# ASSESSING THE ECONOMIC AND ENVIRONMENTAL POTENTIAL OF OUT OF AUTOCLAVE PROCESSING

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## 1 Introduction

The rapid growth of the aviation industry coupled with rising fuel costs and concerns over the environment are keeping airframe manufacturers under pressure to improve aircraft efficiency. Lighter airframe structures offer a direct means of raising aircraft fuel efficiency thus reducing emissions and lowering operating costs. However, as aircraft structures also account for a large proportion of their cost, it is imperative that focus remains on keeping manufacturing costs low.

The use of composite materials has steadily increased in recent years in an effort to achieve greater weight savings in aircraft. Until recently the standard method for curing composites for primary aircraft structures has been the autoclave. Heat and pressure are applied to vacuum bagged prepreg laminates enabling high fibre volume fraction and low void content components to be produced. However, the use of autoclaves is also accompanied by apparent high costs, which stem from high acquisition and operating costs. The reduction of these operating costs is a priority for airframe manufacturers, thus stimulating the recent interest in out of autoclave (OOA) processing.

The primary focus of this work is to quantify the economic and environmental differences between autoclave curing and other selected OOA processes through a comparison that assumes appropriately sized ovens and autoclaves.

Key parameters affecting costs are identified along with environmentally dominant stages of the manufacturing processes.

## 2 Approach and methods

A case study approach is applied where production costs are estimated using technical cost modelling (TCM) and related environmental impacts are quantified with life cycle assessment (LCA). A 400 x 400 x 4 mm carbon fibre reinforced panel was chosen as a functional unit to be produced with the following 5 material/curing scenarios:

**Scenario 1 (Auto PP)**, Autoclave processing with unidirectional (UD) carbon fibre (CF) prepreg.

**Scenario 2 (Therm PP)**, Thermal oven curing with a CF OOA prepreg system.

**Scenario 3 (Micro PP)**, Microwave oven curing with a CF OOA prepreg system.

**Scenario 4 (Therm inf)**, Thermal oven curing with liquid resin infused (LRI) CF non-crimp fabric (NCF).

**Scenario 5 (Micro inf),** Microwave oven curing liquid resin infused (LRI) CF non-crimp fabric (NCF).

The ovens and autoclave chosen for the study were of comparable volume (0.79 $m^3$ for the thermal oven and autoclave, 0.65 $m^3$ for the microwave).

### 2.1 Cost modelling

Cost modelling is carried out using a technical cost model developed at EPFL which is based upon an activity based costing (ABC) approach [1]. A production process is defined which contains all the relevant processes equipment and labour to produce a specific component. The process is then segmented

into discrete quantifiable activities and a cost estimate is prepared for each activity from input parameters such as labour requirements and costs (direct and indirect), cycle times, materials costs, equipment costs, production volumes, energy use, scrap, reject rates and overheads. Costs for each activity are then combined in order to give a total cost for the production process. Plant installation and maintenance costs can also be included along with depreciation periods. Dedicated and utilisation based amortisation scenarios are also possible where equipment or production cell costs can be allocated to a single product or to multiple products. Final part costs can be obtained as a function of volume together with a segmentation of total cost which identifies the relative contribution of each production parameter. Input data are typically obtained from industrial sources, commercial estimates for materials and equipment, and laboratory based tests.

### 2.2 Life cycle assessment

LCA is a structured internationally standardised methodological framework used for estimating and assessing environmental impacts attributed to the lifecycle of a product or service [2]. The methodology considers a product's full lifecycle from the extraction of raw materials to manufacture, use and finally disposal. Consideration of the complete life cycle enables the full impact of a product to be established together with the relative contributions from each life cycle phase. The approach therefore helps to avoid impact shifting where environmental burdens are decreased in one area, perhaps during process improvement, only to be increased in another. LCA is therefore a very useful decision support tool, which can complement other methods, such as cost evaluation, to support the development of sustainable manufacturing practices. The LCA framework consists of the following four stages:

***Goal Scope and Definition*** describes the purpose of the study, the level of detail and also the boundaries of the product system to be studied. A functional unit is defined to which all impacts are allocated.

