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An Empirical Study of the Energy Consumption in Automotive Assembly

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Abstract

An empirical study of the energy consumption of an automotive assembly line, under various scenarios and demand profiles is presented. With the use of simulation an automotive assembly line of an automotive Body-in-White (BiW) subassembly, the under-Body structure is studied. The production line is investigated in terms of energy consumption, both at a production cell and at a machine level. The study shows that by modelling an assembly line in advance and by including energy considerations, one can possibly save energy and cost.

Keywords: Energy Efficiency; Automotive Assembly Line

1. Introduction

The manufacturing community is concerned more and more about the production energy consumption both due to the constantly increasing energy cost and to the ecological burden related to the energy production and use [1, 2]. Energy efficiency has quickly become a top priority of both international and national policies [3, 4]. The great use of energy for industrial operations is responsible for significant CO2 emissions and thus, climatic changes [5, 6]. Taking into account that most of this energy in manufacturing is supplied in the form of electricity, and that about 66% of all electricity is generated through fossil fuels, it is fair to say that CO2 emissions resulting from manufacturing (also called carbon footprint of manufacturing) have a strong correlation with energy efficiency [7]. However, their impact is not proportional, since electricity is generated and consumed regionally, whereas CO2 emissions, have a global impact [8, 9].There may be unnecessary energy use in the industrial sector in the order of 20-40% [10, 11]. In EU-27, the industrial sector energy use for the years 2004-2005 was 324 Mtoe, namely 28 % of the total energy use [5]. Under this prism, all manufacturing processes need to be assessed in terms of their energy efficiency.

A research done in Sweden revealed that less than half of all production companies have a strategy for working with energy efficiency [3]. A particular problem is that current definitions of energy efficiency actually can be rather misleading [12, 13, 14]. Unander [4] for instance, describes how aggregate data show that the energy efficiency of manufacturing in 10 IEA countries increased during a certain period, but that decomposition of the data revealed that this was due to a structural shift to less energy-intensive branches rather than to an actual improvement of energy efficiency.

The total energy consumed during the complete life cycle of a car can be summarized into four main stages: Raw material processing, car manufacturing, car use and car recovery (Fig. 1). According to Bhaskar et al. [15], the manufacturing of a car (Press, body, paint and assembly shops) may consume up to 700kwh/vehicle. This energy cost is about 9-12% of the total manufacturing cost. A 20% reduction in energy cost

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shall be about 2-2.4% reduction in the final manufacturing cost. The energy consumption can be reduced through an energy efficient manufacturing system [15, 16].

Table 1. Energy Value for the Production of one Vehicle

Literature Source	Energy Value for the Production of one Vehicle	
VW Golf A III [17]	62 GJ	
Volvo cars	18 GJ (Worst case)	
UNESCO Edu., Sci. &Tech.	20 GJ	
Mid-sized vehicles (1995) [18]	Conventional Lightweight	104 GJ 107 GJ

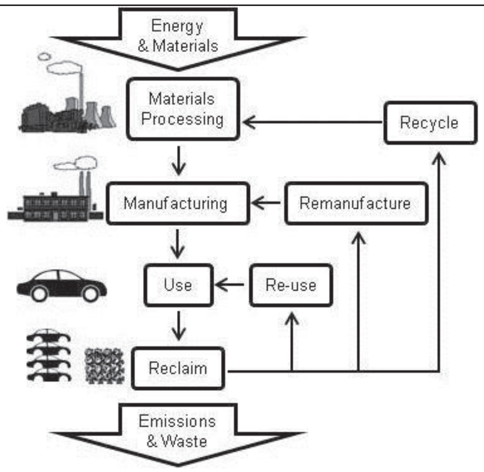

Fig. 1.Car Life Cycle [19]

2. Energy Efficiency Methods

Energy efficiency has been addressed, whereby the environment is regarded as a thermodynamic system [20] [21] [22]. Moreover, some analytical methods have been suggested in order for the process energy efficiency to be calculated [23] [24] [25] [26]. However, the specifically consumed energy as an efficiency indicator [27] [28], does not give detailed information on what measures could be taken for the improvement of the operational energy efficiency of a production plant. In addition, the specific energy consumption as a single key figure does not include any information about other objectives such as throughput time. Since production systems are typically rather complex, simulation techniques and models offer an alternative for evaluating their performance [29, 30].

