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A scalable cost modelling architecture for evaluating the production cost-effectiveness of novel joining techniques for aircraft structures

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Abstract

This work introduces a cost modelling architecture in order to determine the cost-effectiveness of the latest joining technology developments. Riveting is the conventional joining method in the aerospace industry, but is a time-consuming, expensive process that adds excessive weight to a structure. As part of the JTI Clean Sky 2 Joint Technology Initiative, the OASIS project (“Optimization of Friction Stir Welding (FSW) and Laser Beam Welding (LBW) for assembly of structural aircraft parts”) aims to demonstrate the feasibility and cost-effectiveness of novel joining technologies. The technologies being investigated are LBW, FSW and Friction Stir Spot Welding (FSSW). Physical demonstrators, simulation studies and access to industry leading technical expertise from OASIS project partners have helped develop detailed production process maps and input accurate process metrics to determine manufacturing costs. To this end, an activity-based cost modelling architecture has been developed to predict the cost-effectiveness of the joining technologies and assess them against both manual and automatic riveted solutions. The model has been designed in a manner that enables integration into current manufacturing eco-systems, has scalability for large aerospace companies and the ability to perform multi-fidelity process cost models that can be integrated with one another as required.

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1. Introduction

Fierce global competition requires companies to have detailed knowledge of not only their operating manufacturing costs, including direct, indirect, recurring and non-recurring costs, but also the cost estimate breakdown prior to the adoption of potential new technologies or processes. Assessing the feasibility of implementing new joining technologies (LBW, FSW, and FSSW) requires an understanding of the technical/physical requirements alongside the cost implications to get a complete picture of the technology potential.

Cost estimation is often an afterthought carried out independently from other manufacturing functions within a company. A process that has been validated in terms of layout, capacity and demand, is often ‘costed’ at the end of the design process [1]. To maximise the impact of cost modeling activities production configurations (layout, labour, shift patterns etc.) should be optimised based on cost impact. This paper addresses...
this shortcoming by incorporating cost optimisation of potential production configurations into the upfront planning. This is an approach that is missing (especially during process feasibility studies), but should be at the forefront of any planning activities as cost efficiency underpins competitive production.

Traditional cost accounting methods fall short of accurately attributing costs to complex manufacturing processes. Hence, a plethora of cost estimating techniques [2,3] have been developed. These are best suited to individual processes [4] depending on the estimation involved, available data and the fidelity of the answer required [5] and do not address how cost optimisation impacts production configuration. The architecture described in this paper enables the development of generic activity definitions that can contain the relevant process metric inputs and cost algorithms to evaluate cost over a combination of processes in a manufacturing workflow.

Cost estimation methods are broadly classed as 

- qualitative (including analogous and intuitive methods), where historical data is used to help estimate cost using a comparison to other similar products and decisions are based largely on domain expertise and knowledge;
- quantitative methods, like parametric costing, use product parameters to help develop cost estimation relationships. Bottom-up methodologies determine costs in detailed work breakdown structures. These approaches are accurate, but time-consuming due to the effort required.

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Table 1. ABC cost definitions.

<table>
<thead>
<tr>
<th>Cost type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost object</td>
<td>Product, process, service etc.</td>
</tr>
<tr>
<td>Activity driver</td>
<td>operations/machine/hours/quantity</td>
</tr>
<tr>
<td>Activity</td>
<td>Operation being performed</td>
</tr>
<tr>
<td>Resource driver</td>
<td>Cost per item/hour/consumption</td>
</tr>
<tr>
<td>Resource</td>
<td>Materials, equipment, labour etc.</td>
</tr>
<tr>
<td>Cost driver</td>
<td>Production units, labour hours etc.</td>
</tr>
</tbody>
</table>

Activity-Based costing (ABC) [6] is a cost estimation approach that evaluates cost based upon the activities performed during manufacturing production, Table 1. ABC traces how resources and time are consumed by activities. This results in allocation of cost and resources to activities, making the method well-suited for manufacturing methods.

