- deoxidation by vacuum
- diffusion deoxidation

Aluminium deoxidation is the method of choice in most steel making applications. It is the last stage in steel making, carried out during tapping by adding aluminium into the tap ladle.

Aluminium Bars

Material Constraints: The material must have a high affinity for oxygen, readily forming oxides which are either gaseous or forms slags. Any detrimental effects on the quality of the steel during post-processing must minimal.

Material: Aluminium (98% purity) is a very effective deoxidant. It reacts with the dissolved oxygen to form aluminium oxide. Aluminium also forms pin grain boundaries, preventing grain growth during heat treatments. Approximately 1.8kg of aluminium is used for every tonne of steel produced.

Mass: The aluminium is added as circa 10kg bars.
Process: The details of the procedure vary depending on the desired carbon content of the steel.

When the metal in the ingot mould begins to solidify, oxygen is liberated from the melt, and reacts with the carbon to form carbon monoxide.

The steel must be deoxidized once the desired level of carbon has been attained (deoxidation prevents further evolution of carbon monoxide). The process may be represented by the equation below, the solid inclusion of alumina the result.

$2[Al] + 3[O] \Rightarrow Al_2O_3(s)$

Depending on the level of deoxidation, and hence the carbon and oxygen content, the ingots range from fully killed, through semi-killed and capped to rimmed steel.

Killed Steel – these are deoxidized to such an extent there is no gas evolution during solidification. This is required when a homogenous structure is necessary, such as for forging steels and extra deep drawing steels.

Semi-killed Steel – deoxidized less than killed steel, there is some oxygen present. Suitable for carbon contents in the range of 0.15-0.3%, with a wide application for structural shapes

Capped Steel – The rimming is arrested after several minutes, and the mould sealed with a cast iron cap. This is suitable for carbon contents >0.15%, and is usually applied to sheet, strip, wire and bars

Rimmed Steel – Brisk evolution of carbon monoxide upon solidification, resulting in an outer skin of material low in carbon and other solutes (C<0.25%, Mn<0.6%), resulting in a ductile surface good for cold working. This is best suited to the manufacture of steel sheets.

Nb: There are some applications where aluminium deoxidation of steel is not desirable. The deoxidation process forms alumina, increasing the viscosity of the steel. The crystalline inclusions can act as stress concentrators and crack nucleation sites. These adverse effects have prohibited the use of aluminium to deoxidise steel destined for critical applications where the steel will be embrittled by low temperatures or have to endure large cyclical loads, such as rail steel. Recent research has been looking at the treatment of aluminium-deoxidised steel with calcium, creating complex, but benign, liquid inclusions (of the type $12CaO.7Al_2O_3$) from the hard alumina inclusions.

The alumina inclusions also cause difficulties in piping, particularly in continuous casting, where casting difficulties and poor surface conditions have prompted the use of other forms of deoxidation.

References

[1] Deoxidation of Steel (Dr Dmitri Kopeliovich)
Online:
http://www.substech.com/dokuwiki/doku.php?id=deoxidation_of_steel
Last Accessed: 27th October 2010

[2] Ofengenden AM and Nesterovich RP. 1958. Reducing the amount of Aluminium for Deoxidation of Steel. Springer New York. Volume 2, no. 6.

[3] Steel Deoxidsation: Part one
Online: http://www.keytometals.com/page.aspx?ID=CheckArticle&site=kts&NM=216
Last Accessed: 28th October 2010

[4] Steel Deoxidation: Part two
Online: http://www.keytometals.com/page.aspx?ID=CheckArticle&site=kts&NM=218
Last Accessed: 28th October 2010

[5] Vinogradov S, Fetisov A and Zhuchkov V. Improving the Quality and Castability of Steel by improving the technology used for deoxidation during its treatment outside the furnace. Metallurgist. Vol 47. Nos 9-10, 2003

(23) Aluminium Lithographic Plates (Production ≈ 0.5Mte/yr, 1% Total)

A lithographic plate is used to repeatedly print images and text. The plate is covered in photosensitive emulsion and a negative of the intended image placed onto the surface. The plate is exposed to ultraviolet light, producing a hard and durable polymer beneath the text and graphics. The plate is then washed, removing the remaining emulsion and leaving a hydrophilic aluminium surface. The areas of hardened polymer present a hydrophobic surface ready for the transfer of ink[1]. This sensitization process is performed automatically in modern printing, with a levelling process typically performed immediately afterwards[*].

Recent research areas include the inability to directly transfer an image from a computer to the printing plate. Lines of inquiry have included jetted ink that directly changes the chemical composition at the surface of the litho plate[1].

Design Constraints[2,*]: The limiting criteria are typically flatness and a degreased high surface quality. Other important characteristics of aluminium are flexibility and wetting (hydrophobic/hydrophilic) response. The durability to mass print copies can also be an issue (prompting the use of a stronger alloy).

