AIAA AVIATION Forum
August 2-6, 2021, VIRTUAL EVENT
AIAA AVIATION 2021 FORUM
10.2514/6.2021-3058

An open source part cost estimation tool for MDO purposes

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Abstract

Within Multi-Disciplinary Optimization (MDO), multiple disciplines of a part or product are evaluated in order to determine the performance in these disciplines. Manufacturing cost is not a discipline usually evaluated in an MDO analysis. However for aircraft part and component manufacturers manufacturing cost is one of the most important performance indicators because it directly affects the profitability of such companies. Cost is often not included because no cost evaluation tool is available. In this paper a cost estimation tool is presented that relates geometric features to recurring manufacturing cost. The tool uses only data from the public domain and will be open source to ensure anyone can use it, improve it and include manufacturing cost in their MDO frameworks.

I. Introduction

Within Multi-Disciplinary Optimization (MDO), multiple disciplines of a part or product are evaluated in order to determine the performance in these disciplines. Manufacturing cost is not a discipline usually evaluated in an MDO analysis. However for aircraft part and component manufacturers manufacturing cost is one of the most important performance indicators because it directly affects the profitability of such companies. Decisions and design choices made at high level MDO exercises do have a profound effect on the manufacturability and therefore manufacturing cost of the parts or products designed [1]. Therefore, for aircraft part and component manufacturers to reap the benefits from MDO analyses it is essential that manufacturing cost is taken into account in the MDO process.

One of the reasons cost estimation is not included in the MDO analysis is that the availability of tools evaluating cost is limited. When cost tools are available, they are often proprietary and can therefore not be used in for MDO studies in the public domain. However, because of this lack of tools the knowledge of how to include cost estimation in MDO is only showing limited growth. Developing and providing a non-proprietary cost estimation tool based on data from the public domain will solve this problem.

In a conceptual MDO analysis, the exact quantification of cost is usually not important. It is more important to understand the relative impact on manufacturing cost. In other words, it is important to see which manufacturing method is cheaper or which design aspects incur more manufacturing cost. Therefore, even a cost estimation method that does not provide exact results but is correct in showing the comparative effects is useful.

One of the Agile 4.0 project [4] objectives is to be able to include manufacturing cost analysis in optimization flows. In Agile 4.0 optimization workflows are set up that run trans-company and trans-national. Industry, research institutes and Academia work together to find ways to include manufacturability in MDO flows. As an industrial partner GKN Aerospace is highly interested in optimization flows including manufacturing. However due to competitive reasons it cannot provide its own proprietary cost estimation models.

To ensure cost estimation will be included in MDO analyses and ensure that public domain knowledge on how to do this increases, a tool is required that is open for use in the public domain. In this paper a cost estimation method is be presented that estimates the manufacturing cost of parts using formulas relating geometry part characteristics to part cost. It is developed at GKN Aerospace in the context of Agile 4.0, however the code for this method will be made available in the public domain and all methods and data used are taken from the public domain.

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II. What are the requirements for an open source cost estimation method with respect to use in MDO

To ensure a cost estimation tool can operate in an open MDO environment such as used in Agile 4.0 there are several requirements. These requirements apply to the cost method itself but and to the context in which the cost estimation method is developed. These requirements are:

1. **Link geometric features to cost**. Most other disciplinary analyses have geometry as the basis for their analyses. Therefore, it makes sense to use the available geometrical information in the cost estimation. By linking the cost to physical geometry, it makes it easier to understand for non-cost experts how the tool operates. Therefore, the estimation method must link geometric elements to cost.
2. **Be causal, changes in design result in a logical change in cost**. Causality between design or geometry changes and cost is essential for the cost estimation method to be accepted even by non-experts. Such a causality could for example be a larger and or more complex product having a higher manufacturing cost, the advantages of causal cost estimation methods are shown in [6].
3. **Include manufacturability features as an input**. This requirement is linked to the previous one. Features that have an influence on cost such as curvature should result in a cost increase to ensure the optimization process gets the correct feedback from the cost estimation method.
4. **Be easily extendible with new manufacturing methods**. New manufacturing methods are developed all the time and often the goal of an optimization is to determine if such a manufacturing method results in lower manufacturing cost. Therefore, to add in a manufacturing method to the cost estimation method must be simple.
5. **Have standardized data input and output.** In order to fit in MDO frameworks the way to provide input to the cost estimation method must be clear and preferably use standard data formats.
6. **Data used must come from the public domain**. To ensure everyone can use the cost estimation method, the data should be available in the public domain. In this way parties that don't have access to proprietary data can still use the tool for cost estimation.
7. **Must be based on open source software packages and therefor not require proprietary tools**. Like the data, the tools used must also be available in the public domain to ensure everyone can have access to the tool
8. **Can be used by people not familiar with all the ins and outs of cost estimation**. People in the MDO community are often not familiar with cost estimation tools. The goal is that these people will use this tool. Therefore, the tool should be sufficiently simple to be used by people that are not cost estimation experts.