***Inventory analysis*** determines the inputs and outputs of the system related to raw materials, waste flows and emissions.

***Impact assessment*** translates the contributions of the emissions, waste and resources determined in the inventory analysis into potential environmental impacts,

***Interpretation*** where the results from the impact assessment are summarised, conclusions are drawn and recommendations made against the original study goals.

### 2.3 Assumptions and data

A typical LCA study would consider all phases of a component's life cycle (raw materials, manufacture, use, and end of life). In this study only the first two phases are considered (materials and manufacture) as we assume only small weight variations based upon final geometry. Therefore, the remaining life cycle phases (use and end of life) are assumed to be identical. Production of the raw materials such as carbon fibres, epoxy resin and consumables are considered as well as their transportation from their initial production site to the location of panel. Intermediate production processes such as conversion of carbon fibre to prepreg and carbon fibre to NCF have also been included. Life cycle inventory (LCI) data was primarily sourced from the Ecoinvent database for [3]. Inventory data for carbon fibre production is not present in this database and was sourced from literature [4]. All transportation was assumed to be via truck, total distances covered by materials were 1500 km and 2500 km for the infusion materials and prepregs respectively. The materials used in the comparison were MTM 44-1 for the pre-preg and Saertex 540 gsm NCF combined with RTM 6 for the infusion.

The panel production process assumes that an automated cutting machine with a cost of 110 k€ is used to cut the plies required for each scenario (8 for NCF, 14 for PP) as well as the associated consumable materials. A cutting speed of 0.5 m/s was assumed and a 60s change over time was included for each material which required cutting. Compiling of cut materials into kits took a further 5 mins. A 20% cut waste factor was assumed for all sheet materials and disposal assumed transportation

by truck and incineration with energy recovery. During lay-up 1 ply was applied every 90 s, bagging times were 10 min and 20 min for the prepreg and infusion processes respectively. A flat direct labour rate of 35 €/hr was applied to cutting, lay-up and autoclave/oven operation. For the prepreg processes total time allocated to loading, setting up and extracting the panel from the autoclave or oven was 1 hr, an additional 30 mins was added for the infusion processes. Panel thicknesses achieved with the two different materials were 4.07 and 4.11 mm for the infused and prepreg panels respectively.

Scenarios 1-3 utilise the same prepreg material which has the possibility to be cured both in and out of an autoclave. When cured without autoclave pressure an overnight de-bulking operation is required and has also been included in the power consumption estimates. Manufacturer's guidelines were followed when determining the cure cycles for all the materials which are given in table 1. Energy consumption was measured during lab scale tests for the microwave and thermal ovens. Autoclave energy use estimations were obtained from industry and verified with measurements in our own lab scale autoclave.

| | ***Auto PP*** | ***Therm PP*** | ***Micro PP*** | ***Therm inf*** | ***Micro inf*** |
|---|---|---|---|---|---|
| Ramp 1 (°C/min) | 2 | 2 | 5 | 2 | 5 |
| Dwell 1 (min) | 120 | 120 | 120 | 30 | 30 |
| Dwell 1 temp (°C) | 180 | 120 | 120 | 120 | 120 |
| Ramp 2 (°C/min) | - | 2 | 5 | 2 | 5 |
| Dwell 2 (min) | - | 120 | 120 | 120 | 120 |
| Dwell 2 temp (°C) | | 180 | 180 | 180 | 180 |
| Cooling (°C/min) | 2 | 2 | 5 | 2 | 5 |
| **Cycle time (min)** | **275** | **395** | **271** | **305** | **181** |

Table. 1. Ramp and cure times per process.

Materials cost were estimated at 100 €/kg 75 €/kg and 42 €/kg for the prepreg, NCF and infusion resin respectively. Estimates were obtained from industry for autoclave, thermal and microwave ovens which were 130 k€, 7 k€ and 100 k€ respectively.