Material[3]: 1xxx series alloys are often used (such as AA1050 and AA1100). Alternatively, 3xxx series alloys are used (such as AA3103 and AA3003), as they are stronger and deemed more durable for mass printing.

Thickness*: 0.15-0.4mm (0.3mm standard). Thicker plates are more durable but less flexible.

Coatings[3]: The grained aluminium surface is anodized, producing an oxide layer approximately 1μm thick. This protects against excessive wear, and promotes adhesion with photosensitive coatings.

Printing Process[3]: The printing plate is coated with a thin layer of water, and then oil-based ink. The printing plate transfers the image to a hydrophobic rubber offset, which in turn prints the image to paper.

Process supply chain of predominant material (1xxx/3xxx series plates)

Production may be from primary or recycled material. Recycling is performed in closed loops, with rates approaching 100%. Often, a recycling agreement will be part of the initial contract between the supplier and printer[4].

The aluminium is rolled to a flexible gauge (the material sold by the supplier as H18-H19 temper[*]). Tension levelling (stretcher) and degreasing then produces flat, degreased coils[*]. The surface must be roughened to improve water retention and adhesion. AC-electrograining, electrolysis in HCL or HNO_3, results in this pitted, roughened surface[3]. The plates are then cleaned in an acid neutralizing solution[3], and a final levelling operation compensates the coil set[*].

Economics[*] The aluminium material accounts for more than 50% of the cost of the litho coil before any treatment (electrograining, anodizing, etc.).

Historical development Aluminium superseded limestone as the plate material in the mid-20th century. Suppliers have recently developed new alloys (based on AA1050 with additional alloying elements) to produce better mechanical properties and fatigue resistance, allowing more prints[*].

Current Reuse: Negligible. However, recently developed technology may allow reuse: laser technology can modify the surface of the aluminium oxide, switching the plate from a hydrophilic to hydrophobic state[5]. The hydrophobic regions are then able to accept ink in the printing process. After printing, the plate may be allowed to 'stand', naturally reverting to its hydrophilic form. The plate may then be reused for a different image. This process also eliminates the need for coating chemicals and processing equipment.

Current Life Expectancy: It is common for commercial print shops to go through more than 100 hundred plates each day

References

[1] Gloster D and Andreottola M. Direct Computer to plate printing. American Ink Jet Corporation

Available Online: www.*americaninkjet.com/images/Direct.pdf*

Last Accessed: 29th November 2010

[2] Lithographic Aluminum Sheet. Alcoa Mill Product Datasheet

Available Online:

https://www.alcoa.com/mill_products/.../lithographictechsheet.pdf

Last Accessed: 29th November 2010

[3] Case Study: Lithographic Printing Plate. Alumatter

Available Online:

http://www.aluminium.matter.org.uk/content/html/eng/default.asp?catid=107&pageid=2144416259

Last Accessed: 29th November 2010

[4] Email: Chris Bayliss (IAI) 16th September 2010. "RE: IAI Spreadsheet Sector Definitions"

[5] JPI. 2010. Technology White Paper – Miracle Plate

Available Online: http://miracle-plate.com/app/download/1816088102/Technology+White+Paper21st+July_RMP.pdf

Last Accessed: 16th September 2010

[*] Alcoa

3. Potential for reusing metal components

After the completion of all the interviews, all existing reuse activities and barriers were examined and the opportunities and constraints reduced to those shown in Tables S25 and S26.

Table S25: Reuse strategies

Table	...and are used in the same type of product	...and are used in a different type of product
The component(s) undergo extensive reconditioning...	**Remanufacture** Eg. Remanufactured engines	**Reform** Eg. Ship plate to reinforcing bar
The component(s) undergo superficial reconditioning...	**Relocate** Eg. Recovered aluminium alloy wheels put on another car	**Cascade** Eg. Reclaimed structural steel used as shoring

S26: Reuse constraints

When	...relative to before product fabrication	...relative to new components
The components performance has declined...	**Degraded** Eg. Offshore corroded steel	**Inferior** Eg. Building cladding
The components value has declined...	**Irretrievable** Eg. Rebar in foundations	**Incompatible** Eg. Bespoke fabricatted structural sections

demand for the service provided is high and the component is in a good condition it may simply be **relocated** (typically a large single component) into another product with little refurbishment, such as cleaning and simple repairs/adjustments. When both demand is low and the condition poor or unknown, the component may be **cascaded** to a less demanding use, or **reformed** (re-shaped) to form a new, more useful, geometry. If demand exists but the component has suffered significant degradation, or an upgrade is needed, the component/sub-assembly may need to be **remanufactured**. Remanufacture typi-

cally entails further disassembly (of a sub-assembly), re-drilling and metallic spraying/thermal techniques to recover worn and fatigued surfaces.
Component reuse demands that the component or sub-assembly is **retrievable** from the rest of the product at end of life. Even for components that can be easily recovered and are neither damaged nor obsolete, they may be **incompatible** with new products as the component design is not standardised, or the component of unknown specification. Both these constraints reduce the value of the old component to the designer. The performance of the retrieved component can prevent reuse if its condition is **degraded** beyond repair or remanufacture. Products with a high rate of technological evolution are difficult to reuse due to falling demand for older products, and their components performance can be classed as **inferior**.