Many cost estimations require a combination of multiple cost modelling approaches in order to use appropriate methods for different manufacturing processes, e.g. using a parametric approach to estimate the cost of two similar components in the manufacturing bill of materials (MBOM). However, for overall assessment of manufacturing production processes an overarching cost methodology is required. Selection of ABC due to its manufacturing suitability enables traceability of cost consumption between resources, processes and products.

For the cost comparisons of the manufacturing processes in the OASIS project, the following objectives will be addressed:

- Develop process maps for the manufacturing processes
- Design a scalable, reusable and editable cost model
- Develop process cost estimation models to predict recurring and non-recurring costs
- Leverage digital manufacturing simulations to predict cycle times that will drive costs
- Cost optimise production layout and configuration
- Evaluate the cost-effectiveness of the different joining methods against the baseline riveted approach

2. Cost model design

The structure of the ABC-based model developed in this work is shown in Fig. 1. It depicts how resources are consumed by activities to give an overall process cost description.

Process and resources specifications are captured to produce: manufacturing bill of activities (MBOA) containing the activities defined by the detailed process mapping of the manufacturing processes; the manufacturing bill of resources (MBOR) contains the resources consumed by the activities. The resources are categorised into five distinct resource pools:

- **Materials**: comprised of bought-in components, raw materials and consumables to produce the MBOM.
- **Equipment**: includes machines, robots, tools etc. to produce a manufacturing bill of equipment (MBOE).
- **Labour**: personnel required to perform activities.
- **Infrastructure**: temporary/permanent structures, floor space etc. required for production.
- **Energy**: consumption of energy by activities.

The model is structured, Fig. 1, so model inputs (resource costs, production data, process times etc.) are absorbed by activities to define appropriate drivers ($/item, mm/s, $/litre etc.) to enable cost and quantity calculations to be performed.
2.1. Cost model architecture

The architecture has three key modules: storage, process and visualise, Fig. 2. This division enables key information (production, resource and process metrics) to be input and retained in a standardised manner. This addresses certain shortcomings of current cost modelling approaches by providing a platform to integrate cost modelling within a company’s existing manufacturing management solutions.

Fig. 2 Cost model architecture

2.2. Storage

The value of data to a company is ever increasing, especially with the emergence of Digital Twin technologies and advanced data analytics solutions for maximum exploitation. Therefore, proper management and storage of data is crucial. In this work, data storage has been implemented using Microsoft SQL Server. Similar databases underpin many commonly used industrial manufacturing planning systems, making the current solution easily scalable within large production environments if integrated openly with these existing manufacturing systems, e.g. simple SQL queries can retrieve data from other databases.

Multiple databases have been designed to store specific information, simplifying integration with existing systems, Fig. 3. The production database stores operational data (production rates, available hours) and overheads (labour overheads, tax, energy). The resource database stores material, equipment, labour and infrastructure attributes like hourly rates, geometric data (e.g. join lengths), and equipment specification.

Fig. 3 Cost model relational database entity-relationship diagram

2.3. Process

Processing the cost calculations in a separate module (developed using Python Jupyter Notebook) enables this portion of the model to be isolated from users, allowing their sole focus on the definition of standardised activities and process maps of the production process. The model works as follows:

- Initiate model with activities list defining the production process as outlined by detailed process map.
- Identify MBOM resources consumed by activities.
- Define equipment and infrastructure resource cost drivers, including recurring and non-recurring costs.
- Determine activity cycle times accounting for non-value added and efficiency losses.

Fig. 4 Standardised activity definition

Fig. 5 Activity calculation breakdown
• Calculate **resource quantities** and cost consumed by activities, e.g. consumables and energy.
• Calculate **learning rates for activities** to adjust yearly production requirements in terms of time and quantity.
• **Bottleneck identification and optimization** of cell and shift configurations based upon cost and capacity analysis.
• **Output key performance indicators (KPIs).**

The python-based module interrogates the databases using custom-built SQL queries to retrieve the cost calculations data. Activities are processed to determine resource quantity and time consumption per activity, Fig. 5. Standardised activity definitions enable activity drivers, shown in Table 2, to be extracted and used in conjunction with resource attributes (MBOM data or geometry attributes) to define the activity calculation logic. This process is re-useable across all activity definitions once the correct structure is implemented.