III. Implementation details of the cost estimation tool

In the context of the Agile 4.0 project GKN Fokker is developing a cost estimation tool that meets the requirements from the previous paragraph. The implementation details of this tool will be described in this paragraph.

A. What is the calculation method used

The calculation methods of the tool are based on the principles and data of [2] and [3]. Reports describing the cost estimation methods developed and the data used can be found in the public domain and are therefore applicable for this tool. The methods and data provided only cover composite manufacturing processes and are probably out of date. However, as a starting point they do provide a solid amount of data to start with. Furthermore, the cost estimation methods directly link geometrical features cost. In this paper only a short summary will be given but more details about the method and its subsequent developments can be found in [2], [3] and [5].

At the basis of the cost estimation is the principle that every manufacturing method can be broken down into a series of manufacturing steps. For each of these manufacturing steps the manufacturing processing time and the material used in the step is calculated. Multiplying the processing time with hourly rates of the resources used in the manufacturing step and multiplying the materials used with their unit cost results in the total cost of a manufacturing step. By summing all the calculated costs, the total recurring cost of a part or assembly produced by the method is calculated.

As discussed before the manufacturing process times for each manufacturing step must be calculated. This is done using the following formula [2]:

$$t = \tau_{overall} \cdot \sqrt{\left(\frac{A_{total}}{\nu_{overall} \cdot \tau_{overall}} + 1\right)^2 - 1} \qquad (1)$$

Where:

$\tau_{overall}$ = Acceleration parameter, time it takes to achieve 63% steady state
$A_{overall}$ = Cost driver, for example area of a composite sheet
$v_{overall}$ = Steady state speed of the manufacturing process

To execute this formula for each manufacturing step the variables in it must be calculated. $A_{overall}$ depends on the manufacturing type but usually relates to the geometry of the part and can be measured using for example a CAD model of the part.

$\tau_{overall}$ and $v_{overall}$ depend on the manufacturing process used and on the characteristics of the geometry of the part. The characteristics such as part complexity are related to an adjustment of a base number stored in a database. In order to properly adjust the number the characteristics must be quantified. For surface based manufacturing methods, smooth normal and geodesic curvatures and sharp angle changes are used as complexity indicators. In the figures below examples are shown of these geometric features.

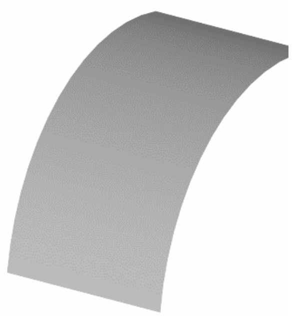

Figure 1 Single curved surface

Figure 2 Double curved or geodesic curved surface

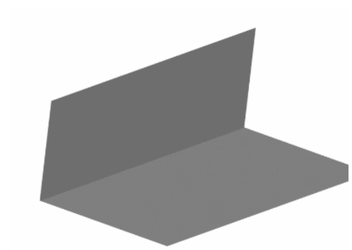

Figure 3 Sharp connection

The complexity indicators used to adjust $\tau_{overall}$ and $v_{overall}$ are called I_n, I_g, I_{sharp} respectively. I_n and I_g can be determined by integrating the surface curvature over the manufacturable surface. I_{sharp} can be calculated by multiplying the sharp angle change with the length of this angle change. A more though explanation of how this can be done can be found in [5]. Using the complexity indicators $\tau_{overall}$ and $v_{overall}$ can be calculated as follows:

$$\tau_{overall} = \tau_0 + b_n \cdot \sum_{n}^{NoOfShrpConnections} I_{sharp}$$

$$v_{overall} = \frac{v_0 \cdot A_{flat} + v_{single} \cdot \left(A_{single} + A_{double}\right) + v_{double} \cdot A_{double} + V_d}{\left(A_{flat} + A_{single} + 2 \cdot A_{double} + \sum_{n}^{NoOfCurvedConnections} A_n\right)}$$

Where:

$$v_{single} = \frac{v_0}{1 + \left(\frac{v_0}{c_n}\right) \cdot \sum_{i}^{NoOfSurfaces} I_{n_i}}$$

$$v_{double} = \frac{v_0}{1 + \left(\frac{v_0}{c_d}\right) \cdot \sum_{i}^{NoOfSurfaces} I_{g_i}}$$

$$V_d = \sum_{n=1}^{NoOfCurvedConnections} \frac{v_0 \cdot A_n}{1 + \left(\frac{v_0}{c_g}\right) \cdot \theta_{d_n}}$$

In the formula's above c_n, c_d and c_g are added to the formula's. These factors describe the actual influence of part complexity on the manufacturing process. These factors have to be determined for each manufacturing process and are currently not all available in the public domain databases. They will have to be determined based on estimations or test.

Finally, to achieve the total manufacturing times a delay factor is also added. This is the time required to start the process such as machine set up. Resulting in:

$$t = t_{delay} + \tau_0 \sqrt{\left(\frac{x}{v_0 \cdot \tau_0} + 1\right)^2 - 1}$$

Now the manufacturing times can be calculated and the basis for the cost estimation is established. Material cost is added by simple multiplication of material quantity and material unit cost.