3.1 Transport

Automobiles and trucks

An average passenger car weighs 1440kg, containing 960kg steel and 120kg of aluminium. We already re-use some car and truck components through salvage yards and second-hand dealers, and some component remanufacture occurs. However, as the design of engines and gearboxes changes rapidly, component reuse will remain limited. Assuming step-changes in engine and gearbox design every 20 years sufficient to dissuade remanufacture, and a car life expectancy of 14 years, implies a possible reuse rate of 40% (6 divided by 14). Other than vehicles involved in accidents, it is assumed that all alloy wheels could be relocated on another vehicle, therefore a relatively high reuse potential of 80% is used. The suspension is classed as effectively irretrievable without damage, and although some aluminium heat exchangers (AC units) could be reused, many are subject to corrosion and damage from front-end vehicle collisions. Table S25 presents aluminium car components, concluding an average reuse potential of 40%.

Table S25: Reuse potential of aluminium components in passenger cars

Component	% of aluminium mass	% viable for reuse	Reuse strategy	Reuse constraint
Engine block	34%	40%	Remanufacture	Inferior
Transmission casing	14%	40%	Relocate	Inferior
Chassis, suspension, steering	11%	0%	/	Irretrievable
Wheels	15%	80%	Relocate	Degraded
Heat exchanger	10%	10%	/	Incompatible
Other components	16%	40%	Relocate	N/A
Overall potential		40%	Relocate	Inferior

The reuse potential of 'other components' is taken as the average of the other components. Closures account for an average 54kg of the steel in a car. Assuming a 50% reforming yield, equivalent to the yield in stamping of sheet automotive parts, gives 10% reuse potential of the "body structure, panels and closures" (see product design description (1) in section 2 of this SI). Table S26 presents the potential reuse of steel car components.

Table S26: Reuse potential of steel components in passenger cars

Component	% of steel mass	% viable reuse	Reuse strategy	Reuse constraint
Body structure, panels and closures	34%	10%	Reform	Incompatible
Drivetrain	23%	40%	Remanufacture	Inferior
Suspension	12%	0%	/	Degraded
Other components	31%	20%	Remanufacture	/
Overall potential		20%	Remanufacture	Incompatible

The reuse potential of 'other components' is taken as the average of the other components.

The life of a passenger car is typically determined by the drivetrain, whereas for tractor-trailer heavy trucks the standardised long-lasting trailer will be used on multiple tractors. A typical weight distribution is 7te in the tractor, and 12te in the trailer. There is some reforming potential of the sheet used in the trailer, therefore up to 50% reuse is assumed. However the reuse potential of the worn out tractor is likely to be like a passenger car, giving an overall reuse potential for both metals of approximately **40%**.

For light trucks, ultimate failure is likely to be due to a degraded drive train, where little can be reused due to “inferior” constraints. A reuse potential similar to that of passenger cars is assumed – **40%** for aluminium and **20%** for steel. It should be noted that specialised rigid trucks, with expensive bodywork, may have their drivetrain replaced rather than have the whole vehicle being scrapped. Operators currently known to facilitate reuse of rigid trucks are known as 'bodybuilders' and 'chassis engineers' who can convert/build new truck bodies. For example, converting 4 axle standard trucks to 6 axle tippers, or shortening and lengthening of the wheel base.

Ships

India, Pakistan and Bangladesh dominate the ship breaking industry, with roughly half the world’s ships dismantled in India alone. At end of life, ship plate salvaged from ship-breaking is currently re-rolled into plates and reinforcement bars for the construction industry. With the Indian sub-continent dominating the global ship breaking industry it may be difficult to expand this activity further. Tilwankar et al (2008) (ref. S38) state that over the life-span of the ship, approximately 10 % of the steel is lost by corrosion. 95% of the remainder is in the form of re-rollable sheet, allowing approximately **85%** of the ship’s original steel mass to be reused.

Aluminium components used for the structure on the top-side of cruise ships could be largely standardised to allow reuse by direct relocation. However, corrosion in an aggressive marine atmosphere is a problem. Aluminium is also used for the hulls of some yachts, which will also suffer from a degraded reuse constraint. Overall, a conservative **10%** reuse of aluminium used in shipping is assumed.

Other

It is difficult to quantify this small category of transport end use, therefore only a small amount of potential reuse is assumed, estimated at **10%.**

3.2 Construction

The significant steel components in buildings and infrastructure are structural steel, reinforcement, sheet cladding, cold formed sections, rail track and line pipe. Aluminium used in construction is dominated by building use, with window and door frames, curtain walling (commercial building glass facades) and cladding.

