Specific energy analysis for the manufacturing of light-weight automobile body

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Abstract: This manuscript analyses the specific energy requirements to produce two hybridised vehicle structures on current automotive assembly lines. It provides quantitative and specific electric (kWhr/vehicle) and fossil-fuel (MMBtu/vehicle) energy predictions of the body-in-white (BIW) manufacturing processes including body panel forming, welding, painting, and final assembly, in addition to the facility heating ventilation and air conditioning or HVAC consumption. Two hybridised BIW design criteria are analysed; the first is based on minimising the added cost per unit weight saved (+$/–kg), while the second is based on maximising the percentage of weight saved (% –kg). Also a new criterion; that is the added specific-energy per unit weight-saved or (+kWhr/vehicle/–kg) is proposed. The light-weight structures comprise body parts made of aluminium and steel. To compute energy consumptions, the study utilises the energy performance index (EPI) stochastic model in addition to complementing it with a panel-forming energy model. Cost analysis is also provided for all the major vehicle body-panels using an in-house Excel macro. The study reverse engineers a passenger vehicle BIW using a full-size coordinate measuring machine (CMM). The presented work further highlights the monetary value of the associated emissions when increasing the specific energy.

Keywords: light weight; body-in-white; BIW; energy performance index; EPI; long-term energy forecasting.

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Biographical notes: Mohammed Omar is an expert in the field of material selection for automobile Structures, and he published related articles about eco-material selection using fuzzy TOPSIS, using QFD/AHP for material selection, analysis of vehicular cabins' thermal sensation and comfort state, under relative humidity and temperature control, using Berkeley and Fanger models cited on the references list.

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1 Introduction

Current dynamics in the operating environment of the automotive industry have led to changes in the way OEMs managed their product portfolio. Such dynamics are caused by the following challenges: the market over-capacity, and the lack of differentiation among products and their classes, the penetration and rise of new powertrain options (hybrid and full electric), and the push to more sustainable production practices and material usage. To furnish a numeric illustration, in 2000 the automotive facilities had the capacity to generate 25 million more vehicles than the world needed as reported by Clarke (2005), at the same time, the OEMs from South Korea produced around five times their estimated domestic needs. Moreover, the trend to *greening* the automobile has also resulted in hybridised body-in-white (BIW) panels made from steel, aluminium, and even carbon-based composites. Such hybridised structures have resulted in an added cost and an added energy requirement, when making these vehicles (Omar, 2011). Energy consumption for US vehicle production facilities came at about $3.6 billion in 1999, still this is a small percentage of total output sales, estimated at nearly $350 billion for the same year (Galitsky and Worrell, 2003). Thusly, less emphasis has been placed on energy efficiency as a mean of cost reduction; still, there are unique benefits of a more energy efficient production, when compared with other cost-reduction strategies, such as reducing energy consumption does not generally have a direct effect on the product quality or yield (i.e., production rate). Hence and in addition to being quality/ quantity-neutral, the improved energy consumption can lead to better certainty in terms of production costs, and consequently in more predictable earnings predictions and even more effective production planning. Additionally, reducing the energy consumption can lead consequently to lower harmful emissions, especially from factories in the USA. A number of regulatory policies have also been proposed to cap carbon emissions or fine companies with excess emissions. If such policies are adopted, then it will have a significant impact on the OEMs' strategies and assembly practices. Also, any increase or fluctuation in the electricity and/or fossil-fuel pricing will lead to fluctuations and a monetary impact on the manufacturing rates and plans.

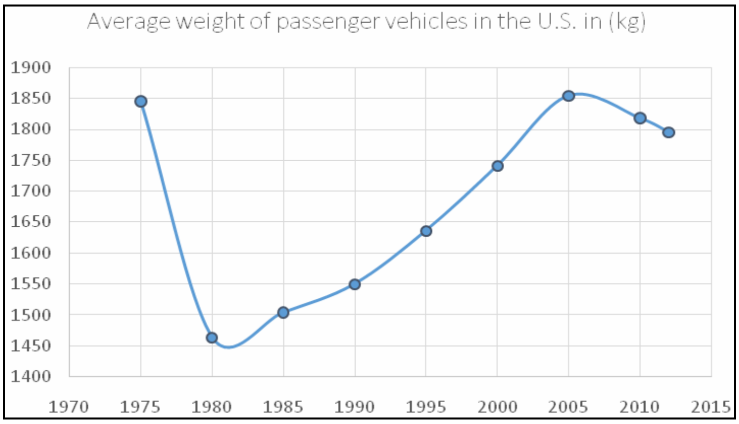
The aforementioned discussion may motivate a strategy supported with a systemic approach to help assess and benchmark the energy-expenditure trends among different automotive production facilities. This is done to help define potential best practices and opportunities for energy savings specific to the automotive industry. This strategy can be done based on two perspectives; a facility-specific (changes within one unique facility over time and production plans), or as an industry-specific exercise; the research from Omar et al. (2015) presented one potential approach to target a single/unique facility energy expenditures and its potential improvements using a hybrid (continuous and discrete) simulation effort, while Zhu et al. (2015) presented the addition of a linear programming algorithm to help drive an optimisation loop to identify a best case scenario (in terms of energy-mix among following resources: landfill gas, natural gas, and electricity from the grid).

The industry-specific energy analysis or benchmarking efforts can be classified per studies from the American Council for an Energy Efficient Economy (ACEEE) by Patil et al. (2003) and Boyd (2003), into two parts: the long-term energy forecasting (LIEF) methods and the environmental protection agency (EPA) energy performance indicators (EPI). The LIEF methods focus on market solutions to achieving 'best practices' in energy consumption, by assuming that the energy intensity can be modelled as a function of the market energy prices (Ross and Thimmapuran, 1993); furthermore, the LIEF collects its data sets from an entire industrial sector. On the other hand, the EPI highlights the technical aspect through specific solutions that uses plant level data. The EPI approach might be more useful for the proposed study, in providing specific, plant level energy consumptions. In essence, LIEF assumes that the difference between average performers and best practices is based on energy prices, while EPI assumes the difference to be of technical nature.

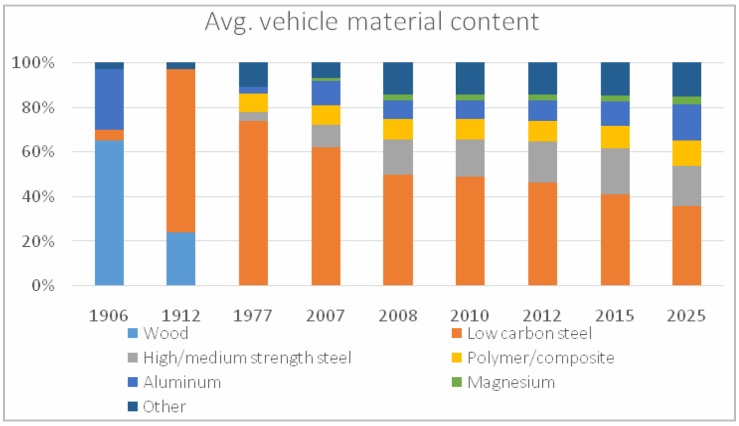
The automotive industry specific EPI was developed by the Lawrence Orlando Berkley National Lab (LBNL) in 2005, with focus on the energy inputs as defined through the study by Galitsky and Worrell (2003), which used survey data from a focus group that included 35 facilities comprising 104 observations. Still, the analysis (per collected data) is limited to US assembly operations. Also, the scope of the EPI is limited to plant-level performance, i.e., not process-specific, while it excludes the stamping or the panel-forming energy expenditures, which according to a study conducted by the Automotive Parts Manufacturers' Association (APMA), accounts to nearly 19% of total energy consumption in the manufacturing of vehicles, (APMA, 2000).