B. What kind of data is used for the calculations and how is it available.

For the calculations different kinds of data are needed. These are supplied to the system in different data files. The different data kinds are:

1. ***Manufacturing process and manufacturing method data***. Data describing the individual manufacturing processes and the manufacturing methods in which they are used.
2. ***Manufacturing environment data***. Data describing the environment in which the manufacturing takes place.
3. ***Material data***. Data describing the cost and other data of the materials used for manufacturing a part.
4. ***Connection material data***. Data describing the cost of the materials used for manufacturing a connection, such as fasteners.

1. Manufacturing process and manufacturing method data.

In order to calculate the cost of all the manufacturing processes data about these processes is required. Because the method must be available to people and parties not having access to this data it must be provided with the tool itself. At the moment data is available for a limited amount of manufacturing processes. The data available comes from [2] and contains data for most common composite manufacturing sub-processes. From these manufacturing sub-processes templates have been created combining then into complete manufacturing methods such as hand lay up or Automated Tape Laying.

Currently the available data is stored in a Comma Separated values (CSV) file that is provided with the tool. In future the database can be expanded by adding more sub process entries to the database or by combining sub processes in to templates for overall manufacturing methods. The variables describing sub processes have to be defined by measuring or estimating actual manufacturing times and establishing the relationship to the geometry. An example of the data stored in the CSV file can be seen in Figure 4.

Description	Process_ ID_Number	Equation _Number	Setup	Delay	Vo_1	Tau_1	VarDesc1	Source	Machine_ Rate_ID
Protect_skin	1435	2	420	0	4301.067	36.66	tool_area_c/t_layup_mandrel_OML_cure_tool	tbd	0
Protect_prepreg_charge	1440	2	60	0	17354.8	1436.4	part_area	Neoh1995	0
Pultrude_resin_shell_1895	1450	2	240	0	129.032	0	pultrusion_length	Neoh1995	2
Remove_hoist_assisted_mandrel_braiding	1460	2	60	30	241.935	32.4	tool_length_c/t_layup_mandrel_braiding	Neoh1995	0
Remove_hoist_assisted_part_from_NC_trimmi	1470	2	60	60	387.096	0	part_length	Neoh1995	0
Remove_hoist_assisted_part_from_ultrasonic_	1480	2	60	60	387.096	0	part_length	Neoh1995	0
Remove_hoist_assisted_winding_tool	1490	1	720	0	0	0	0	Neoh1995	0
Remove_lines_resin_injection_RTM_mold	1500	2	40.08	0	7774.178	0	injection_mold_length	Neoh1995	0
Remove_lines_resin_injection_pultrusion_die	1510	1	40.2	600	0	0	0	Neoh1995	0
Remove_lines_thermocouple_RTM_mold	1520	2	100.2	7.2	1554.836	0	injection_mold_length	Neoh1995	0
Remove_lines_thermocouple_pultrusion_die	1530	1	120	300	0	0	0	Neoh1995	0
Remove_lines_thermocouple_cure	1540	2	60	60	580.644	0	part_perimeter	Neoh1995	0
Remove_lines_vacuum_RTM_mold	1550	2	100.2	7.8	6219.342	0	injection_mold_length	Neoh1995	0
Remove_lines_vacuum_cure	1560	2	60	30	4301.067	0	bag_perimeter	Neoh1995	0

Figure 4 Example of some of the manufacturing process data stored in the CSV file

The manufacturing methods are stored in a template file. In this file, the manufacturing processes for each manufacturing method are stored. Furthermore, the cost driver element for the manufacturing method is stored. This can for example be length area or removed volume. The format in which this data is currently stored is JSON. An example is shown in Figure 5.


```
'RTM': {'ID': [240, 50, 1210, 6010, 1250,
               90, 110, 140, 380, 390,
               1500, 1520, 1550, 1770,
               1780, 1730, 240],
        'Layup': [860],
        'MatCostBased': 'Volume'},
```


Figure 5 Manufacturing method data for the RTM process

In addition to the already available data, new manufacturing processes have been added to the database. These processes, in combination with existing processes have been used to add new manufacturing methods. For example the metal machining method has been added by adding the machining roughing and finishing methods and combining these with existing processes into a manufacturing method.