The production location was assumed to be in Western Europe where there are 250 factory working days and the possibility to run three 8 hr shifts per day. A production volume of 1032 panels per annum was considered representative of typical aerospace volumes and therefore applied. The European average power mix was used for electrical energy, the cost of which was estimated at 0.1 €/kWh.

## 3 Results and discussion

### 3.1 Manufacturing costs

Figure 1 shows the estimated panel cost for each manufacturing scenario with contributions from materials, labour, tooling, consumables and energy. The total estimated cost of production for the panel produced with baseline autoclave process was € 229. The thermal oven infusion process achieved the lowest production cost with a 14 % reduction against the autoclave. This was followed by microwave infusion, and the thermal oven prepreg process with 9% and 6% reductions respectively. The microwave cured prepreg panel was estimated to cost 231 € to produce which was a 1% increase over the baseline autoclave process.

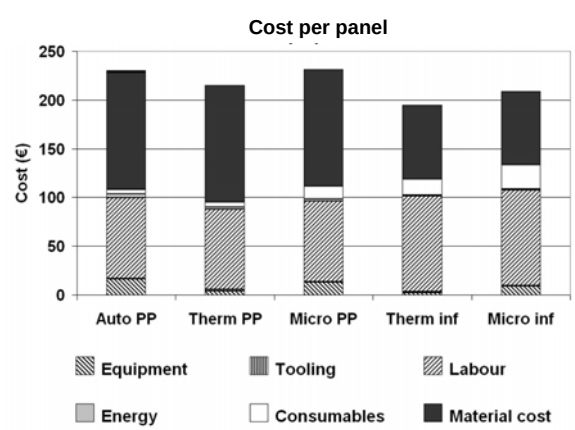


Fig. 1. Manufacturing costs per process.

The dominant costs in all scenarios came from materials production (carbon fibre and epoxy resins) and labour costs which, combined, contributed to

between 82% and 90 % of panel production costs. Processes utilising prepregs had 60% higher material costs than the infusion processes, which utilised lower cost materials and combined resin and fibres on site. However, the infusion processes were more labour intensive and subsequently incurred a 16 % increase in labour costs over the prepreg processes.

Consumables costs made up only 2 % of total costs for the autoclave and thermal oven prepreg scenarios, this increased to 5% for the microwave prepreg panel. Consumables costs were of course higher for the infusion processes and made up 8 % and 11 % of total cost for the thermal oven and microwave infused scenarios. The higher consumables costs associated with the microwave scenarios stemmed from the use of higher temperature vacuum bags deemed necessary to avoid process induced puncturing from localised heating.

Equipment costs contributed to between 6% and 4% of the total cost for the autoclave and microwave processes respectively. This contribution was less than 2 % for the thermal oven processes due to the significantly lower purchase costs of a thermal oven. Energy costs had little effect on the total cost for all scenarios and in the worst case (autoclave) formed 2% of the total cost and just 0.7% for the infusion processes.

Of the prepreg processes microwave curing led to costs comparable with the autoclave. The microwave oven purchase costs were not dissimilar to that of an autoclave, material and labour costs were the same. The higher cost of the consumables pushed the part cost above that of the autoclave as no real benefits were obtained through energy saving due to its low impact on part cost.

The resin infusion processes examined achieved lower part costs than the prepreg scenarios despite the higher associated labour and consumables costs. The most significant cost benefits were obtained through the use of the lower cost dry fibre NCF materials. When comparing the two infusion processes, the thermal oven cured variant achieved a lower cost despite the cycle time of the process being reduced by 40% in the microwave. Higher consumables and oven purchase costs offset the benefits gained from the faster cycle times for this production rate.

Sensitivity analysis was carried out on: material, labour, equipment and energy costs in addition to lay-up add cycle times with each parameter varied by ±20%. Labour and materials costs were the most sensitive to change influencing cost by 20-25 € for the infusion and prepreg processes respectively. The remaining parameters affected total cost by 1-5 €.