The current text quantifies the specific (i.e., per vehicle) electric or (kWhr/vehicle) and the specific fossil-fuel or (MMBtu/vehicle) energy expenditures for two light-weight design criteria: the maximum weight saved per minimum cost added, and the maximum total weight saved. The novelty of presented analysis provides useful information about the impact of the lightweight engineering decisions on the manufacturing energy requirements, which might aid in highlighting the manufacturing variables involved in the total life-cycle of an automobile. This is becoming an important issue, because most of the automotive OEMs are focusing on lightweight engineering efforts to prepare for potential changes in the corporate average fuel economy (CAFE) standards. Also, most of the lightweight engineering designs are based on replacing steel with aluminium and other light alloys and composites, which typically tend to have higher, but yet un-quantified manufacturing energy signature. This trend is clear in the material break-down difference between 1975 vehicles and today's vehicles, where average passenger vehicle weights declined from about 4,000 lb (~1,800 kg) in 1975 to less than 3,200 lb (~1460 kg) in 1982, where the OEMs tried to use less steel in the vehicles, see Figure 1(a), Over the same time period. The amount of Al used in a typical US passenger vehicle increased from about 3% in 1977 to about 12% today (US EPA, 2009). The average vehicle weight has increased again where it reached about 4,150 lb (~1,890 kg) in 2008 (US EPA, 2009). Today, the typical US family vehicle weighs about 1,400 kg (3,080 lb) (Mcauley, 2003), with iron and steel accounting for the majority of this weight, as displayed in Figure 1(b). However, the new trends in vehicle light-weighting aim at enhancing the vehicle fuel efficiency as well as improving its driving performance while lowering its emissions (Mayyas et al., 2013). A general rule of thumb says that a 10% reduction in vehicle weight translates into a 5%–7% increase in its fuel economy in terms of miles per gallon (MPG) (Cheah et al., 2009; Carlson et al., 2010).

Figure 1 (a) Light duty vehicle weight trends for model years 1975 to 2012 (b) Historical trend in vehicle composition (see online version for colours)



(a)



(b)

Source: (a) Several reports from United States Environmental Protection Agency, (http://www.epa.gov)
(b) Lutsey (2010a)

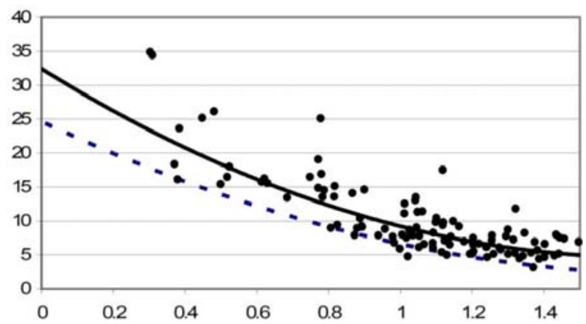
Further, the interest in vehicle structures with Al percentages of > 30% (of the vehicle total weight) is being renewed as in Stodolsky et al.'s (1995b) study of aluminium intensive vehicles (AIV).

To assess the actual manufacturing energy requirement for each of the design criteria, the text constructs a model that is process specific and includes the stamping and forming operations. This is done in two steps: the first extracts the actual energy requirement from the EPI index as (kWhr/vehicle), and (MMBtu/vehicle) for the welding, painting, final assembly and HVAC; while the second step computes the panel forming energy requirements for steel and aluminium panels. Additionally, the study provides the cost analysis for each of the two designs' major panels. The manuscript structure starts by introducing the EPI stochastic and the look-up computation in Section 2, while Section 3 addresses the correlations and assumptions used to predict the forming energy requirements of the reverse-engineered BIW in automotive stamping and blanking lines. Section 4 discusses the proposed methodology within the context of previous studies and proposals. Finally the conclusion summarises and discusses the findings, recommendations, and future work.

2 Specific energy requirements from the EPI model

In brief, the EPI is designed as an assessment tool that provides a percentile ranking of an automotive manufacturing facility, when compared with the best practices in the industry. The main inputs to the EPI interface are the annual energy expenses, the line speed, the vehicle wheelbase, and the plant location. The plant location is used in conjunction with data from Energy Star ®, which describes the total number of days and degrees a facility's HVAC systems will be required to heat or cool the building, the HDD and the CDD respectively, which are taken from the same data used by Energy Star to rate energy performance of commercial buildings.

Figure 2 CLOS approach to stochastic frontier regression (see online version for colours)



Greene (2005) described the stochastic frontier regression, wherein a standard regression curve of the form shown in equation (1) would presume that any deviation from the curve is a result of random and normally distributed error, *ε*. However, stochastic frontier regression assumes that deviation from the 'best practices' curve is primarily due to inefficiency, *u*, in the process being described. This principle is used in the EPI ranking system, and is further pictorially illustrated by Figure 2 in which the solid line represents a standard least squares regression curve while the dashed line represents a corrected ordinary least squares (COLS) approach to stochastic frontier regression. Hicks and Dutrow, (2001) used this approach in deciding on the average and the best practices for the milk and the beverage industries. Furthermore, using this approach enables the inefficiency of a manufacturing process to be described mathematically by equation (2).

$$E_i = \alpha + \beta y_i + \varepsilon_i \tag{1}$$

$$u_i = E_i - Y_i \times \left(h\left(I_i, \beta\right) + \vartheta_i\right) \tag{2}$$

where u_i is the process inefficiency, E_i is the energy consumed, Y_i being the annual production, h is frontier specific energy use (kWhr/vehicle) which is a function of I_i the system inputs and β a coefficient vector to be estimated, and finally ϑ_i is the noise in data set.

For the purpose of developing a percentile ranking, inefficiency must be assumed to follow some statistical distribution, which yields an EPI score given by equation (3); where P is the probability that energy use is greater than the 'best practice' level and F is the probability density function for some appropriate one-sided distribution for inefficiency.

$$P = \left[u_i \geq E_i - Y_i\left[h\left(I_i, \beta\right) + \vartheta_i\right]\right] = 1 - F\left({E_i}/{Y_i} - \left[h\left(I_i, \beta\right) + \vartheta_i\right]\right) \tag{3}$$

This study used a gamma distribution to describe the inefficiency and hence predict the energy consumed per vehicle (kWhr/vehicle) from the EPI model. The result of this statistical analysis yielded two equations for electricity and fossil fuel consumption as described mathematically in equations (4) and (5) respectively; with the *WBASE* being the wheelbase of the vehicle, and the *Util* is the facility utilisation.

$$\begin{aligned} {E_i}/{Y_i} &= A + \beta_1(WBASE) + \beta_2\left(HDD_i\right) + \beta_3\left(HDD_i^2\right) \\ &+ \beta_4\left(Util_i\right) + \beta_5\left(CDD_i\right) + \beta_6\left(CDD_i^2\right) + u_i - \vartheta_i \end{aligned} \tag{4}$$

$$\begin{aligned} {F_i}/{Y_i} &= A + \beta_1\left(WBASE_i\right) + \beta_2\left(HDD_i\right) + \beta_3\left(HDD_i^2\right) \\ &+ \beta_4\left(Util_i\right) + \beta_5\left(Util^2\right) + u_i - \vartheta_i \end{aligned} \tag{5}$$

The complete β_i coefficients for both equations can be found in Table 2 from Boyd (2005). Here, the utilisation is simply defined based on a capacity to actual production volume for a seven hour shift, two shifts per day, and 244 working days per year. Additionally, the current text established a lookup algorithm to identify the energy inefficiency associated with the EPI rank value as supplied by the user. The combination of EPI 'best practice' energy use and inefficiency, form the specific energy consumptions; E_i/Y_i (kWhr/car) and F_i/Y_i (MMBtu/vehicle), for the process being evaluated.