2. Manufacturing environment data

The manufacturing environment data describes the environment in which the manufacture is taking place. This is factory dependent data such as labor rates and the hourly rates of the machines used for the manufacturing processes. Currently this data is stored in the xml format. An example using made up values can be seen in Figure 6.


```
<man_env name="Netherlands_HLU_Batch20" ID="1">
    <info>"This manufacturing environment is a sample environment.
        The values should be used as indicative values, not as reality.
        No sources are used for the data in this environment.
        Created by dr. ir. T. van der Laan."
    </info>
    <ScrapRate>0.1</ScrapRate>
    <BatchSize>20</BatchSize>
    <HourlyRate>90</HourlyRate>
    <MachineRates>
        <info>"These machine rates are sample rates, which may not represent reality.
            The rates are used as indicative values. No sources are used to create these rates."
        </info>
        <MachineRate ID="0">0</MachineRate>
        <MachineRate ID="1">5</MachineRate>
        <MachineRate ID="2">15</MachineRate>
        <MachineRate ID="3">300</MachineRate>
        <MachineRate ID="4">200</MachineRate>
        <MachineRate ID="101">21</MachineRate>
    </MachineRates>
</man_env>
```


Figure 6 Manufacturing environment data example

3. Material data

The material data is the data related to the material used and the main material for manufacturing the part. Currently this consists of a unit cost and of a density. This data is stored in a JSON file. An example can be seen in Figure 7.


```
"Carbon_PPS": {
  "unit_cost": 40,
  "density": 1500
},
"Carbon_PEKK": {
  "unit_cost": 60,
  "density": 1500
},
"AL_2024": {
  "unit_cost": 10,
  "density": 2780
},
"AL_7075": {
  "unit_cost": 15.33,
  "density": 2810
},
```


Figure 7 Example of material data

4. Connection material data.

The connection material data is a combination of data used for determining the fastener cost and data used for determining the material cost for a bonded connection. For fasteners two models are implemented. One for simple unit cost of the faster and one the scales the cost with the size of the fastener. This data is stored in a JSON file. An example can be seen in.

```
# The preset connection materials for bonding can be found here #
'Bonding': {
    # specified adhesives
    'some_glue': {'unit_cost': 18000},
    # a global unit cost for the use of adhesives
    'global_adhesive': {'unit_cost': 10000}
},
# The preset connection materials for mechanical assembly can be found here #
'MechAsm': {
    # exact specified fasteners
    'a_specific_fastener': {'unit_cost': 0.05},
    'standard_blind_rivet_1433478': {'unit_cost': .0412},
    'hex_bolt_rcb6_75': {'unit_cost': .31},
    'AN_6_12_cad': {'unit_cost': .224},

    # general quadratic fits
    'rivet_global': {'quadratic_term': 0.0169,
                     'linear_term': -0.1074,
                     'additive_term': 0.1881},

    'rivet_SS': {'quadratic_term': 0.004687,
                 'linear_term': -0.02175,
                 'additive_term': 0.0738},
```

Figure 8 Example of connection material data

C. What is the software platform used

The software platform used must be publically available. Therefore Python [7] was chosen as the implementation platform. This software is available at most companies and institutes involved in MDO. Therefore, by choosing this platform the software code behind the estimation method is accessible. In the python platform, no proprietary libraries are used to ensure the tool itself remains publically available. Used as a python library the cost estimation tool can also be easily integrated into other python tools.

D. What are in and output formats and content

As was stated in the requirements the in- and outputs of the tool must be transparent and accessible by other software tools to fit in an MDO framework. For these reasons, the XML format was chosen to provide in and output for the tools.

Inputs

The tool gets the input through an XML file defining the parts and connections of a complete assembly. The cost analysis tool will determine the cost of all the specified parts and connections (Figure 9). For a part the information required consists of part name, material information, manufacturing information, geometrical details and complexity information. Some of the inputs are optional, such as the complexity information (Figure 11 and Figure 12). For a connection the connected parts and the geometric and manufacturing details of the connection must be specified (Figure 10). The inputs for the cost estimation tool can also be contained in a CPACS file [8]. The CPACS format is a standardized XML format containing an aircraft system. In this case, the assembly XML node must be specified in the tool specific part of the CPACS file.

```xml
<Assembly>
    <Parts>
        <Part...>
        <Part...>
    </Parts>
    <Connections>
        <Connection...>
        <Connection...>
    </Connections>
</Assembly>
```

Figure 9 Definition of the assembly in the cost tool input

```xml
<Connection>
    <name>Upper Skin Connection</name>
    <connected_parts>
        <part>
            <idx>0</idx>
            <name>Upper Closure Rib</name>
        </part>
        <part>
            <idx>1</idx>
            <name>Skin Panel</name>
        </part>
    </connected_parts>
    <manufacturing_process>IndWelding</manufacturing_process>
    <interface_area>7342</interface_area>
    <interface_width>15</interface_width>
    <interface_length>100</interface_length>
</Connection>
```

Figure 10 Connection details in the cost tool input

```xml
<Part>
    <name>SKIN | side_1 | panel_0</name>
    <manufacturing_process>Hand_Layup</manufacturing_process>
    <manufacturing_environment>Netherlands_ATP_Batch10</manufact
    <part_avg_thickness>1.9407628603201001</part_avg_thickness>
    <part_length>3510.626003419448</part_length>
    <part_width>1119.1963448801253</part_width>
    <part_height>114.91252643263316</part_height>
    <part_weight>9.094220924582823</part_weight>
    <part_perimeter>9259.644696599145</part_perimeter>
    <interface_area>207942.80706443544</interface_area>
    <part_area>3089435.9906716123</part_area>
    <a_flat>2276549.7633424695</a_flat>
    <a_single>693000.7112594831</a_single>
    <a_double>0</a_double>
    <i_single>3975.769901955379</i_single>
    <i_double>0.2599552586326477</i_double>
    <i_sharp>0</i_sharp>
    <layup...>
    <sharp_geodesic>[]</sharp_geodesic>
</Part>
```