### 3.2 Environmental Impacts

The commercially available LCA software Simapro was used to carry out the LCA [5]. Impact assessment was carried out with the IMPACT 2002+ methodology where LCI results are grouped into 14 impact categories at midpoint level, then to four end point damage categories which consider climate change, resources, human health and ecosystem quality [6]. Results are shown in $CO_2$ equivalent emissions only, as the same trends in terms of impact reduction and process rankings were observed across all damage categories considered.

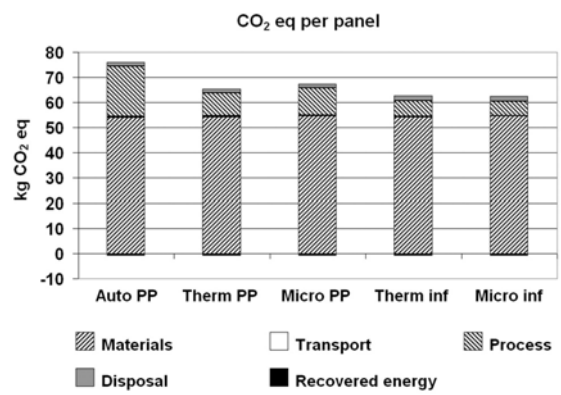


Fig. 2.Total $CO_2$ eq emissions per panel produced for each scenario.

Figure 2 shows the resultant $CO_2$ eq emissions generated per panel and segmented to show contributions from materials, transportation, processing energy and the disposal of production waste through incineration. Energy recovered from the incineration process is also shown as a negative in the figure signifying avoided emissions from alternative power generation.

Emissions from the transportation of materials were small in comparison to other emissions at 0.3 kg and 0.16 kg $CO_2$ eq. for the prepreg and infusion scenarios respectively. These contributed to less than 0.5% of total emissions despite the relatively long distances covered by the materials. Emissions related to the disposal of production materials were higher for infusion than for the prepreg scenarios due to the quantities of consumables required for the process. However, emissions associated with disposal (transportation and incineration of waste) only accounted for 2-3% of total emissions before consideration of recovered energy from the incineration process.

The largest contribution to emissions for each scenario is from the manufacture of materials. This creates around 54 kg of $CO_2$ eq for each process and makes up between 69% and 87% of total emissions for the scenarios examined. A breakdown of emissions contributions from materials production is shown in table 2. The manufacture of carbon fibres is the largest source of emissions at around 84% of total for materials. The remaining burdens were spread between consumables, resin and the material conversion step (pre-pregging and weaving). The conversion process associated with NCF fabric production was approximately 12 times less energy intensive than the conversion of carbon fibre to unidirectional prepreg, however this benefit was offset by larger amounts of resin and consumables required for the infusion, resulting in relatively similar emissions associated with materials in each process.

| | **Prepreg Kg $CO_2$ eq** | **Infusion Kg $CO_2$ eq** |
|---|---|---|
| Carbon fibre | 45.6 | 46.8 |
| Epoxy resin | 2.2 | 2.6 |
| Consumables | 3.3 | 4.6 |
| Conversion | 2.5 | 0.2 |
| **Totals** | **53.6** | **54.2** |

Table. 2. Material $CO_2$ eq emissions per process.

Figure 3 shows process related emissions for each production scenario in terms of kg of $CO_2$ eq. These emissions are related to processing the materials within the factory and result from the use of electricity during the cutting of materials, the use of vacuum pumps and oven/autoclave operation. Energy related emissions from the combined processes for the baseline autoclave scenario were estimated at 20 kg of $CO_2$ eq and made up 25% of total emissions from the autoclave process. The remaining scenarios had process related emissions values 50-70% lower which made up 10-16 % of total emissions coming from each scenario.

Process related emissions from the thermal oven cured prepreg were 55% lower than for the autoclave, despite a 120 min increase in cycle time and the additional overnight de-bulk operation which increased emissions by 16%. Microwave curing of the same material resulted in higher process related emissions compared with the thermal oven despite the faster cycle time. These increased emissions resulted from a higher rate of energy use during the curing phase, the overnight de-bulk remained the same.