Structural steel used in buildings is typically undamaged at end of life (S39), only fire causing permanent damage, and therefore it is not 'degraded'. The standards for steel sections have been relatively stagnant over the previous decades, therefore the steel is also not technically 'inferior' to any new equivalents. The cost and time implications of deconstruction over demolition inhibits reuse, however, given alternative economics or contractual planning to make use of the time between dereliction and current demolition, this may change. Most structural steel is bolted together, and only the bases of a minority of columns are embedded in concrete. Structural steel under composite floors (profiled sheet decking and concrete) may also be recovered: the steel decking could provide a safe working platform for deconstruction, and all the concrete could be hammered out and the shear studs and profile decking cut out. The de-constructors would work their way along the primary beams cutting the steel decking from the beam, and the sections then unbolted/hot cut and lifted out. Therefore, structural steel is not 'irretrievable'.

Once deconstructed, the properties of the steel sections can be unknown. However, the steel may be downgraded, a paper trail can give confidence in the original specification, or economical testing may be developed. However, not all structural steel is of the correct length for new designs, and designers are used to having standardised lengths to choose from. Additionally, approximately 5% of structural steel is not formed by standardised hot rolling, but by the welding of 3 plates to form a bespoke section. The ultimate constraint on structural steel reuse is therefore the 'incompatible' barrier. It has been estimated up to **80%** of hot rolled structural steel used in buildings may be reused by direct relocation.

Sections fabricated from plate are assumed to be more difficult to reuse by relocation, however a combination of relocation and reforming (cutting out plate sections) for reconfigured sections may account to a modest **10%** reuse potential. In contrast, structural steel in infrastructure suffers from corrosion and fatigue damage, and therefore is constrained by the 'degraded' barrier. Some cascading reuse may take place, however the demand for temporary structures and buildings is insufficient and is soon saturated, allowing only **10%** reuse of structural steel from infrastructure.

Connections consisting of bolts, cleats and fin plates are often damaged during assembly or disassembly therefore no potential reuse is assumed for these components.

Reinforcement bars used in buildings are typically undamaged at end of life, however can not be retrieved without damage from the concrete. Reinforcement bars in foundations are also irrecoverable and are typically left in the ground at end of life. Research by Wace et al (1993) (ref. S40) investigated using microwaves to crack the concrete and allow recovery of the rebar, however this technology is in its infancy, and the necessary microwave penetration distances into the concrete make this an unlikely solution. Pre-cast concrete allows relocation of the module at end of first life. However, connections between such modules often contain in-situ concrete, limiting the recovery opportunity. Approximately 20% of the worlds concrete production for buildings use is pre-cast. Assuming 20% of these modules could be effectively recovered results in an estimate of **4%** of the reinforcement bars in buildings potentially being reused. Reinforcement in infrastructure suffers from corrosion and fatigue, and therefore **negligible** reuse is assumed.

Sheet is used in construction for cladding, cold formed sections, metal decking for composite floors, and sheet piling. Purlins are often damaged during deconstruction (‘irretrievable’ barrier), and cladding is subject to changing standards for thermal insulation ('inferior' barrier), so reuse is currently restricted to agricultural sheds. However, the opportunity to reuse cladding is likely to increase as new insulation standards become widespread. **50%** of sheet in cold-formed sections and cladding is assumed to be reusable. The metal decking for composite floors is 'irretrievable', and therefore **no** reuse is assumed. Sheet piling used in infrastructure is difficult to retrieve from the ground at end of life, however 4% of sheet piling in infrastructure is currently reused by relocation (S41). Given greater economic incentive and better workmanship to ensure easy extraction, it is assumed this could rise to **10%**.

Line pipe infrastructure suffers from corrosion and fatigue damage, however, it is assumed that, in a similar method to the re-rolling of ship plate in Asia, large diameter lien pipe could be reformed into construction products (rebar etc.) therefore it is assumed that up to **80%** reuse is possible. Retrieving the line pipe from the ground and deep water will limit this reuse potential. Structural tubes used in buildings could be reused by either direct relocation or by re-rolling into construction products (rebar etc.), therefore a high **80%** reuse is estimated. Due to corrosion and fatigue damage this is reduced to only **20%** for structural tube used in infrastructure. Up to **50%** of handrails and fences used in buildings could be reused by direct relocation, but due to bespoke and fragile geometry it is assumed only **10%** of small air and gas tubes can be reused. Handrails, fencing and street furniture used in infrastructure is subject to corrosion and therefore reuse of estimate of **20%** for handrails and fencing and **10%** for street furniture are used.

Drawn wire in construction is used predominantly as a fine reinforcement for concrete. This is irretrievable at end if life, and therefore **negligible** reuse is assumed.