Figure 11 Part details in the cost tool input

```xml
<layup>
    <layer>
        <layer_idx>0</layer_idx>
        <material>Carbon_PPS</material>
        <thickness>0.31</thickness>
        <orientation>45.0</orientation>
        <area_fraction>0.9999999971610956</area_fraction>
        <quantify>1</quantify>
    </layer>
    <layer...>
    <layer...>
</layup>
```

Figure 12 Lay-up details in the cost tool input

Output

The baseline output format is XML, because most other software tools can interpret this. The exported data in the output XML is configurable through a configuration file. This means that one can only export the total cost and or manufacturing times for assembly parts and connections or one can request all the details for all sub processes of all manufacturing methods. In which case all costs and times for all manufacturing processes are reported. Using this feature the output can be tailored to the specific needs of the MDO flow or environment in which the tool is used. Example of some typical XML outputs are shown in Figure 13, Figure 14 and Figure 15.

Besides the XML format the tool also supports exports in the XLSX and PDF formats. Like with the XML outputs the content and form of the output can be configures though a configuration file. The support of these formats increases the compatibility with more MDO flows and increases user acceptance and user interaction as these formats, because these formats are better human readable.

```xml
<Assembly_Totals>
  <Total_cost>618.9</Total_cost>
  <Material_cost>108.05</Material_cost>
  <Machine_cost>16.0</Machine_cost>
  <Process_cost>494.85</Process_cost>
  </Assembly_Totals>
```


Figure 13 XML entry for assembly cost totals


```xml
<Part_Totals>
  <Costs>
    <total_cost>67.85</total_cost>
    <material_cost>0.67</material_cost>
    <total_labour_cost>61.7</total_labour_cost>
    <total_machine_cost>5.48</total_machine_cost>
    </Costs>
  <Times />
  </Part_Totals>
```


Figure 14 XML entry for part cost totals


```xml
<Connection_Totals>
  <Costs>
    <total_cost>29.55</total_cost>
    <material_cost>0</material_cost>
    <total_labour_cost>28.48</total_labour_cost>
    <total_machine_cost>1.07</total_machine_cost>
    </Costs>
  <Times />
  </Connection_Totals>
```


Figure 15 XML entry for connection cost totals

IV. Examples of tool integrations

A. Example Integration of the tool in KBE framework

At GKN Fokker the cost estimation tool is integrated in a KBE framework for designing and optimizing aircraft wings and wing movables called the Multi-Disciplinary Modeler (MDM), part of this MDM is the moveable generator [9]. This KBE framework is developed in Python using a commercial python KBE library called Parapy [10]. This framework uses several different analysis tools of which the open source cost tool is one. In the framework, the user can calculate the part cost or the total component cost using the Graphical User Interface. It is also possible to export the cost results in a predefined template. An example of the total cost determined in the MDM by the open source cost tool is shown in Figure 16.

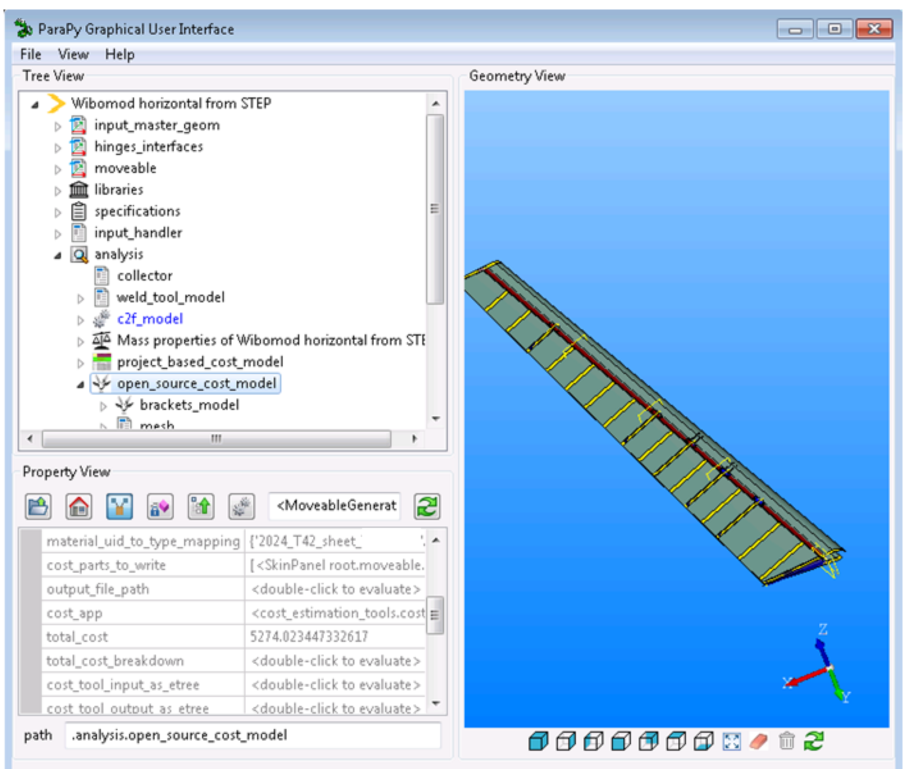

Figure 16 MDM instantiation of an aircraft movable with total cost determined by the open source cost tool