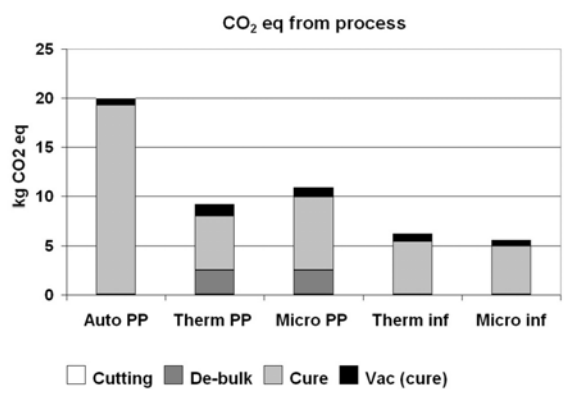


Fig. 2.Total $CO_2$ eq emissions per panel and scenario.

The infusion processes achieved process related emission reductions of 69% and 72% for the thermal and microwave ovens respectively. Cycle times were faster than for OOA prepreg materials and no overnight de-bulking was required. In this case the microwave faired better than the thermal oven which was contrary to the situation for OOA prepregs. The energy consumption plots for the thermal and microwave oven are shown in figure 3 for both prepreg and infusion scenarios.

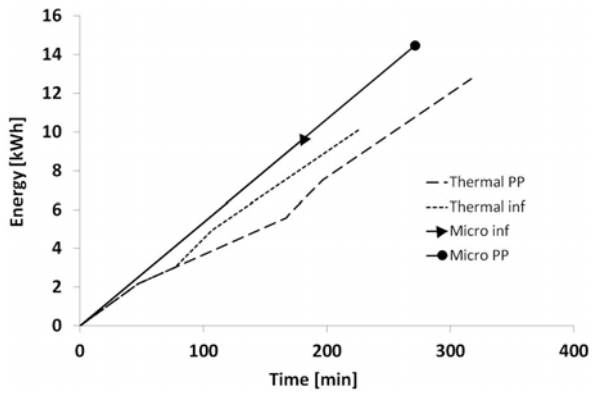

Fig.3. Energy consumption against process time for the OOA processes.

Processes carried out in the thermal oven had energy consumption rates similar to that of the microwave oven during their ramp up phases. However, after reaching the required dwell temperatures, energy consumption was reduced as the internal oven temperature had only to be maintained. Energy consumption rates for the microwave processes were higher than that of the thermal ovens. This is thought to be caused by constant heat loss from the curing components to the oven cavity during the process, despite the components being insulated during cure.

The dominant sources of emissions for all production scenarios were raw materials production followed by processing. Electricity production was responsible for 100% of processing related emissions and 45% of materials related emissions. Two sensitivity scenarios were chosen to determine the effects on emissions with alternative electricity production mixes. Substituting the European average energy mix with a fossil intensive alternative led to $CO_2$ eq increases of between 43% and 58% for all scenarios. A hydro/nuclear power mix led to reductions of $CO_2$ eq emissions which were between 52% and 40 % for the autoclave and infusion processes respectively. The fossil fuel intensive energy mix increased emissions from each process but did not affect the results of the study in terms of processes ranking. The cleaner energy mix reduced the emissions of all the processes to similar levels which were between 36 and 38 kg $CO_2$ eq and did affect the process ranking. In this case the autoclave process performed the best followed by the OOA prepreg methods and then the infusion processes.

## 4 Conclusion

OOA processing can reduce the manufacturing costs and improve the environmental performance of composite manufacture. Materials make up a higher proportion of component costs than energy and equipment. As a consequence the infusion processes, which utilised lower cost material, achieved better cost reductions.

The expected benefits of the microwave oven cure were not achieved despite faster cycle times, due to higher energy consumption rates, more expensive consumables and high purchase costs.

Energy use contributed more to the environmental impact of processing than to cost, as the OOA processes used less energy better environmental performance was achieved. Materials, in particular carbon fibre manufacture, were responsible for the highest proportion of emissions for each process. Strategies to reduce these, such as through the use of cleaner energy, would greatly reduce the impact of manufacture, however OOA processing still brings improvements that are not negligible.

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