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Aircraft Bi-level Life Cycle Cost Estimation

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Abstract. In an integrated aircraft design and analysis practice, Life Cycle Cost (LCC) is essential for decision making. The LCC of an aircraft is ordinarily partially estimated by emphasizing a specific cost type. However, an overview of the LCC including design and development cost, production cost, operating cost and disposal cost is not provided. This may produce biased cost estimates. Moreover, aircraft LCC estimation is largely dependent on the availability of input parameters. It is often a problem for the analyst to supply a limited group of data into a detailed cost estimation process. Therefore, it is necessary to provide flexibility in conducting both high level and detail level LCC assessments based on the data accessibility. An input-dependent bi-level LCC estimation method is proposed. It illustrates the comprehensive estimation of the cost elements in the LCC with clearly defined high level and detail level analyses to form the final cost. Knowledge of the product and the life cycle process are structured based on a pre-defined meta model and logic rules. Cost is then evaluated by traversing the meta model linked with computing capabilities. This method is applied on a case study concerning A330-200 aircraft. With the support of weight estimation and bottom-up process-based parametric cost estimation methods, it builds up a practical costing approach in quantifying the influence of LCC to the product life cycle.

Keywords. Life Cycle Cost, cost estimation, design for cost

Introduction

LCC analysis was initiated in the early 70s by the US DoD [1-4]. It aimed at providing guidelines for equipment/system procurement. Gradually, life cycle costing has been employed to support decision making. Various authors have reviewed the state of the art in LCC analysis over the years [5-9]. In summary, LCC estimation tends to achieve accurate engineering simulations by modelling product and relevant processes, identifying cost compositions, evaluating cost driving parameters, and establishing analytical relationships, especially parametric Cost Estimation Relationships (CERs).

When reviewing the recent research on LCC estimation, most LCC models are dedicated to certain LCC components such as manufacturing cost and operating cost. However, an integrated and systematic LCC estimation methodology is still missing. Furthermore, most of the LCC analyses are largely dependent on the availability of the input parameters and their level of detail. It leads to obstacles for analysis with limited resources. This paper presents an input-dependent bi-level LCC estimation methodology which is built on the basis of both high level and detail level costing

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methods. The emphasis is also drawn on the integration of the cost module with aircraft geometry and life cycle process details. In Section 1, the proposed framework is illustrated along with the corresponding costing methods. Section 2 shows the initial attempt of applying the method on an A330 Aircraft (A/C) case. Next, conclusions considering the framework implementation and challenges are highlighted. It is followed by the discussions of future steps for this development.

1. Methodology

The framework addresses a systematic LCC estimation process. Two levels of analysis methods based on the availability of input parameters are developed, see Figure 1. If only weight estimation can be conducted based on the geometric and material parameters, high level LCC estimation adopting weight as the main cost driving parameter is implemented; if the parameters and rules relevant to geometry re-segmentation and process planning are available, the detail level cost estimation using extended Bill of Materials (BOM) will be implemented. The process planning is conducted based on the process meta model and operational rules to obtain a product specific LCC process. Thereafter, an extended BOM containing lists of product properties is generated for detail level LCC estimation. After all the cost elements needed for the economic indices are obtained, the cost estimation is completed. If the cost estimation method is not designated in advance, the detail level LCC estimation will supersede the high level LCC estimation. The high level LCC estimation method is only applied when there is not enough data available for the detailed level LCC estimation, *i.e.* when the parameters for the detailed LCC estimation are missing or cannot be derived.

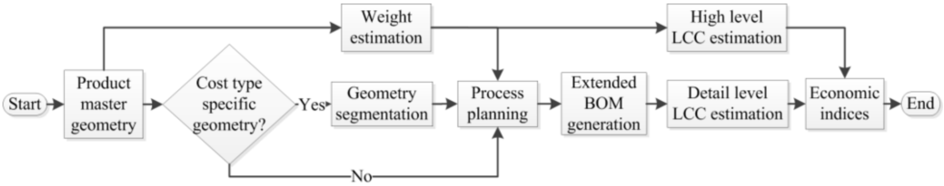

Figure 1 Bi-level cost estimation framework

1.1. Aircraft component in life cycle process

1.1.1. Product model

Based on the cost type which will be evaluated, the parameters needed for the estimation vary correspondingly. This leads to a pre-processing step of generating categorized data groups, which are specific to certain geometry properties and processes. Therefore, the detailness and the emphasises of the product models needed for different cost types are distinct, in the meantime, they are all on the basis of the same master geometry. For high level cost estimation in this research, only weight information evaluated based on the master geometry is needed. Whereas, for detailed level cost estimation, geometry re-segmentations and/or cost type specific properties extraction are needed for all four cost types involved in the LCC.

1.1.2. Life cycle process model

The A/C life cycle is processed in four major phases: Research, Development, Test and Evaluation (RDT&E), production, operating & maintenance and disposal & recycling. Each phase is further elaborated into respective process flow meta model. The activities involved in a specific A/C life cycle is predicted based on the process flow meta models and the rules used for deriving detailed activities according to the design and process properties. An example of an applicable process model for the operation and maintenance life cycle phase is given in Figure 2.