In the KBE platform, all the inputs needed for the open source cost tool are automatically extracted from the geometry. Most of this data is extracted using measurement tools incorporated in the Parapy platform. However, for some of the inputs more complex algorithms are used. For example, the curvature or complexity contents described in section II.b are extracted using the built in mesh capability of the KBE platform. What this looks link in the MDM is shown in Figure 17.

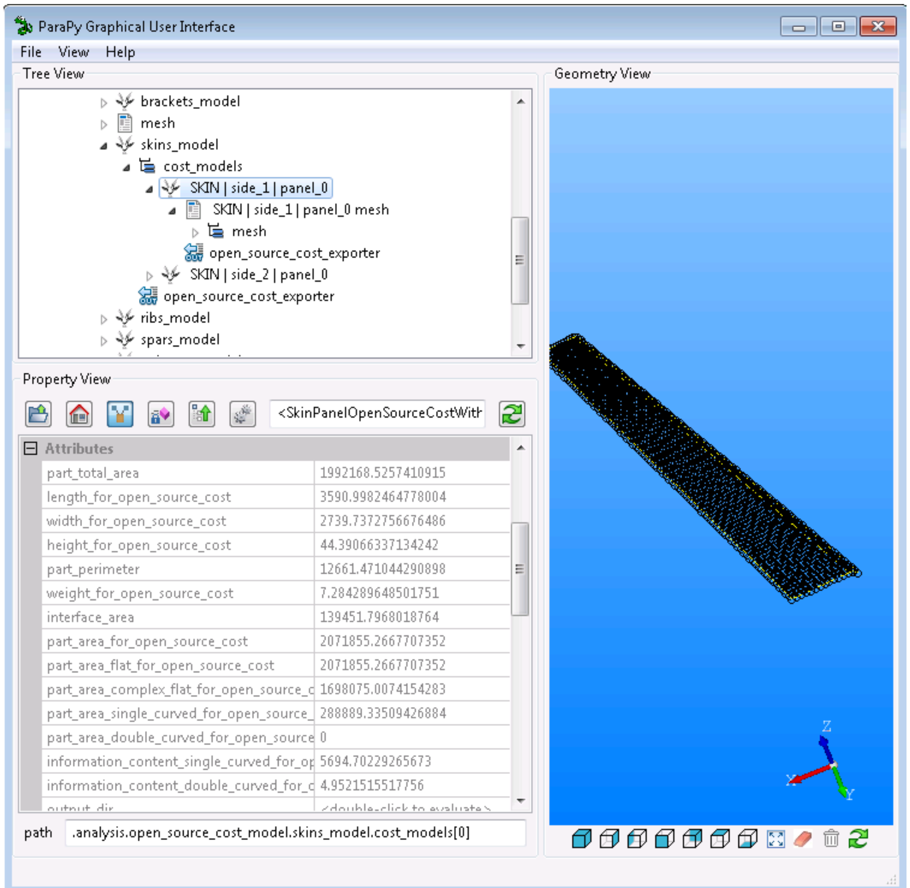

Figure 17 Definition of open source cost tool inputs in the MDM determining complexity data using built in meshing capability

Because the MDM is a python tool it is actually possible to use the open source cost tool without going through in and output files. It uses the tool directly by loading it as a python library. Advantage of this is that the performance is much better then when using in and output files. This performance advantage will become even more apparent when doing large Design Of Experiments or when doing optimizations.

B. Example Integration of the tool in multi company and multi-national optimization framework

Within the AGILE 4.0 consortium the cost estimation tool is going to be used in application cases focusing on including manufacturability in the optimization process. For this purpose a multi company and a multi-site workflow is set up to perform a Multi-Disciplinary Analysis (MDA). In this MDA the open source cost tool is run as a stand-alone tool. It gets its data from the flap generator, which is in fact part of the MDM described in the previous section. The flap generator is running at GKN-Fokker while the open source cost tool is running at Delft University of Technology as a separate python tool. The workflow software used in RCE [11] while cross company dataflow issues are being taken care of by BRICS[12]. In this MDA the data required by the open source cost tool is stored in the tool specific part of a CPACS file. The workflow is depicted in Figure 18.