Re-use of aluminium window frames and other building components is not yet practised, and is inhibited by the difficulty of extracting used components without damage, unstandardised extrusions, and by water staining of older frames. The connection could be adjusted to allow easier deconstruction, perhaps using a snap fit or sacrificial connection. Greater standardisation could happen in the future though currently there are many different extruders producing bespoke cross-sections. Reuse is ultimately constrained by the “broken” barrier. Reuse of window frames is possible so we assume it will develop to some extent. For example, buildings typically last approximately ten years longer than aluminium window frames, allowing only the second set of window frames to be reused, and therefore 50% the upper limit used. The same issues apply to aluminium cladding as for steel, so we’ll assume that up to 50% of it could be reused in future.

Other aluminium use in buildings is for gutters and spouts. These can easily be removed from buildings and relocated, but the bespoke geometry limits there use after removal, and therefore are constrained by being "Incompatible". Given similar issues as cladding and aluminium framing systems, greater standardisation in the future could allow up to **50%** reuse.

The corrosion and fatigue loadings on line pipe limit the possibility of direct relocation and reuse as pipeline. However, line pipe could be cascaded: re-rolled, like ship plate, into construction components. It is estimated this would allow up to **80%** reuse. Retrieval from remote on and offshore locations limits this reuse.

There is significant potential to increase the life of rail track by using a replaceable high wearing boron steel push-fit cap, or cascading to secondary routes after the rail head has become too worn for the mainline. However, this is considered product life extension, and not reuse, and therefore will not be included in the reuse analysis.

3.3 Industrial equipment

Electrical equipment

Steel and aluminium are used both to provide the structural infrastructure for electrical grids, and as an active electrical component in distribution and use. Galvanised steel towers (pylons) create electrical corridors that criss-cross nations as they distribute electricity from centralised power stations. The failure of one of these pylons would cause power-cuts and widespread disruption, so pylons are typically well maintained and only replaced when corrosion has undermined the integrity of the tower, the 'degraded' barrier constraining reuse. However, some electrical routes become obsolete with falling energy demand from dis-industrialisation. Power companies will, however, often keep the pylons standing as regaining building permission can be difficult if they needed to in the future. Therefore, there is limited opportunity to reuse these towers, estimated at **10%** in the interviews. Electrical steels, with high silicon content, are used in large transformers throughout the electrical network, for example to step down the voltage from power stations to household voltage. At end of life, the steel tank surrounding the transformer could be reused, along with up to 60% of the transformer itself. Transformer design has been fundamentally stable for the last

50 years and therefore reuse could be increased up to high levels, estimated at **80%** in the interviews.

Steel and aluminium are both used in electrical transmission and distribution cables. The aluminium conducts the electricity while the steel provides the strength to span the long distances between pylons. End of life for overhead transmission cables is often by corrosion of the steel originating at the connection with the steel pylon. Good workmanship can prevent this and therefore could be limited in the future. Another main source of failure is that over time the cables are required to transmit more power than initially intended. This excess power causes the cable to heat up causing annealing and thus a permanent reduction in tensile strength. This, in combination with the tension in the cable, causes structural sag, prompting replacement before or after contact with an obstacle such as a tree. Proactive overhead cable replacement in the future may allow reuse of cables on lower power routes, so we have assumed potential for up to **50%** reuse as conservative as with good installation and correct use they could last over 50 years (according to the interviews).

When underground cables fail, they are usually repaired rather than replaced, unless additional capacity is required or the insulation has failed. Underground cables are not reused at present because they cannot be certified, and the insulation could be degraded. This is unlikely to change in the future.

Aluminium strips (known as bus bars) are used to connect elements in switchboards, and aluminium conduits protect wires and cables. Such components are small, bespoke and dispersed, and therefore reuse is limited by the 'incompatible' constraint. However, some reuse is certainly possible, therefore 1**0%** has been assumed.

Mechanical equipment

In our analysis of mechanical equipment, we have focused largely on rolling mills, and also some smaller workshop appliances, such as lathes and pillar drills. In terms of failure, this is nearly always physical, and so some components cannot be reused due to the 'degraded' constraint. However, typically the physical failure occurs to only a small fraction of the overall mass of metal. Reuse of components can then be hindered by a lack of standardisation, and obsolescence - companies will take the opportunity to upgrade during replacement rather than settle with the old components. Standardised modular products would reduce the variety demanded of mechanical production equipment that could support further standardisation and reuse. In addition to relocation of components and remanufacture of wear parts there are large plate sections that could be re-formed for reuse. Overall, a conservative reuse potential of **10%** has been assumed.

3.4 Metal products

Packaging

Food and drinks cans could be used several times if the cans were stronger to avoid damage in use, and could be cleaned and recoated in a way that meets food safety standards. Steel aerosol cans could equally be refilled and re-sold. With collection rates around 50–60%, nearly half the material in drinks cans is also lost after first use. Assuming up to 80% of collected cans could be used again, approximately 40% could be used again.