In this paper a simulation model of a "real life" automotive assembly line was first created. With the help of this model the energy aspects of the line were investigated including also other performance measures.

3. Simulation model

3.1. Structure and processing of the under-body

The assembly line to be modeled and simulated was the line for the assembly of the under-body of the car because it is one of the most critical parts of an automotive Body-in-White (BiW). It is the structure that carries and connects several significant car components such as engine, transmission, and suspension, contributing significantly to the car's stiffness. Additionally, it determines the length of the vehicle and to a great extent, its final shape.

This particular underbody is a modular one [32]. A modular under-body is considered as a platform segment from which alternative BiW variants, in terms of shape and dimensions, can be produced [33].

The main process used for the assembly of the under-body is the Resistance Spot Welding (RSW) which is a multi-parametrical process and the energy consumed from the entire unit is the result of the sum of each parameter's contribution [31].

3.2. Line configuration

The assembly line was configured in such a way so as to enable the production of 3 different underbody variants for addressing the need for multi-variant vehicles. The final products are the underbody variant 1 (UV1), the variant 2 (UV2) and the variant 3 (UV3) [32]. The entire production includes four sub-assembly lines. The three first sub-assembly lines are working in parallel (Front end module, floor module, rear end module) while the fourth one (main underbody assembly) makes the final assembly.

The Front module sub-assembly line produces the front end which consists of the rail sub-assembly and the front end main line. The floor module sub-assembly line can produce floor type 1 (length L1) and type 2 (length L2).The material of the parts produced is common. The module contains two sub modules: a) the floor panel sub-assembly, b) the front floor sub-assembly and the main line. The rear module assembly line can produce rear type 1 (length L1) and rear type 2 (length L2).

The final assembly system configuration and decomposition of the under-body structure is accomplished at the main underbody assembly line and is based on the following assembly configuration (Fig. 3):

- Sub-Cell#1 (s1): The front module assembly and re-spot sub-cell
- Sub-Cell#2 (s2): The floor module assembly and re-spot sub-cell
- Sub-Cell#3 (s3): The rear module assembly and re-spot sub-cell

- Main-Cell#1 (1): The Front and floor modules assembly
- Main-Cell#2 (2): The Output from Main-Cell#1, rear module and re-spotting

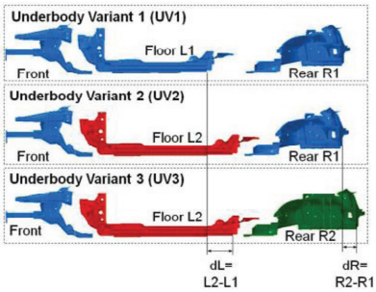

Fig. 2. Modular under body structure variants different lengths within floor (dL) and rear (dR) [32].

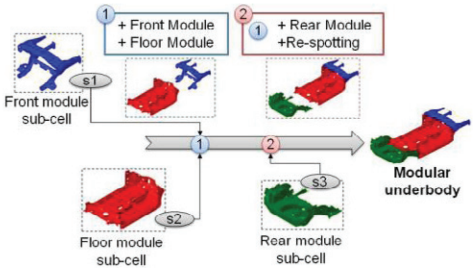

Fig. 3. Under body assembly configuration (UV3) [32].

3.3. Assumptions

The processing time and energy consumptions calculations are based on a series of assumptions taken into consideration. The two major issues for modeling and calculations are assumed to be the energy (busy & idle state) and time (cell total, busy & idle state)

A generic vehicle demand profile (Fig. 4) for a period of two years is assumed [32]. A high peak in its profile appears after production starts, while a demand reduction due to market competition may follow. A marketing campaign, at the end of the first year, can create a second lower peak, before the end of the production phase [32]. After the second peak, an overlap with the next generation of product may appear.

The total production turnout for two years is 1.200.000 vehicles. The factory works three shifts (7.5 hours/shift) per day and 240 working days per year are taken into account. In total, seven vehicle models (Fig. 5) are produced by the factory.

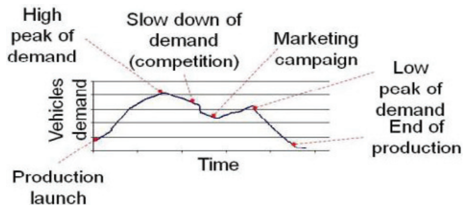

Fig. 4. Vehicles demand profile for a period of two years [32]

The production volume distribution per vehicle variant is based on the current European automotive industry trends [34]. In general, the demand for sport / high performance vehicle variants is lower than that for family / large space / utility vehicle variants.