Table 1 Material break-down in generic automobile, (kg)

Material	*ca. 1950s automobile*	*ca. 1990s automobile*
Plastics	0	101
Aluminium	0	68
Copper	25	22
Lead	23	15
Zinc	25	10
Iron	220	207
Steels	1,290	793
Glass	54	38
Rubber	85	61
Fluids	96	81
Other	83	38
Total weight	1,901	1,434

Table 2 Electricity model estimates

$\beta_{Elec.Estimate}$	$\beta_{Fossil.Estimate}$
$\beta_{Constant} = 369.39$	$\beta_{Constant} = 3.82$
$\beta_{WBASE} = 2.77$	$\beta_{WBASE} = 3.22E\text{-}02$
$\beta_{HDD} = -18.11$	$\beta_{HDD} = -0.544$
$\beta_{HDD^2} = 4.79$	$\beta_{HDD^2} = 0.1099$
$\beta_{Util.} = 138.61$	$\beta_{Util.} = -6.78$
$\beta_{CDD} = -59.32$	$\beta_{Util.^2} = 2.39$
$\beta_{CDD^2} = 41.91$	

Source: Boyd (2005)

The proposed look-up function in this study operates on the EPI database by scanning its inefficiency tables, searching for a match of the plant rank and zip code. Then, the code computes the specific electric and fossil fuel energy consumptions using equations (4) and (5) respectively. The proposed search subroutine also extracts the CDD and HDD from the *Energy Star* database and decides on the data error using a statistical model. Additionally, the HVAC consumption was further analysed in proposed subroutine to correlate the production data with the outdoor air temperature using current multi-variable tools such as the lean energy analysis (LEA) from Kissock and Seyak (2004), and Kissock and Eger (2006).

Also, the macro converts the fossil fuel consumption F_i/Y_i (MMBtu/vehicle) into the total specific energy to be represented in (kWhr/vehicle), which is useful in translating the consumption into CO_2 emissions, as will be discussed in section 4.

3 Panel forming energy

The specific energy extracted from EPI does not include the panel-forming expenditures. This section addresses the panel forming energy consumptions for both Al and steel coils using current automotive press-lines, which include energy consumed in; blanking, bending, deep drawing, trimming and stripping, as described mathematically in equation (6):

$$E = (1+\alpha)\sum_{k=1}^{m} E_k \tag{6}$$

where E is the total energy consumed in (MJ), α being the rejection rate, m the number of processes (blanking, drawing, trimming, etc.) for each component and E_k is the energy consumed per process, which is further described in equation (7):

$$E_k = n \cdot F_k \cdot \beta \cdot \frac{t}{a} \tag{7}$$

where n is the number of shots required in making the component; F_k the force required doing cutting, blanking, bending, deep drawing and stripping, β is press velocity (constant), t is the time taken for the operation, and a is the number of parts per shot or the number of die cavities.

Finally, the force required for each operation is computed using equation (8):

$$F_k = L \cdot th \cdot s \tag{8}$$

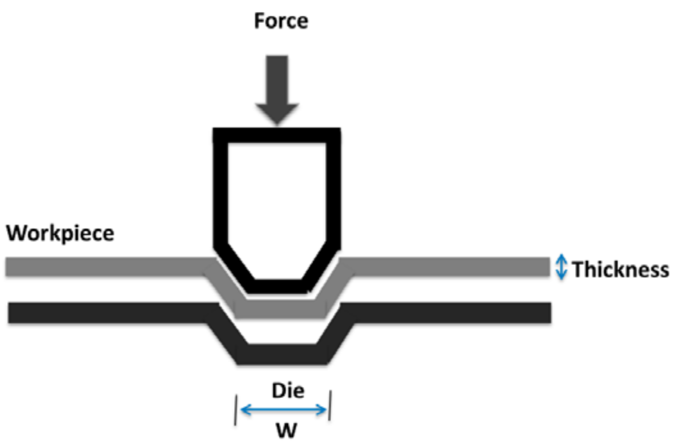
where L is length of the cut (for trimming), or the length of draw (for drawing), th is the panel thickness, and s is the material strength (shear for cutting, yield for drawing).

Another equation to estimate forming force is:

$$F = \frac{L \cdot th^2}{W} UTS \tag{9}$$

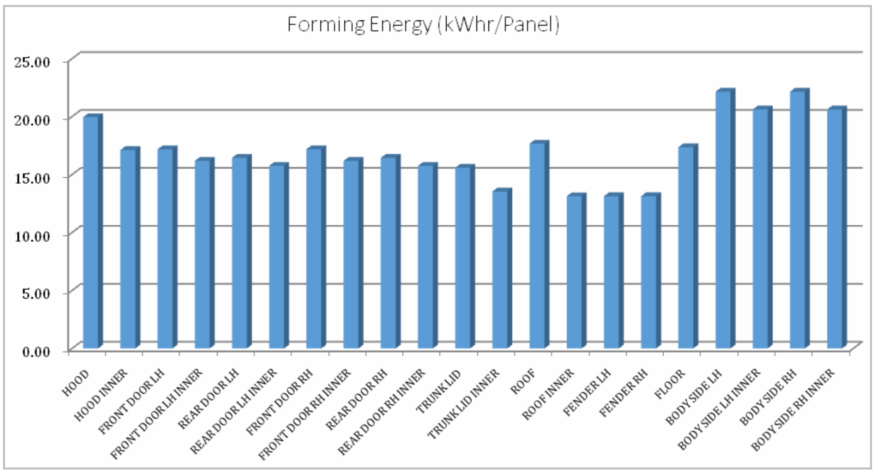
where th is sheet thickness, W is the width of die opening, L = total length of bend, and UTS = ultimate tensile strength of material (see Figure 3 for illustration).