Foil, used for the cooking and preparation of food generally, is difficult to reclaim as the waste stream is highly dispersed, and therefore mainly lost to landfill or incineration after first use. However, even if the foil could be collected effectively, the foil has been cut into shorter pieces, and will have been torn and folded, limiting any reuse by the 'degraded' constraint.

These packaging goods are products, opposed to components, and therefore a secondary use is classed as life extension and is not included in this component reuse analysis.

Domestic appliances

Use of the two metals in appliances is dominated by fridges and washing machines, which incorporate mechanical components, such as motors and compressors, and panelling. Although the overall dimensions of white goods is standardised to fit under kitchen units, the interior components have not been standardised and this often prevents interchangeable parts. Also, the panelling could be made clip-on and off to allow reuse, but currently is not designed for this. Product failure is typically due to small components, such as the bearings in washing machine drums or the carbon brushes in the motors. Motor and transmission technology in appliances is stable, and therefore these components could be repaired and reused. This is currently hampered by some components being irretrievable – the sealed drum prevents replacement of worn bearings in most washing machines.

Electric motors and fridge compressors can be remanufactured, and the sheet metal panels could be reformed into alternative shapes if not directly relocated onto a new machine. An approximate mass breakdown for white goods is 25% in the motor/compressor, and 75% in the structural components (considering the ass of the compressor in refrigerators). Assuming a 50% yield on the reforming, or relocation, of the panelling and a 40% potential remanufacture of the mechanical components (assuming similar technology advancement as for car mechanical components), implies an overall potential reuse of **48%.**

Table S27: Reuse potential for domestic appliances

Appliance	Mass distribution (%)	Reuse potential (%)	Reuse strategy	Reuse constraint
Paneling / Structural	75	50	Relocate	Incompatible
Mechanical	25	40	Remanufacture	Incompatible
Overall	100	48	Steel (Rel.) Al. (Reman.)	Ste. (Incom) Al (Incom.)

Steel wire products

These drawn wire products are mainly used as barbed wire in agriculture, wire ropes in the mining sector, wire springs etc. It is assume due to corrosion and fatigue concerns little of these components could be reused, and therefore a low estimate of **10%** potential reuse is assumed.

Other steel goods (inc. other packaging)

The reuse potential for this sector is taken as the average of the steel metal goods sector, **22%.**

Lithographic plate

A lithographic plate is used to repeatedly print images and text. The plate is covered in photosensitive emulsion and a negative of the intended image placed onto the surface. The plate is exposed to ultraviolet light, producing a hard and durable polymer beneath the text and graphics. The plate is then washed, removing the remaining emulsion and leaving a hydrophilic aluminium surface. The areas of hardened polymer present a hydrophobic surface ready for the transfer of ink.

Many print houses use several hundred lithographic plates in a day, and they are quickly redundant as the hardened emulsion only corresponds to one printed image. The base aluminium is 'irretrievable' preventing reuse without melting. Recently developed technology may allow reuse in the future: laser technology can modify the surface of the aluminium oxide, switching the plate from a hydrophilic to hydrophobic state. The hydrophobic regions are then able to accept ink in the printing process. After printing, the plate may be allowed to 'stand', naturally reverting to its hydrophilic form. The plate may then be reused for a different image. However, as this process is only in its infancy it has not been considered in this analysis.

Aluminium deoxidation of steel

The reuse potential of the aluminium used to deox. the steel is effectively the overall reuse potential of all the steel components, corresponding to **27%** according to Table S28. The main barrier is the predominant constraint on steel reuse, 'incompatible'.

Tables S28 and S29 present the overall reuse potential for component reuse in steel and aluminium intensive products.

3.4 Overall potential reuse of components

Table S28: Potential reuse of steel components (2008)

Steel	End use per annum		Potential Reuse
	Mte	Fraction	
Transport	131	13%	37%
Cars and light trucks	70	7%	20%
Cars	51	5%	
Light trucks	19	2%	
Heavy trucks and buses	15	1%	40%
Heavy trucks	13	1%	
Heavy buses	2	0%	
Ships	31	3%	85%
Other (rolling stock, aero, military)	15	1%	10%
Construction	540	53%	29%
Buildings	364	36%	38%
Structural Steel	61	6%	79%
Hot rolled	60	6%	80%
Fabricated plate	1	0%	10%
Connections	6	1%	0%
Reinforcement steel	110	11%	4%
Reinforcing bar	73	7%	/
Wire rod	37	4%	/
Sheet	152	15%	47%
Cold formed sections	122	12%	50%
Cladding	21	2%	50%
Decking	10	1%	0%
Drawn wire	8	1%	0%
Tube	27	3%	46%
Str. Tube	11	1%	80%
Non-str Tube	9	1%	34%
Handrails	5	0%	50%
Fences	5	0%	50%
Air and gas small tubes	7	1%	10%
Infrastructure	176	17%	11%
Structural Steel	20	2%	10%
Hot rolled	19	2%	
Fabricated plate	1	0%	
Connections	2	0%	0%
Reinforcement steel	98	10%	0%
Reinforcing bar	65	6%	
Wire rod	33	3%	
Sheet – sheet piling	6	1%	10%
Rails	10	1%	0%
Drawn wire	7	1%	0%
Tube	32	3%	53%
Linepipe	18	2%	80%
Str. Tube	4	0%	20%
Non-str Tube	10	1%	14%
Handrails	2	0%	20%
Fencing	2	0%	20%
Street Furniture	6	1%	10%
Industrial Equipment	166	16%	17%
Mechanical Machinery	135	13%	10%
Electrical Machinery	31	3%	48%
Motors and Transformers	17	2%	80%
Other (pylons, cables, sheathing)	14	1%	10%
Metal products	187	18%	22%
Packaging	26	3%	0%
Shipping containers	16	2%	0%
Drinks cans	1	0%	0%
Aerosols	3	0%	0%
Food cans	6	1%	0%
Consumer durables	28	3%	50%
Fridge/freezers	12	1%	
Washing machines	8	1%	
TV	3	0%	
Other appliances	5	1%	
Wire products*	20	2%	10%
Other goods (inc. other packaging)	113	11%	22%
Total	1024	100%	**27%**