The Robotic moves & processing time assumptions are the following:

- All robots make two moves: Vertical position of Tip about 2m (average value for up and down) & Rotation of Tip 180 degrees, 6m (average value)
- The average weight lifted by the handling robots per cell is the total weight of the parts per handling robot used in the particular cell

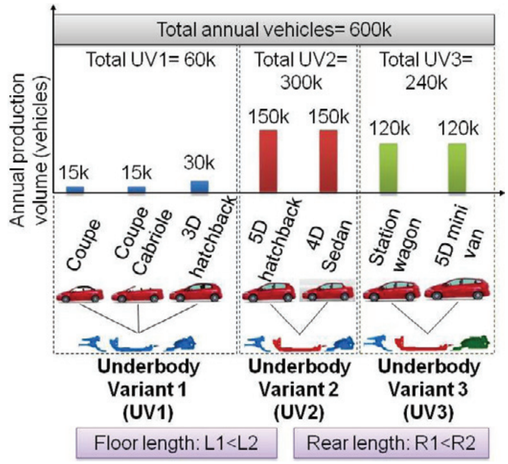

Fig. 5. Under-body structures variants and two years production volume created by one assembly line [32]

- Average spots made by each robot in a particular cell:

$$Average \quad SW = \frac{Total \quad SW}{Total \quad SW \quad Robots} \tag{1}$$

- The average time for the spot welding to perform a spot is assumed to be 2 sec

The energy consumption assumptions are the following:

- Energy per spot welding (2.4mm total thickness of steel): 0.018kWh
- Average power absorbed by robots on the idle state: 500W

3.4. Simulation

The modeling and analysis of the test case was performed using a commercially available simulation tool [35].

The sub-assembly lines include working stations that are assigned to specific jobs and include different numbers and kinds of robots (both handling and joining). Each working station is simulated on the basis of the calculations described above.

4. Results

The results obtained (fig. 6, 7 & 8) indicate obviously that the energy consumption is promotional with the order input, because the higher the workload the higher the energy required. The energy consumption during the idle state is too low compared with the active (busy) one. However, with proper line balancing and planning, the idle phase can be eliminated, saving energy and reducing the final cost. Another problem is the energy optimization during the busy state. Modeling and simulation can assist in resolving the aforementioned problems by identifying the bottlenecks of the assembly line.

Fig. 8, depicts the amount of energy that is required per under-body throughout the different production phases. During the high production phase (days 161-240) the energy per produced part is minimum (68.9 MJ). On the contrary, during days 401-480 when the production phase is minimum the energy per produced part is maximized (83.3 MJ), having a 17% difference in terms of energy consumption and final cost. During the high production phase, the machine utilization rate is higher. During the idle state the machines consume energy without producing, thus reducing significantly their energy efficiency levels.

According to Galitsky et.al [36], the average electricity consumption in vehicle assembly plants for the welding can be about 288 Mj/car (80 kWh/car). Taking into consideration that the under-body constitutes about 45% of the welding in a car and the assumption that the designed line will be using new technology electric robots (compared to the old hydraulic ones) that will reduce the energy to a 20 % [36] and this number can be recalculated to 103 Mj/under-body.

In this study, the average value for a two-year simulation run is about 73 Mj/under-body, giving 29% difference from the estimated average value. This can be attributed to the different assumptions and simplifications made: The average mid-sized car contains 4800 spot welds [37] while in our case we used 4474 spot welds for a complete BiW and about 49,6% of these spots goes to the under-body. So we seem to be close to reality.

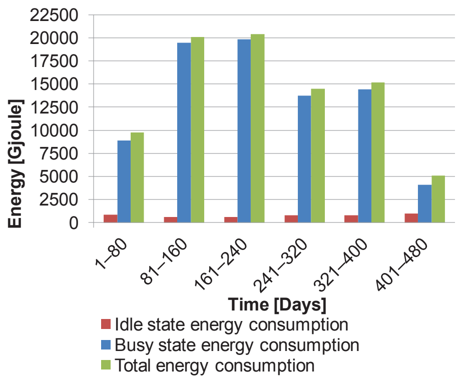

Fig. 6. Energy consumption during busy & idle state under different time periods.