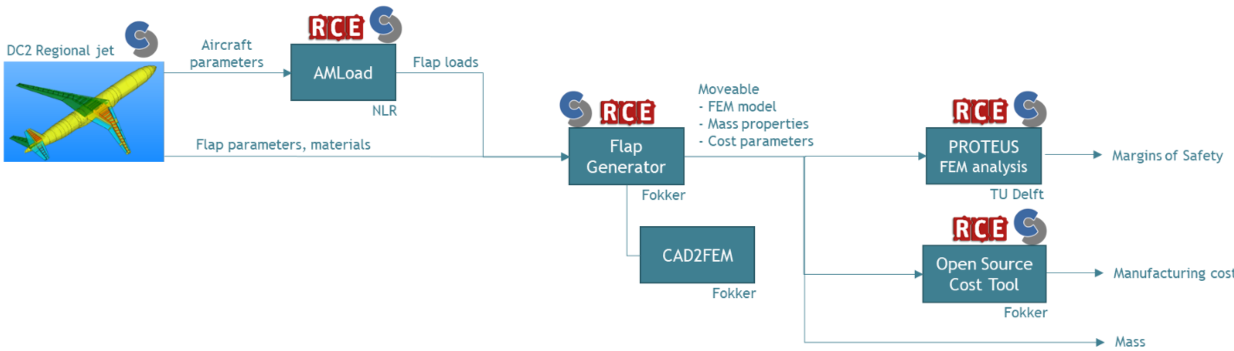

Figure 18 Agile 4.0 MDA workflow including the open source cost tool

In Agile 4.0 a simple flap is used as the test case. The flap generate is positioned in a regional jet type aircraft. Different flap kinematics and sizes are analyzed in separate MDA's so they can be compared. What one of those flap concepts looks like can be seen in Figure 19.

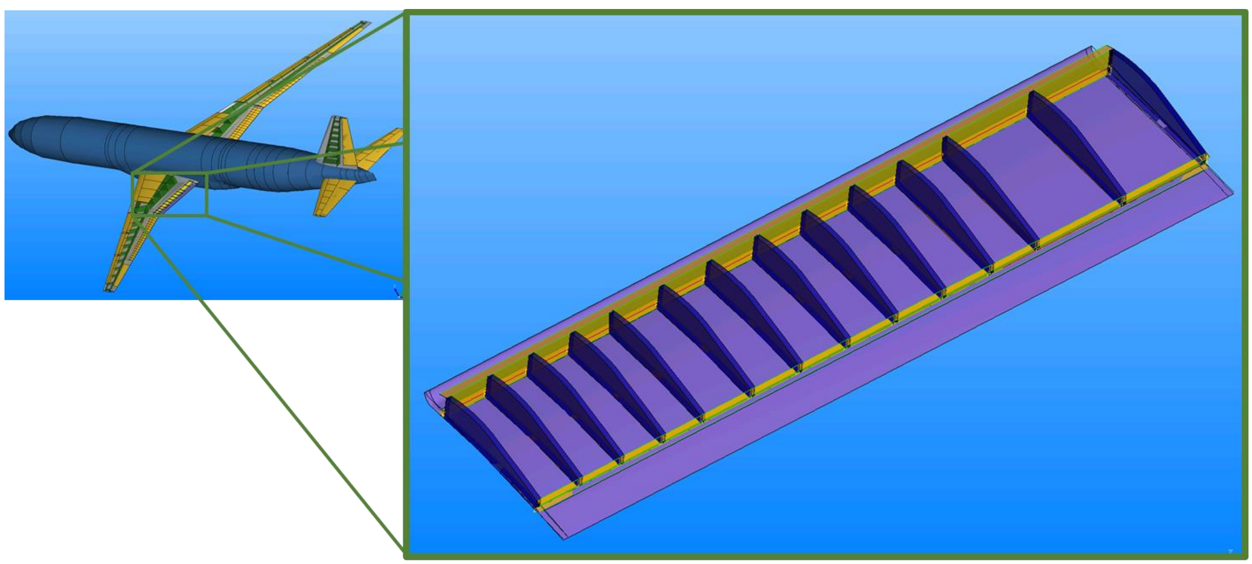

Figure 19 Flap analyzed in the Agile 4.0 MDA

The results of the open source cost analysis of a flap are shown in Table 1. When analyzed the result from the open source cost tool show that all parts in the flap that are part of the movable generator model can be included in the analysis. Currently the connections are missing because they are not part of the flap generator model. Therefore, the cost will be underestimated. The part cost themselves also seem to be on the low side when comparing to proprietary in house cost estimation tools. Finally, the movable generator is only generating data for the main structural elements, missing smaller elements such as connection angles. This again means the manufacturing cost is underestimated.

Despite the underestimation of the cost, the different MDA's do show the correct direction of cost. So if certain parameters change, like flap size, the cost change in the same direction as when using an in house proprietary tool. Therefore, the open source cost tool will provide the correct cost estimation direction when used in an optimization.