Figure 3 Illustration of the forming force in sheet metal forming (see online version for colours)



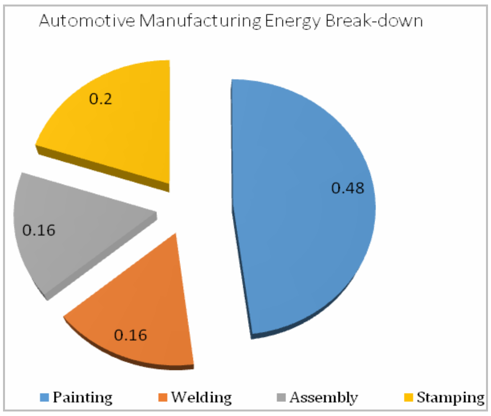
To calculate the total forming energy for the BIW panels, a passenger vehicle structure is scanned using a *Pro-T* ® Zeiss coordinate measuring machine (CMM), to retrieve each of the major body panel dimensions. A typical BIW consists of around 400–500 stamped panels however following panels govern the body design and consume the majority of the forming energy; body-side outer, hood inner and outer, trunk inner and outer, roof inner and outer, door inner and outer panels, under-body, and finally the fenders. Equation sequence (6) through (8) is run for each of the above panels, considering the number of operations, panel dimensions and thickness, in addition to the actual die and press used for each one. A typical 1% rejection rate is set for steel and 3% for aluminium due to its lower *n*-value and narrower deformation window. The number of forming and piercing stations is set based on the part complexity and final shape, to accommodate any post-draw needed to counter any expected spring-back. Also, the forming model distributes the energy consumption of the press mechanical losses and non-value added work on the different panels. A draw quality (DQ) cold rolled carbon steel and 5,052 Al are used for the panels. Figure 4 shows an example calculation for the DQ steel grade, displaying the different components comprising the BIW. To validate the proposed model, the total energy computed to form an Al BIW is found to be 1,220 MJ/vehicle and for a steel BIW around 967 MJ/vehicle, which is comparable with the results of the International Iron and Steel Institute (IISI) energy audit in 1994 (IISI, 1994) for stamping Al and steel BIWs, IISI results are: Al around 1,200 MJ/vehicle and for steel around 1,000 MJ/vehicle. Even though Al has lower yield strength, its lower *n*-value increases the number of shots required to make the same shape, when compared with steel, in addition to a higher spring-back, thus increasing its forming energy requirements.

Figure 4 Forming energy distribution for each major body-panel when made from DQ steel (see online version for colours)

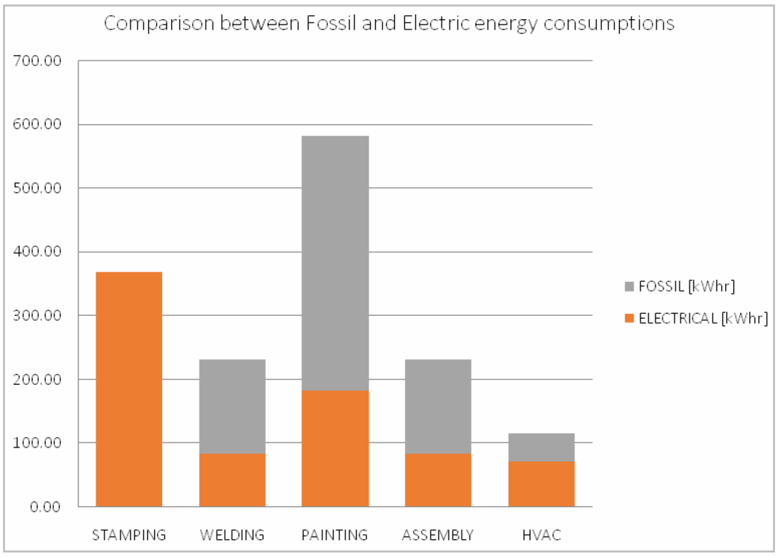


Combining the panel forming model with the look-up macro into a unified code can provide useful insights on the automotive manufacturing energy break-down, as displayed in Figure 5(a) and the energy type in Figure 5(b). Such analysis reveals processes or practices that should be targeted for energy saving efforts. From this study, a complete steel BIW will consume around 600 kWhr/vehicle, while a complete Al BIW consumes around 820 kWhr/vehicle.

Figure 5 (a) Total energy break-down within an automotive manufacturing plant (b) Total energy break-down and the expended energy type (see online version for colours)



(a)



(b)

To further illustrate with an example, the presented results can be further viewed as a sensitivity plot (of ±20% changes) as in Figure 6, to show the impact of the vehicle design options on the total forming energy. From Figure 6, one can see that from a product perspective, designing vehicles with smaller size (i.e., less surface area), thinner panel thickness, and less complicated features (less draw depth, and fewer shots) can result in lower manufacturing energy consumption cost, also increasing the stamping lines utilisation can further reduce the energy consumed per part.

Figure 6 Sensitivity analysis for forming energy perspective, +/– 20% changes (see online version for colours)

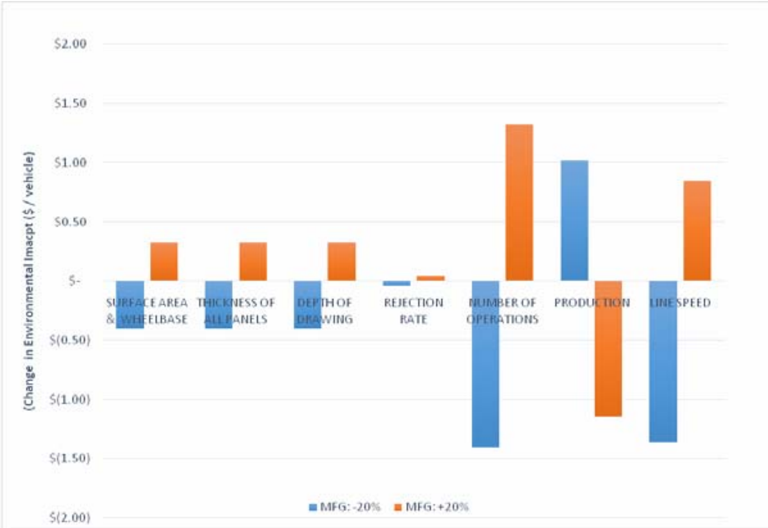
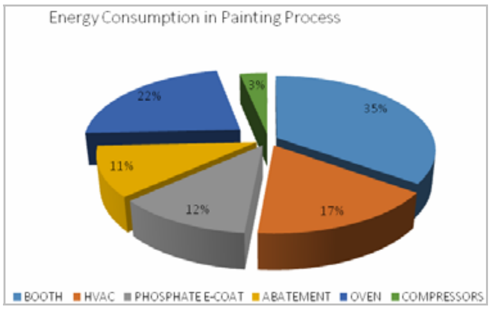
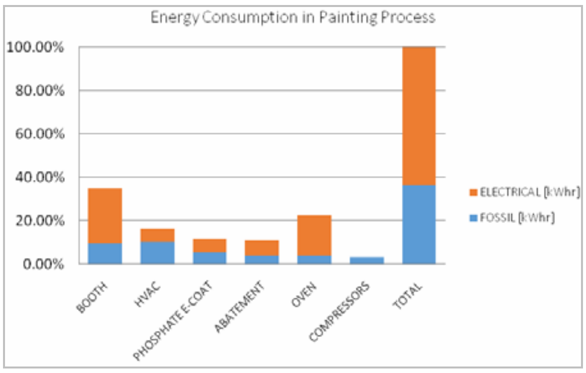


Figure 7 (a) Energy break-down within an automotive painting booth (Klobucar, 2004)
(b) Energy break-down within an automotive painting booth, showing fossil and electric portions (see online version for colours)



(a)