Table 2. Activity drivers.

<table>
<thead>
<tr>
<th>Activity driver</th>
<th>Duration driver</th>
<th>Quantity driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>min/operation</td>
<td>Number of operations</td>
<td>Usage/operation</td>
</tr>
<tr>
<td>min/item</td>
<td>Number of items</td>
<td>Rate/item</td>
</tr>
<tr>
<td>min/m</td>
<td>Length</td>
<td>Coverage/m</td>
</tr>
<tr>
<td>min/m²</td>
<td>Area (mating surface)</td>
<td>Coverage/m²</td>
</tr>
</tbody>
</table>

Cost estimation is performed over a specific period (10 years), where yearly production quantity forecasts are driven by a combination of production demand, scrap and yield as dictated by activity definitions. This enables resource costs of material, consumables, labour, equipment, infrastructure and energy to be calculated. Direct/indirect material costs are calculated to account for purchase price and material burden. Equipment costs are divided into non-recurring (double-declining depreciation) and recurring costs (tax, insurance, maintenance). Labour costs are direct (including shift uplifts) and indirect costs (wrap rates). Energy costs are divided into direct (equipment energy usage for specific tasks) and indirect (carbon emission factors and carbon tax rates) costs.

Overall production quantities (as dictated by activity consumption) and process times are modified using learning rates to estimate and forecast progression (reduced time and cost to perform tasks) during future production activities. Ultimately, the cost of the first unit is greatest and as production continues the unit costs become less. In aerospace, the typical learning rate is assumed to be 80% [5]. However, as each activity within the production process has its own specific capacity for learning there are a series of typical learning rates that can be applied (general assembly – 85%, machining – 95%, welding – 92%, aircraft assembly – 80%). The ABC approach enables individual activities to be assigned specific learning rates to make more appropriate adjustments.

Learning model implementation is based on the unit time model by Crawford [7]. Different stages of learning in production, including ramp-up, full production and diminished learning, need to be accounted for, e.g. estimating the specific number of units for production ramp-up a theoretical first unit time is calculated with the average unit cycle time of the ramp-up period. An experience factor added to the Crawford model accounts for established experience at performing different activities, thus adjusting typical learning rates. Learning rate impacts are calculated yearly to estimate cycle times that define labour hours, equipment usage, resource consumption and available capacity. Yearly costs calculations are adapted to account for typical inflation rates and labour pay scales.

Capacity analysis and cost optimisation of the production configuration is carried out as follows:
• **Determine throughput** from the operational availability and the production quantities required.
• **Identify utilisation** of all production cells based on calculated activity durations.
• Identify the **bottleneck cell/activity** in the process. This is the cell/activity with maximum utilisation.
• **Excessive utilisation** of bottleneck cell/activity (100% plus acceptable overtime) requires optimisation for cost.
• Cycle possible **cell-shift configurations**, adjusting cap-ex, labour costs etc. to determine total **configuration costs**.
• **Select optimal configuration** based on cost and utilisation.

2.4. **Visualisation**

Optimal configuration costs are output as resource costs, which in turn are allocated to activities according to their consumption. Costs are broken down into different cost types (recurring and non-recurring) with KPIs automatically output to the visualisation module. The standalone visualisation module has been developed using Microsoft PowerBi, where custom and interactive cost dashboards, consisting of cost KPIs and production metrics, are used for detailed cost evaluation.

3. **OASIS case study**

To enable non-biased and independent trade studies, industrial partner Saab have provided (as part of OASIS and Clean Sky 2) a reference aircraft cargo door structure, Fig. 6. The skeleton structure consists of a skin with pockets and seven frames which are joined to the skin. The cost-effectiveness of novel methods of joining (FSW, FSSW and LBW) is benchmarked against traditional riveted (both manual and automatic) joining of the reference structure.