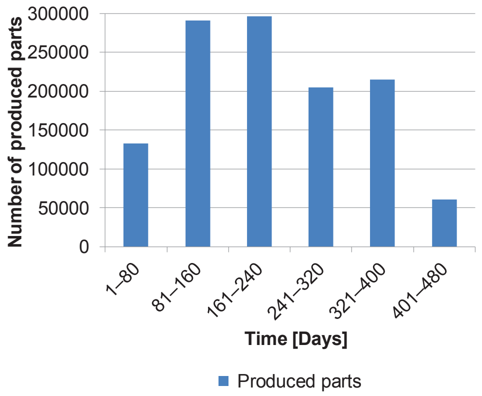

Fig. 7. Produced parts under different time periods.

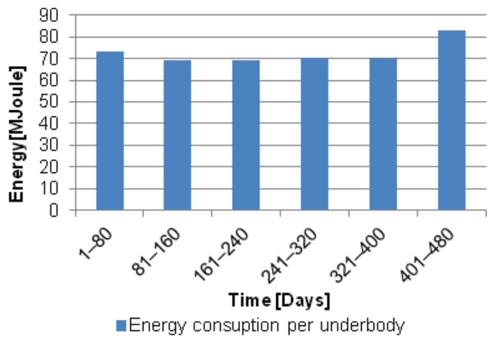

Fig. 8. Cost per product under different time periods.

Table 2. Energy consumption detailed calculations

Symbol	Description (units)	Comments & Assumptions
Nh	Number of handling robots (-)	Line design
Wpart	Weight of part (kgr)	Line design
Wrobh	Weight of robot handling (kgr)	2450 kgh (Robot specs)
Wgrip	Weight of Gripper (kgr)	200 kgh (average)-
Eh	Energy handling (J)	$[Dh \times (Wpart + Wgrip + 0.8 \times Wrobh) \times Vh] \div (Me \times Tbh)$ (2)
nj	Number of joining robots (-)	Line design
Nspot	Number of spots (-)	Line design
Espot	Energy per spot (J)	54000 (J)
Ehj	Energy handling during joining (J)	$[Dhj \times (Wgun + 0.8 \times Wrobh) \times Vj] \div (Me \times Tbhj)$ (3)
Wgun	Weight of gun (kgr)	125 kg
Wrobj	Weight of robot joining (kgr)	1100 kg
Ej	Energy joining (J)	$Espot \times Nspots$ (4)
Eidle	Energy idle/controller (J)	500 (J)
Me	Electric Motor Efficiency (%)	85% (Robot specs)
TEb	Total Energy busy per cell (J)	$(Eh \times nh) + [(Ehj + Ej) \times nj] + [Eidle \times CT \times (nh + nj)]$ (5)
TEi	Total Energy idle per cell (J)	$IT \times Eidle \times (nj + nh)$ (6)
TE	Total Energy per cell (J)	$TEb + TEi$ (7)

Table 3: Robotic moves & processing time detailed calculations

Symbol	Description (Units)	Comments & Assumptions
Dh	Distance handling average (m)	8(m)
Vh	Velocity handling average (m/sec)	1.7(m/sec)
Tbh	Time busy handling (sec)	$Dh \div Vh$ (8)
Dhj	Distance handling joining average (m)	$(Nspots \times Dspots) + \left(\frac{Dh}{2}\right)$ (9)
Dspots	Distance between spots (m)	0.03 (m)
Vj	Velocity joining average (m/sec)	1.5 (m/sec)
Tspot	Time for a spot (sec)	2 (sec)
Tbj	Time busy joining (sec)	$Nspots \times Tspots$ (10)
Tbhj	Time busy handling joining (sec)	Dhj / Vj (11)
Tj	Time joining (sec)	$Tbhj + Tbj$ (12)
IT	Idle Time (sec)	Simulation result
CTcell	Cycle time of cell (sec)	$(Tbh \times nh) + Tj$ (13)

5. Conclusions

In this work, the assembly of an automotive Body-in-White (BiW) under-body structure was modeled and investigated in terms of energy consumption to be calculated. The model developed can provide fast and easy prediction of the energy consumption for a given input. The same model can be used several times in order to test energy consumption under various scenarios. Furthermore, the model can be upgraded in order to test not only the energy but also other important factors such as machine utilization etc. The study shows that by modeling an assembly line in advance and by including energy considerations, one can possibly save energy and cost.

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