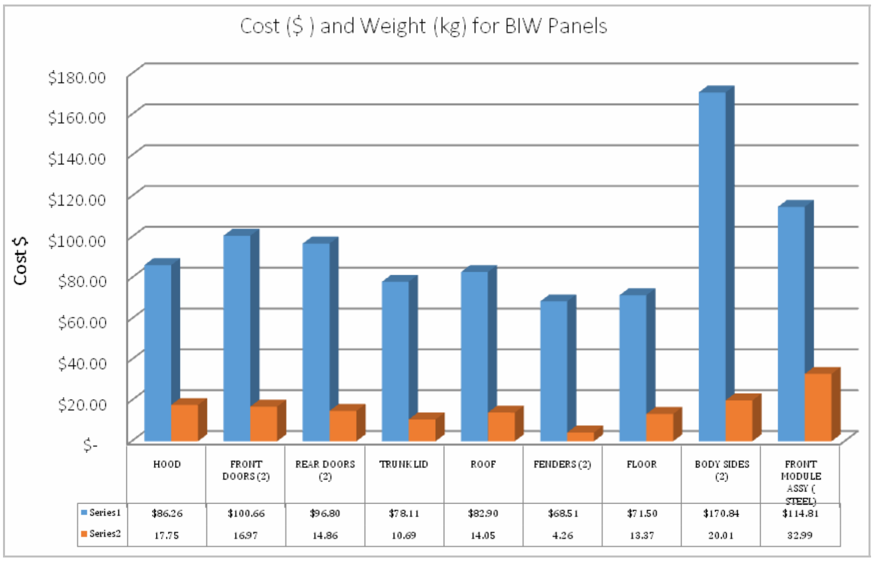
(b)

For the painting booth energy break-down, Klobucar (2004) proposed Figure 7(a) to show the energy break-down for each operation within the booth, also from our study Figure 7(b) displays the detailed energy type for the different painting operations. Such information is very useful to guide energy savings efforts and to help evaluate certain environmental decisions and their effects on the plant EPI ranking.

4 Hybridised structures selection and energy implications

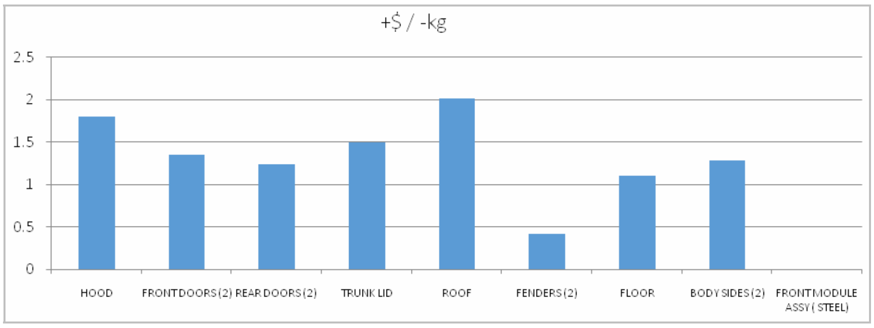
In section 2 and 3, the total energy consumed per vehicle is computed for all assembly operations; this section decides on the energy consumption for each of the two hybridised mixtures of the 5,052 Al and DQ steel. In either design, the front module will be made of steel due to functional requirement and other manufacturing complexities. Also, the thickness of the new Al panels is selected based on available coil thicknesses and the weight to strength ratio required for each panel function, mainly durability and crash worthiness.

Figure 8 Cost and weight information for each body-panel, DQ steel case (see online version for colours)



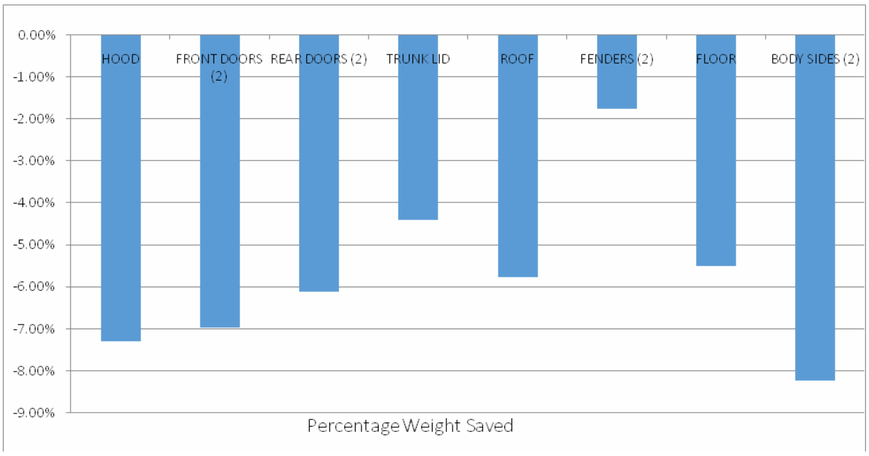
For the first criterion, the total cost associated with material purchase and fabrication per panel, is first computed. The cost consists of the material cost, the fabrication cost, and the overhead cost. Figure 8 combines the cost and weight information for each panel, when fabricated from DQ steel; combining the cost and weight information for Al results in Figure 9, which that shows a cost increase in $ per kg saved for each of the panels if made from Al. This figure indicates that replacing the fenders has the best savings. This is consistent with the current trend in the industry where OEMs have replaced the steel fenders with plastic ones as in the case of the BMW X-series.

Figure 9 Cost added per kg saved for each panel, when replacing DQ with Al (see online version for colours)



The cost calculations adopted an 4.8:1.0 ratio between the Al and the DQ material prices, in addition to the added cost in spot welding and joining Al panels. For the second criterion, the weight of each panel if made from Al is subtracted from its original steel weight and then divided by the total steel BIW weight, to generate Figure 10, which indicates that the highest weight savings around 8% will be when replacing the body-side outer. However, stamping the body side out of Al is not practical due to the different complicated geometries involved. So, an Al hood is selected for the second hybridised BIW. This selection also agrees with current commercial examples, as in the case of the Toyota Crown and the BMW X-series, both having Al hoods.

Figure 10 Percentage weight saved of total weight, when replacing panels of DQ with Al (see online version for colours)



The specific energy for each design, all steel BIW with Al fenders and all steel BIW with Al hood, can be computed to show the manufacturing energy implication. The Al fender design adds around +10 kWhr/vehicle, while the Al hood design adds around +15 kWhr/vehicle. Furthermore, new design criteria might include the specific energy in the form of (+kWhr/vehicle/–kg) for future designs. This analysis allows for incorporating the manufacturing energy-efficiency in light-weight engineering decisions. Using such criterion, the Al hood design allows for +15 kWhr/vehicle per –10.57 kg saved in other words around 1.42 kWhr/vehicle/kg, while the Al fender design adds around 3.55 kWhr/vehicle/kg, which makes the Al hood design three times more energy efficient. To further describe the advantages of the new proposed criteria, one can study the emission implications of the added energy consumption, using such conversion tables from Newell (1998). The data is included here in Table 4, which shows the conversion of the consumed energy into the emission species controlled and monitored by the EPA and termed as ‘criteria air pollutant’. For the case of CO_2, the results are in agreement with a CO_2 audit reported in Peters (1997). Furthermore, each species’ impact can be quantified in terms of dollar amount following the studies reported by Hohmeyer and Ottinger (1992), Zuckerman and Ackerman (1995) and Rowe (1995), which facilitates the conversion of (+kWhr/vehicle/–kg) into (+$/–kg) as in Table 5. Using the information from Tables 4 and 5 for each design option can show that the Al fender design adds $34,000 worth of environmental damage per year, while the Al hood option adds $45,000 per year; these values do not include the extra cost of energy. Even though the added environmental damage is not significant, when compared with production sales, still it highlights each design monetary impact, which might be implemented in the form of a governmental fine or added tax.