Table S29: Potential reuse of aluminium components (2008).

Aluminium	End use per annum		Potential Reuse
	Mte	Fraction	
Transport	13	28%	36%
Cars and light trucks	9	20%	40%
Cars	6	14%	
Light trucks	3	6%	
Heavy trucks and buses	2	4%	40%
Heavy trucks	2	4%	
Heavy buses	0	0%	
Marine	2	4%	10%
Other (eg. Aerospace)	0	0%	36%
Construction	11	24%	50%
Window and door frames	4	8%	50%
Curtain walls and Facades	2	5%	50%
Cladding	2	5%	50%
Other (gutter, spouts etc,)	3	6%	50%
Industrial Equipment	10	21%	29%
Mechanical machinery	3	7%	10%
Manufacturing equip	3	7%	
Electrical	6	14%	39%
Cables	4	9%	50%
Other (busbars)	2	5%	20%
Metal products	12	26%	17%
Packaging	6	14%	0%
Foil	3	6%	0%
Drinks cans	3	7%	0%
Aerosols	0	1%	0%
Domestic Appliances	3	7%	50%
Fridge/freezers	1	1%	
Washing machine	1	1%	
TVs	0	1%	
Other Con. Durables	2	4%	
Litho plate	0	1%	0%
Deox of steel	1	3%	27%
Other – powder metallurgy etc.	1	1%	17%
Total	45	100%	**33%**

References

S1 WSA. 2009. World Steel Association Steel Statistical Yearbook 2010. World Steel Association

S2 IAI, 2008a. International Aluminium Institute Material Flow Data for 2008. International Aluminium Institute

S3 Wang, T., Müller, D. B., & Graedel, T. E. (2007). Forging the anthropogenic iron cycle. *Environmental science & technology*, *41*(14), 5120-9.

S4 Hatayama, H., Daigo, I., Matsuno, Y., & Adachi, Y. (2010). Outlook of the world steel cycle based on the stock and flow dynamics. Environmental science & technology, 44(16), 6457- 63.

S5 Moynihan and Allwood (2012). The flow of steel into the construction sector. Currently under review at the journal of Resources, Conservation and Recycling

S6 Wang, Jinlong, & Graedel, T. E. (2010). Aluminium in-use stocks in China: a bottom-up study. Journal of Material Cycles and Waste Management, 12(1), 66-82

S7 Recalde, K., Wang, J, & Graedel, T. (2008). Aluminium in-use stocks in the state of Connecticut. Resources, Conservation and Recycling, 52(11), 1271-1282

S8 OICA. 2007. Organisation Internationale des Constructeurs d'Automobiles » Production Statistics.

Online: http://www.oica.net/category/production-statistics/

Last Accessed: 23rs November 2011

S9 Bertram, M., Buxmann, K., & Furrer, P. (2009). Analysis of greenhouse gas emissions related to aluminium transport applications. The International Journal of Life Cycle Assessment, 14(S1), 62-69.

S10 Light Vehicle Weight on the Rise. (2007). US Department of Energy. Retrieved September 12, 2011, from http://www1.eere.energy.gov/vehiclesandfuels/facts/2007_fcvt_fotw475.html

S11 Cullen, J. M., Allwood, J. M., & Borgstein, E. H. (2011). Reducing Energy Demand: What Are the Practical Limits? - Supporting Information. Carbon, 1-63.