Table 1 Cost estimation results for a flap

part_name	manufacturing_method	total_cost [$]	total_proc_time [sec]
SKIN | side_1 | panel_0	Hand_Layup	6091.09	19930.74
SKIN | side_2 | panel_0	Hand_Layup	5895.69	19499.83
RIB | station_0 | group_0 | rib_0	RubberForming	143.56	4646.54
RIB | station_1 | group_0 | rib_0	Hand_Layup	310.84	7599.84
RIB | station_2 | group_0 | rib_0	Hand_Layup	309.84	7588.1
RIB | station_3 | group_0 | rib_0	Hand_Layup	308.96	7577.64
RIB | station_4 | group_0 | rib_0	Hand_Layup	308.21	7568.96
RIB | station_5 | group_0 | rib_0	Hand_Layup	307.44	7559.82
RIB | station_6 | group_0 | rib_0	Hand_Layup	306.63	7550.23
RIB | station_7 | group_0 | rib_0	Hand_Layup	305.79	7540.31
RIB | station_8 | group_0 | rib_0	Hand_Layup	304.93	7529.95
RIB | station_9 | group_0 | rib_0	Hand_Layup	304.18	7520.96
RIB | station_10 | group_0 | rib_0	Hand_Layup	303.22	7509.44
RIB | station_11 | group_0 | rib_0	Hand_Layup	302.39	7499.47
RIB | station_12 | group_0 | rib_0	Hand_Layup	301.52	7489
RIB | station_13 | group_0 | rib_0	RubberForming	128.58	4189.03
SPAR | station_0	Hand_Layup	552.22	9352.06
SPAR | station_1	Hand_Layup	407.37	8243.44
inboard_mechanism_smart_flap_carriage	Machining	1008.3	3931.62
inboard_mechanism_smart_flap_support	Machining	119.39	1031.81
inboard_mechanism_rotation_actuator	Machining	52.24	737.17
inboard_mechanism_translation_actuator	Machining	65.4	801.53
outboard_mechanism_smart_flap_carriage	Machining	1089.09	4075.05
outboard_mechanism_smart_flap_support	Machining	115.79	1023.11
outboard_mechanism_rotation_actuator	Machining	52.92	740.58
outboard_mechanism_translation_actuator	Machining	68.01	814.03
Totals		19463.6	169550.26

V. Discussion, how can the tool be used and what should be done to improve its usefulness

Currently the tool supports a limited number of manufacturing and connection methods. These methods suffice to support most common concepts in aeronautical structural design however; some methods are bound to be missing and should be added to future versions.

The absolute values of the cost tools are not comparable to the results created with proprietary cost tools and for some methods not even in the same ballpark, e.g. 50% off. This makes it difficult to compare completely different manufacturing concepts. Within the manufacturing concepts themselves the trends are correct. This should be taken into account when using the open source cost tool in an MDO environment.

Complexity measurements, while included in the core of the tool, are not fully supported yet. Currently all tests are performed without taking complexity into account. It is the goal to first get proper understandable results for the manufacturing methods without considering complexity and then switch the existing complexity code on. However, this will happen only in a future release.

Finally, the processes used for defining the manufacturing methods must be checked for correctness. Currently some results show an overwhelming effect of certain manufacturing sub processes reducing the influence of other sub-processes in a manufacturing method. The logic behind this needs to be checked, is it, from a manufacturing point of view, logical that this one sub-process is so important. Another aspect is the age of the database data, because it is 25 years old it might have been overtaken by the current state of the art. When considering this it should be noted that the cost tool is only intended to be used to give qualitative feedback on manufacturing cost in an MDO environment. In other words, the actual quantification of the cost is not relevant as long as the cost feedback is enough to select the most cost effective manufacturing method.

VI. Conclusions

The cost tool described in this paper meets the requirements for applicability in an MDO environment. It used open source data and therefore has no proprietary limitations. It also used geometrical input and differentiates based on differences in geometric complexity. This allows for example the integration in a framework where aerodynamics and manufacturing are included. Aerodynamic optimization changes the geometry and the tool presented here can give feedback on the cost implications. To ensure the tool can be integrated in an MDO framework common programming platforms and data formats are used.

The development of this tool is certainly not finished and should therefore be taken further. The openness of the standards, databases and data formats used allow this. Because this tool only uses data from the public domain anyone can add to it.

VII. Tool distribution

The Open source cost tool will be publically available and will be distributed under the Apache-2.0 License. The tools has been named CATMAC (Cost Analysis Tool for Manufacturing of Aircraft Components). The code is hosted on Github: https://github.com/COC-Design-GKN/CATMAC . However, it is currently not publically available. To get access please sent an e-mail to the main author of this paper. In future CATMAC will also be hosted as a library on the pip server to enable installation through pip install. The authors of this paper sincerely hope that reader of this paper will use, improve and expand this tool.

VIII. Acknowledgments

The research presented in this paper has been performed in the framework of the AGILE 4.0 project (Towards cyber-physical collaborative aircraft development) and has received funding from the European Union Horizon 2020 Program under grant agreement n◦ 815122.

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