Table 3 Conversion of electric kWhr into EPA pollutants

Pollutant	*Kg/kWhr*
CO_2	0.609
CO	1.9E-04
NOx	8.8E-04
SOx	4.0E-04
PAH	4.7E-08

Table 4 Conversion of EPA pollutants into dollar amount

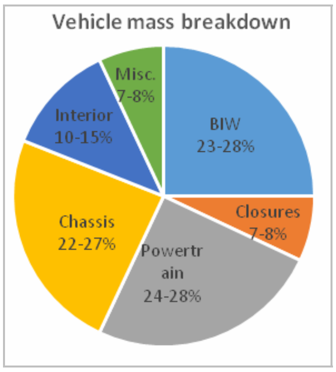
Pollutant	*Base value $/kg*
CO_2	0.014
CO	0.001
NOx	3.055
SOx	13.32
PAH	243.0

Table 5 Selection of environmental indices, ELU/kg

Raw material	*ELU/kg*
Co	76
Cr	8.8
Fe	0.09
Mn	0.97
Ni	24.3
Pb	180
CFC-11	300

Source: Steen and Ryding (1992)

Table 6 Vehicle mass breakdown by system and components (see online version for colours)

System	*Mass breakdown*‡	*Major components*
BIW		Compartment frame, fenders, cross and side bars, roof, front and end structures, floor pan, A, B, C-pillars
Closures		Front and rear doors, hood, and trunk lid
Powertrain		Engine, transmission, exhaust system, fuel tank
Chassis		Chassis, suspension, tires, wheels, steering system, brakes
Interior		Seats, instrument panel, trim, air bags, entrainment system
Miscellaneous		Electrical, lighting, air conditioning system, windows

Note: ‡Based on Stodolsky et al. (1995a), Bjelkengren (2008) and Lotus Engineering (2010) the actual system definitions and system component inclusion can vary, and percentage weight breakdown can vary substantially by vehicle.

Source: Lutsey (2010b)

Table 7 Potential weight reduction vs. steel

Material	*Body*	*Enclosures*	*Chassis*
High strength steel	25%	15%	25%
Aluminium	40%	45%	50%
Magnesium	55%	55%	60%
Polymer composites			
Carbon	> 60%	> 60%	60%
Glass	25%	25%	35%
Titanium	NA	NA	50%
Metal matrix composites	NA	NA	60%

Source: Carlson et al. (2010)

The focus on the BIW in current study for lightweight savings is justified through two main facts; firstly the BIW accounts for the main part of vehicle's curb weight; secondly the BIW has the vast potential of weight savings if compared to other systems like powertrain or chassis. Table 7 summarises the potential weight reduction opportunities upon replacing conventional steel in a mid-size passenger car with other lighter materials. Moreover, more examples of lightweight designs made by several OEMs are summarised in Table 8.

Table 8 Component weight-reduction potential

Vehicle system	*Subcomponent*	*New material or technique*[a]	*Weight reduction (lb)*[b]	*Example automaker (models)*[c]
Powertrain	Block	Aluminium block	100	Ford (Mustang); most vehicles
	Engine, housing, etc.	Alum-Mg-composite	112	BMW (R6)
	Engine	Smaller optimised moulds (Al)	55	Toyota (Camry)
	Valve train	Titanium intake valves	0.74	GM (Z06)
	Connecting rod (8)	Titanium	3.5	GM (Z06); Honda (NSX)
	Driveshaft	Composite	7	Nissan; Mazda: Mitsubishi
	Cradle system	Aluminium	22	GM (Impala)
	Engine cradle	Magnesium	11.0–12.0	GM (Z06)
	Intake manifold	Magnesium	10	GM (V8); Chrysler
	Camshaft case	Magnesium	2	Porsche (911)
	Auxiliaries	Magnesium	11	Audi (A8)
	Oil pan	Modular composite	2	Mercedes (C class)
	Trans. housing	Aluminium	8	BMW (730d); GM (Z06)
	Trans. housing	Magnesium	9–10	Volvo; Porsche (911); Mercedes; VW (Passat); Audi (A4, A8)
Body and closures	Unibody design	Vs. truck body-on-frame	150–300	Honda (Ridgeline); Ford; Kia; most SUV models
	Frame	Aluminium-intensive body	200–350	Audi (TT, A2, A8); Jaguar (XJ); Lotus; Honda (NSX, Insight)
	Frame	Aluminium space frame	122	GM (Z06)
	Panel	Thinner Al-alloy	14	Audi (A8)
	Body	Panel composite	42	BMW
	Closure doors (4)	Aluminium-intensive	5–50	Nissan (370z); BMW (7); Jaguar (XJ)
	Doors (4)	New production process	86	Porsche (Cayenne)
	Door inner (4)	Magnesium	24–47	
	Hood	Aluminium	15	Honda (MDX); Nissan (370z)
	Roof	Aluminium	15	BWW (7 series)
	Lift gate	Magnesium	5–10	

Notes: [a]These technologies can include a change in design, a reduction in parts, a reduction in material amount, and use of various metallic alloys; note that weight (lb) and mass (kg) variables are used in this report. 1 kg = 2.205 lb.
[b]Weight reduction estimates are approximate, based on media sources and technical reports
[c]A number of these models are not available in the USA; some model names have changed in recent product changes

Source: Lutsey (2010b)

Table 8 Component weight-reduction potential (continued)

Vehicle system	*Subcomponent*	*New material or technique*[a]	*Weight reduction (lb)*[b]	*Example automaker (models)*[c]
Suspension and chassis	Chassis	Aluminium	145	Porsche (Cayenne)
	Chassis	Hydroformed steel structure, tubular design	100	Ford (F150)
	Steering wheel	Magnesium	1.1	Ford (Thunderbird, Taurus); Chrysler (Plymouth); Toyota (LS430); BMW (Mini); GM (Z06)
	Steering column	Magnesium	1–2	GM (Z06)
	Chassis wheels (4)	Magnesium	26	Toyota (Supra); Porsche (911); Alfa Romeo
	Wheels (4)	Lighter weight alloy, design	13	Mercedes (C-class)
	Brake system	Heat dissipation, stainless steel pins, Al caps	30	Audi (A8)
	Tires	Design (low RR)	4	Mercedes (C-class)
	Suspension	Control arms (2)	6	Dodge (Ram)
Interior	Seat frame (4)	Magnesium	28	Toyota (LS430); Mercedes (Roadster)
	Instrument panel	Magnesium	7–13	Chrysler (Jeep); GM; Ford (Explorer, F150); Audi (A8); Toyota (Century); GM
	Dashboard	Fibre-reinforced thermoplastic	18	VW (Golf)
	Console and shifter	Injection moulded GFRP	5	Ford (Flex)
Misc.	Windows	Design, material thickness	3	Mercedes (C-class)
	Running board	GFRP	9	Ford (Escape)

Notes: [a]These technologies can include a change in design, a reduction in parts, a reduction in material amount, and use of various metallic alloys; note that weight (lb) and mass (kg) variables are used in this report. 1 kg = 2.205 lb.
[b]Weight reduction estimates are approximate, based on media sources and technical reports
[c]A number of these models are not available in the USA; some model names have changed in recent product changes

Source: Lutsey (2010b)

4.1 The cost of vehicle weight reduction

It is worth mentioning that for accurate costing and comparison of lightweight material options, the analysis should include initial material cost and expected savings over the average vehicle lifetime. Another potential costing methodology can be process-based as in Cheah (2010).