S12 Automotive Steel Weight. (2011). Steel on the Net. Retrieved September 12, 2011, from http://www.steelonthenet.com/files/automotive.html

S13 IAI 2008b. Aluminium in Transport Application (ALFRED). Online: http://www.world- aluminium.org/cache/fl0000172.pdf

Last Accessed: 23rd November 2011

S14 Boeing. 2010. Orders and Deliveries – Boeing

Online: http://active.boeing.com/commercial/orders/index.cfm?content=displaystandardreport.cfm&RequestTimeout=500&optReportType http://active.boeing.com/commercial/orders/index.cfm?content=displaystandardre-port.cfm&RequestTimeout=500&optReportType=AnnOrd&pageid=m15521=AnnOrd&pageid=m15521

Last Accessed: 5th February 2012

S15 Global Aircraft. 2011.

Online: http://www.globalaircraft.org/planes/airbus_a380.pl

Last Accessed: 20th November 2011

S16 Airbus, 2009.

Online: http://www.airbus.com/fileadmin/media_gallery/files/reports_results http://www.airbus.com/fileadmin/media_gallery/files/reports_results_reviews/Airbus-2009resultstable1.pdf_reviews/Airbus-2009resultstable1.pdf

Last Accessed: 10th December 2010

S17 Japan Iron and Steel Institute, 2007

S18 Eurofer. 2008. Economic and Steel Market Outlook 2008-2009. 2008

S19 Singapore Ship Brokers. 2009.

Online: http://singaporeshipbrokers.com/?p=124

Last Accessed: 22nd November 2011

S20 European convention on Constructional steelwork. ECCS. Statistical Bulletin for the production in 2008.

Online: http://www.steelconstruct.com/eccs/annual/2009Statistic.pdf

Last Accessed: 10th December 2012

S21 The American Institute of Steel Construction. 2011

Online: http://www.aisc.org/content.aspx?id=3800

Last Accessed: 22nd November 2011

S22 Richard Howells, 2010 Email to Dan Cooper. 11 November 2010. re: Well-Met2050 – Wire Rod production and Market Query

S23 UK Steel. 2009. UK Steel Key Statistics 2009. EEF

S24 Hillenbrand, 2008. Market situation of Large Diameter Linepipe. Presentation: International Dillinger Offshore Colloquium, Dillingen, 28-30 April 2008.

S25 The aluminium association, 2007. Table 13: Trends in selected Markets. The Aluminium Association

S26 Alufoil. 2008.

Online: http://www.alufoil.org/front_content.php?idart=203

Last Accessed: 25th October 2011

S27 IMF. 2010. Online:
http://www.imf.org/external/pubs/ft/weo/2011/02/weodata/weorept.aspx?p

Last Accessed: 25th October 2011

S28 European Aluminium Foil Association. 2011.

Online: http://www.alufoil.org/front_content.php?idart=203

Last Accessed: 25th October 2011

S29 Waste Online, 2005.

Online: http://www.wasteonline.org.uk/

Last Accessed: 20th October 2011

S30 BAMA. 2011. UK Filling Statistics - British Aerosol Manufacturers' Association (BAMA). Online: http://www.bama.co.uk/uk_filling_statistics/

Last Accessed: 5th October 2011

S31 IMF. 2008.

Online:
http://www.imf.org/external/pubs/ft/weo/2011/02/weodata/weorept.aspx?p

Last Accessed: 10th March 2011

S32 Crown, 2010. Personal Communication. December 2010. Crown Cork and Seal

S33 Allwood, JM, Cullen, JM, Carruth, MA, Milford, RL, Patel ACH, Moynihan M, Cooper DR, and McBrien, M. 2011. Going on a metal diet. WellMet2050 Emissions by 2050. Environmental science & technology, 44(6), 1888-1894.

S34 Truttmann, N., & Rechberger, H. (2006). Contribution to resource conservation by reuse of electrical and electronic household appliances. Resources, Conservation and Recycling, 48(3), 249-262.

S35 Bekaert, 2010. Email to Dan Cooper. 15 October 2010. re: WellMet2050 – Online request about Products and Applications.

S36 Bayliss, 2010. Email to Dan Cooper. 16 September 2010. re: IAI Spreadsheet Sector Definitions

S37 Ofengenden AM and Nesterovich RP. 1958. Reducing the amount of Aluminium for Deoxidation of Steel. Springer New York. Volume 2, no. 6.

S38 Tilwankar, A.K., Mahindrakar, A.B. and Asolekar, S.R., 2008. Steel Recycling Resulting from Ship Dismantling in India: Implications for Green House Gas Emissions. In Dismantling of Obsolete Vessels. Glasgow, pp. 1-10.

S39 Fujita, M. (2008). Reuse Dismantling and Performance Evaluation of Reusable Members. Structural *Engineering International*, *18*(3).

S40 Wace, P., Shute, R., & Hamblin, C. (1993). Microwave Demolition Toll for Mounting on Long Range Manipulator (EMIR). Elsevier Science Publications B.V.

S41 Dinnis, 2012. Sustainability: An introduction to Life Cycle Analysis, followed by a first principle run through demonstrating the considerable Environmental advantages of AZ Steel Sheet Piles. Presentation at Ramboll UK (Cambridge), 17th January 2012