![Fig. 6 Reference aircraft structure](Image)

Detailed process maps for LBW, corner stationary shoulder FSW and refill FSSW are shown in Fig. 7. Industry experts (OASIS consortium) have played a vital role in developing manufacturing process maps for this study. Manual and automatic riveting process steps are the same, aside from automation. Key differences for the joining techniques are:
• **Frame design:** I-section (riveting), T-section (LBW/FSW) and Z-section (FSSW) frame cross-section variations impact cost and weight of the final structure.
- **Surface treatment**: Anodising and priming are performed pre-join for riveting and post-join for FSW and LBW. FSSW masks join locations before anodising and priming pre-join, leaving only the join areas to be treated post-join.

- **Pre-join**: LBW requires light abrasion and degreasing of the surfaces to be joined together. Both riveting and FSSW approaches require sealant application prior to joining.

- **Join**: Process step variations range from temporary fastener insertion and removal for riveting, laser calibration for LBW and in-process rework for FSW and FSSW.

- **Post-join**: separate reworking steps are required for riveting and LBW while sealant fillet seal application is required for both FSSW and riveting methods.

- **Testing**: Destructive testing (10% of components) and non-destructive testing (NDT) consisting of fluorescent penetrant inspection (FPI) to detect surface flaws and ultrasonic testing (UT) to detect internal flaws are required for the LBW, FSW and FSSW methods.

- **Fasteners**: rivet insertion has a spacing of 25mm, while temporary fasteners have 1:10 ratio to rivets.
- **Shielding gas**: usage for robotic welding at 25 litres/min.
- **FPI consumables**: degreaser at 0.08 litres/m², penetrant and developer at 0.04 litres/m².
- **FSW tool**: useful life of approximately 100m.
- **FSSW tool**: useful life of approximately 1000 spot welds.

Key activity duration drivers are:

- **Laser welding**: welding speeds of 2.5m/min for tack and keyhole welds and 1.75m/min for dress welds.
- **FSW**: 4mm/s welding speed.
- **FSSW**: 4.5 seconds/spot weld including dwell time.
- **Rivet insertion**: automatic insertion is 0.4min/rivet, including drilling, countersinking and sealant application. The same manual operation is estimated at 2min/rivet.
- **FPI**: applying developer/penetrant/degreaser at rate of 0.2min/m with dwell times of 20 minutes after both developer and penetrant application.

The above activity drivers only capture the value-added portion of overall activity durations. Other metrics capture non-value added activity times. Operating factors describe the value-added portion of as a percentage of the total time with the remaining portion accounting for non-value added work. Here, operating factors are assigned to different activities, such as manual welding (35%), robotic laser welding (58%), robotic FSW (85%) and robotic FSSW (50%).

Estimates of the operating factors for LBW, FSW and FSSW were taken from simulation models, Fig. 8. This accounts for robot jogging, approach speeds, dwell times etc. FSSW and LBW have lower operating factors than FSW due to their higher process speeds, i.e. the impact of non-value added robot movements is greater. An efficiency factor accounts for other non-value added portions for manual (75%) and automatic (90%) activity times.

Cost outputs for the different joining technologies are in the form of interactive dashboards capturing KPIs, such as unit cost, cap-ex, resource costs and scalable costs such as cost/metre and time per metre of join are shown in Fig. 9 for the LBW method. It is clear for all joining methods that material and labour consume the majority of the unit costs. The labour reduction is due to the massive savings in joining time, Fig. 10. For example, a 95% reduction in LBW join times contribute to 80% reduction in recurring labour costs per unit.

Unit cost savings as a percentage of the manual riveting unit cost and the return on investment (ROI) are shown in Fig. 11.
for the cost optimised production configuration of each joining method. It can be seen the highest unit savings and lowest ROI periods are for LBW and FSW, although all methods make considerable savings w.r.t manual riveting.

**4. Conclusions**

This paper has shown the implementation of a novel cost modelling approach for manufacturing process cost estimation. It has been implemented to assess cost-effectiveness of novel joining techniques of aircraft structures. This architecture enables existing manufacturing data to be leveraged and input to standard activity definitions for cost analysis. Integration with digital twin and industry 4.0 technologies provides a clear pathway for real-time cost impact analysis within production scenarios. Further development of this work requires integration with discrete event simulation techniques in order to evaluate variability of the cost drivers and to understand the cost impact of scheduling on the manufacturing process costs.

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**References**