Table 9 Some lightweight projects with their corresponding cost impacts

Project	*Mass reduction*	*Cost impact*
Porsche engineering UltraLight steel auto body's-advanced vehicle concept (ULSAB-AVC)	Body: 17% (52–67 kg) Vehicle: 19%–32% (200–260 kg)	The total estimated manufactured cost of the mass-optimised vehicles is found to be about \$9,200 to \$10,200 per vehicle. Mass-optimised vehicle designs using high-strength steels had very tiny cost increment (or even had resulted in some savings). Estimated cost impact per unit mass is ranging between \$0.47–1.0 per kg.
Altair SUV frame	Body: 23%	Study showed very small estimated cost impact \$0.68 per kg at high production volumes (220,000 vehicle per year).
Volkswagen AG	Body: 101 kg	Volkswagen estimated the incremental cost of the new mass-optimised high strength steel body to be around \$13 per kg at a production volume of 1,000 vehicle/day.
ThyssenKrupp new steel body	Body: 24%	The ThyssenKrupp steel body design resulted in a 24% body mass reduction, with potential for secondary mass reductions from design optimisation elsewhere on the vehicle. This mass saving had increased manufacturing cost about 2%.
IBIS aluminium-intensive design	Body: 48% Vehicle: 17%	Aluminium body has a \$500–600 cost increase in relative to the steel body (22% increase) with an additional cost of \$100 (1% increase) over conventional baseline vehicle retail price as a direct result of powertrain re-sizing and secondary mass reductions, for a vehicle that had its mass reduced by 17% from its baseline steel-intensive vehicle.
EDAG steel-intensive future steel vehicle	Body: 16%–30% Vehicle: 17%	This project investigated the new mass-optimised body in association with different powertrains (e.g., hybrids and plug-in electric vehicles) and found that the total cost of ownership can be improved significantly as a direct result of the reductions in fuel consumption and other benefits that offset mass-reduction and powertrain costs.
Magnesium-intensive body	Body: 49% reduced part count (–78%) along with reduced mass (–161 kg)	Increased variable cost (3%), decreased investment cost (–46%) Volkswagen-led

Notes: [‡]OEM cost is estimated from Toyota Venza, the baseline vehicle, retail price (MSRP) of \$24,000, assuming markup of 1.4x.
[‡‡]This estimate is the difference in raw material cost only.

Source: Lutsey (2010b), Cheah et al. (2009), Cheah (2010), IBIS Associates Inc (2008) and Dieffenbach et al. (1996)

Table 9 Some lightweight projects with their corresponding cost impacts (continued)

Project	*Mass reduction*	*Cost impact*
Super light car	Body: 14%–39% (40–109 kg)	Project was conducted in the period 2005 to 2009 and funded by European Commission (10.5 € million) while other companies shared another 8.7 € million. Companies involved included Volkswagen, Fiat, Daimler, Porsche, Renault, Volvo, and Opel. This consortium of companies developed and demonstrated a multi-material concept approach, including design, materials, and manufacturing routes. A multi-material vehicle was produced which consists of 53% aluminium, 36% steel, 7% magnesium, 4% fibre-reinforced plastic. This study found major reductions (32%–42%) in all major body-in-white components (body, front end, floor). Other designs were also investigated like the steel-intensive vehicle which achieved a mass reduction of 40 kg (14%) and less than 2.5 €/kg; several multi-material vehicle designs were also produced and achieved mass reductions of 62–114 kg (22%–39%) with an estimated cost of 5–10 €/kg.
Lotus engineering low development	Body: 16% (58 kg) Vehicle: 20% (336 kg)	Lotus engineering investigated several multi-material designs and achieved weight saving of 21%–38% in a crossover utility vehicle by using high-strength steel, aluminium, magnesium, and composites, and by eliminating or consolidating of some auto-body parts. For example, Lotus got a cost decrease of $60/vehicle (18%) through use of advanced steel alloys in the body. This cost saving also resulted in another $300/vehicle (2%).
Lotus engineering high development	Body: 42% (162 kg) Vehicle: 33% (560 kg)	Mass-optimised body using multi materials like high strength steels, aluminium, magnesium and composites throughout the vehicle in association with consolidation of some parts. Lotus is focusing now on the second phase of the project that called high development vehicle for model year 2020 production, which will have a nominal estimated cost increase of 3% (with potential for cost reduction).
Composite-intensive body	Vehicle: 68–444 kg	Several mass optimised body designs were investigated and found that mass reductions up to 400 kg are achievable upon replacing conventional steel by plastic composite materials especially in the vehicles' body. Cost associated with composite materials in the vehicles are relatively high and could increase cost by $2.2–13.68 per kg saved depending on the size, shape, material and manufacturing processes used to make these parts.

Notes: ‡OEM cost is estimated from Toyota Venza, the baseline vehicle, retail price (MSRP) of $24,000, assuming markup of 1.4x.
‡‡This estimate is the difference in raw material cost only.

Source: Lutsey (2010b), Cheah et al. (2009), Cheah (2010), IBIS Associates Inc (2008) and Dieffenbach et al. (1996)

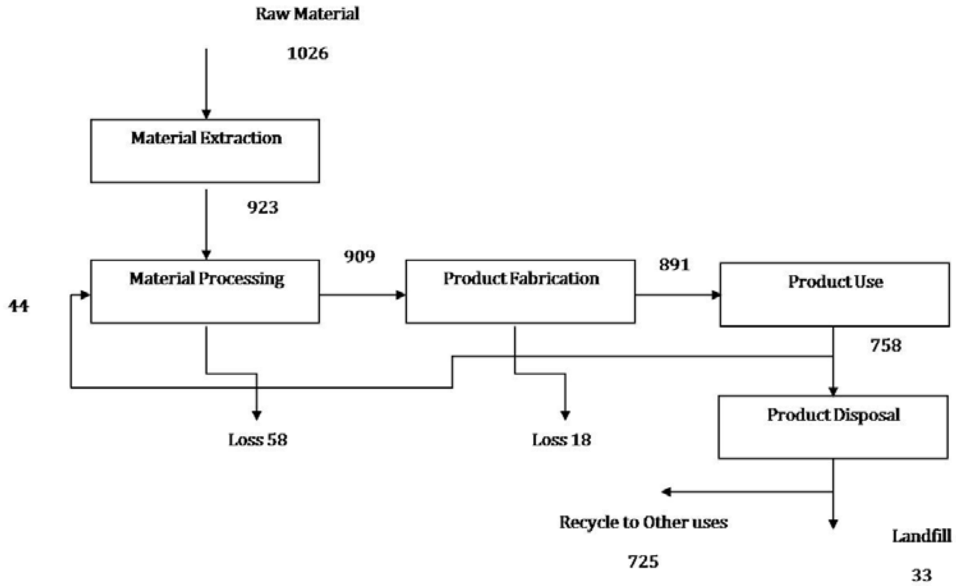
In general the incremental cost per unit weight savings can be achieved by replacing conventional steel grades by high strength steel (HSS) followed by aluminium and potentially polymer composites. Automotive parts made from composite materials are still expensive given high raw material prices and long production cycle times (Cheah, 2010); this may mean that HSS and Al might remain the popular candidate lightweight materials to replace steel in passenger vehicles in the near-term. Table 9 shows some of lightweight projects and their corresponding manufacturing costs in terms of dollars spent per unit mass saved (included here for completeness). While most of these case studies focused on the auto-bodies, some projects aimed to save some weight in other vehicle systems like powertrain and interior systems.

5 Proposed approach vs. other models and approaches

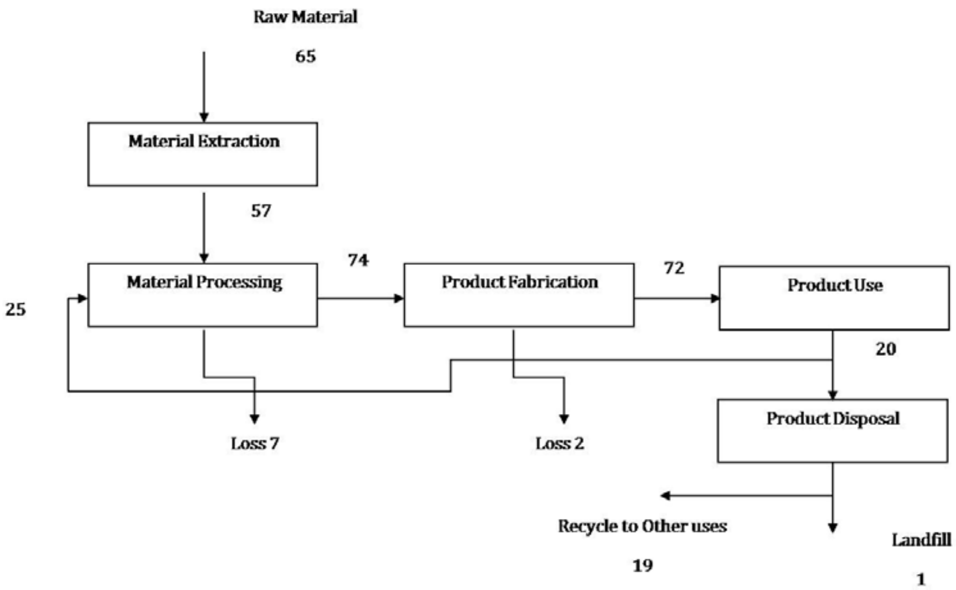
This section discusses previous efforts on incorporating the energy efficiency in design decisions for the automobile structure.

The Swedish Environmental Institute IVL proposed an analytical tool designated as the environmental priority strategy (EPS) for product design in 1992. The EPS as described by Steen and Ryding (1992) designates an environmental index to each type of material used or to be used in the automotive industry to allow designers to select materials and components with low environmental impact. The index is computed based on the material impact during product manufacture, use and disposal, which account to an environmental load unit ELU/kg of material. An example of such an ELU is shown in Table 5. Computing and summing the ELUs for the different parts within an automobile allows for the assessment of the complete vehicle impact. However, the EPS system is limited to its unit ELU, which is not standardised internationally limiting its acceptance. Additionally, the ELUs were computed by ecologists and material scientists, who assumed worst case scenarios of emission and focused on the raw material scarcity. Additionally, the ELU rating does not provide expected energy expenditures, which further complicates the economic calculations for the different design options. Finally, the EPS system requires a complete life-cycle perspective of the material used, which requires extensive studies each time a new material is added and can be cost prohibitive. In terms of materials scarcity one can use a material flow diagram to track the material losses within the different extraction, fabrication and end-of-life phases, as in the diagrams proposed by Ginley (1994) in Figures 11(a) and 11(b) for each steel and aluminium application in the automotive industry, respectively. However, using the material flows to evaluate design decisions for manufacturing energy-efficiency is complicated because of the difficulty in evaluating specific scrap rates; in addition, the recycling modes and energy requirements are different for different materials and at different stages. For example, Al can be recycled horizontally (i.e., same class use or product) but requires higher energy for smelting, while steel is recycled vertically (i.e., into lower class products) but at lower energy requirements. Also, following a material flow approach might motivate the usage of large number of materials to replace the less efficient ones, which typically tend to reduce the scarp rate but at the same time it complicates the recycling because of sorting, in addition it necessitates different fabrication technologies which might challenge standardisation or benchmarking efforts.

Figure 11 (a) Tracking steel for automobiles application (b) Tracking aluminium for automobiles application



(a)



(b)

Source: Ginley (1994)

Finally, the presented analysis of the emissions economic impact is only intended to address the manufacturing emission foot-print and not the complete life-cycle. Several published studies such as the IISI study (IISI, 1994) tackled the complete life-cycle emission analysis for steel and Al BIW designs. However, most of these studies do not include the manufacturing phase due to the highest emissions being in the refining, material extraction and product usage phases in addition to their focus on revolutionary BIW designs, i.e., ultra-light steel auto body (ULSAB) as the one reported in Roth et al., (1998) and aluminium intensive vehicles (AIV). Still, it is important to study the manufacturing foot-print, because it aids in designing or selecting between transitional BIW designs, i.e., traditional steel BIW with Al panels constituting low percentage of total weight (< 30%), which are the most common in the automotive industry for mass production purposes. Also, identifying the specific manufacturing foot-print is important for companies operating globally, under different governmental regulations and environmental taxation systems.

It is worthy to mention that the current study is meant to provide a focused coverage and accounting on the manufacturing phase only without 'the life-cycle' approach; several studies in this have been proposed to discuss methodical (vis structured decision making tools) approaches to sustainable material selection for BIW applications; such as the author work in Mayyas et al. (2011, 2014, 2013). Moreover, other published work presented a comprehensive and recent review of the accounting methodologies for the automobile sector as in Jasinskia et al. (2015) and some are more specific to carbon accounting as in Stechemesser and Guenther (2012).

6 Conclusions

The presented study provided a direct technical, process-based approach to analyse and compute the specific energy consumptions in: electric (kWhr/vehicle) and fossil-fuel (MMBTU/vehicle) units for fabricating a vehicular BIW, under two typically used design criteria (focused on light weighting). The study discussed and analysed the EPI stochastic model and complemented it with a gamma distribution function to extract production inefficiency values, and a look-up macro, to retrieve the actual energy consumption data; moreover the study used the plant location and the LEA approach to extract the air tempering expenditures of the facility, to help capture the overhead energy contribution. The presented calculations included a forming energy consumption model and coupled it with the aforementioned macro to compute the forming energy for both material options (steel and Al panels). The resulting analysis yielded the energy breakdown for the stamping process from a product perspective through a sensitivity plot. The presented sensitivity plot in this work can be used to quantify the potentials for energy savings via operational changes (utilisation, etc.). Moreover, the presented specific energy values computation across this text were converted into a new potential performance indicator that is (+kWhr/vehicle/–kg) for lightweight engineering designs. At the same time, the energy values were further turned into emission species with their associated environmental impact assessed in terms of monetary values. Future work will focus on incorporating a life-cycle perspective for each hybrid BIW design by incorporating the product-usage (miles per gallon) and the Al and steel material extraction and recycling stages. Furthermore, other material options might be included, such as plastics, which require modelling the energy consumption for an injection moulding process.

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