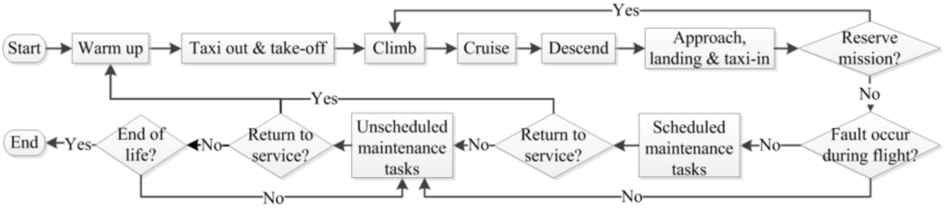

Figure 2 Operation & maintenance process model

1.2. LCC estimation

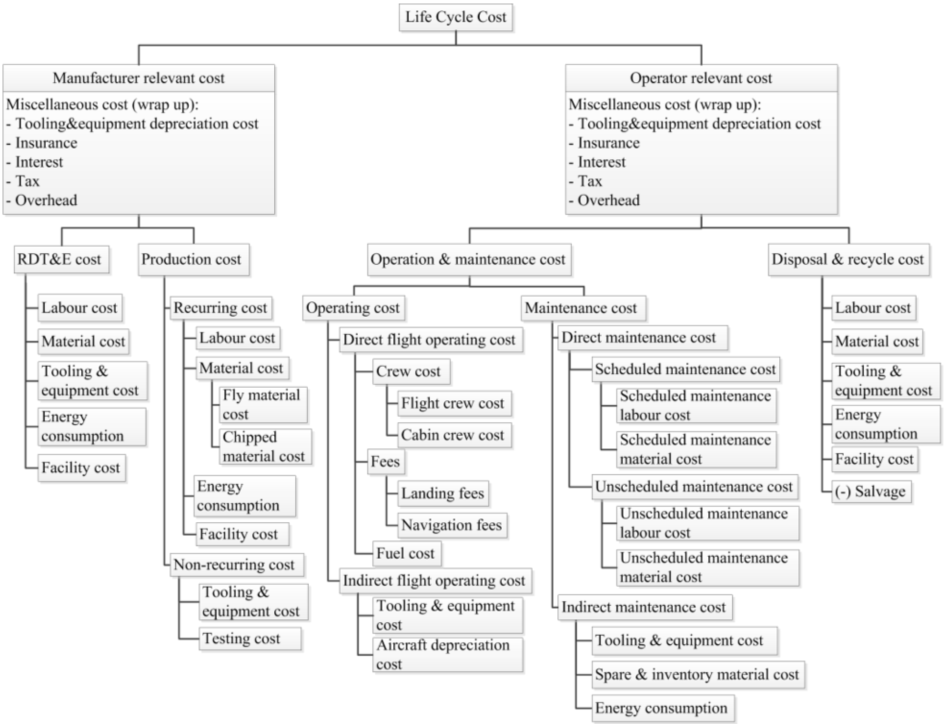

Figure 3 Life Cycle Cost breakdown

The CBS for LCC is illustrated in Figure 3 with a comprehensive division summarized from cost estimation practices. It is divided in two streams on the basis of two main stakeholders: the manufacturer and the operator. Miscellaneous costs such as tooling and equipment depreciation cost, insurance, interest, tax and the overhead, which mainly depends on the companies' strategies, are categorized and quantified as wrap up factors. Some companies allocate percentages on the estimates to represent those cost impacts, while others assign a fixed amount to quantify their influences on the LCC. Furthermore, more detailed cost breakdown is built up separately for the RDT&E, production, operation & maintenance and disposal & recycling cost type. The cost elements under each cost type vary based on the various LCC characteristics. For example, the recurring cost and nonrecurring cost are defined specifically for the production cost, while for operating and maintenance cost the direct cost and indirect cost are established. There are also typical cost types such as labour cost, material cost, tooling & equipment cost, energy consumption and facility cost appear in all cost categories. The labour cost is generally time dependant and the material cost are product dependant, while the other cost types are often related to the company policies. In this paper, the labour and material costs are the most focused elements and are less dependent on the company strategies. Therefore, they are elaborated in next sections 1.2.1 and 1.2.2.

1.2.1. High level model

High level cost model adopts weight/mass as cost driving parameters. It is built based on the product breakdown and the cost breakdown, while due to the limited available knowledge, the process plan is not considered on this level comparing with the detail level cost estimation. The estimations are generalized in Eqs. (1) - (3).

$$C_{i,j} = f_{i,j}\left(W\right) \qquad \text{[when } j \text{ refers to labour cost]} \tag{1}$$

$$C_{i,j} = r_{i,j}W \qquad \text{[when } j \text{ refers to material/fuel cost]} \tag{2}$$

$$C_{LCC} = \sum_{i} C_i = \sum_{i}\sum_{j} C_{i,j} \tag{3}$$

Where, f represents the equation evaluating the labour / material cost (t) for each LCC phase. Generally, the expression is obtained from statistical data analyses based on A/C weight (W) using power law models or polynomial regressions. The weight contains both the flying weight and chipped weight. r stands for the labour rate in $\$/hr$ or the unit price in $\$/kg$. i symbolizes one of the four LCC phases, j is the cost item such as labour cost and material cost shown in the CBS under each LCC cost type.

1.2.2. Detail level model

Detail level model is implemented when the data relevant to the product design and its life cycle operations are accessible. In addition, inference mechanisms relevant to deriving the process properties should also be available when applying this model. The detail level cost estimation allocates the CBS cost items under each process step shown in Figure 2 with the same cost structures (Figure 3) as they are in the high level cost estimation. Comparing with the high level model, an extra layer of process step prediction and relevant processing activities are inserted in the model between the product geometry and the cost estimation, which can also be observed from Figure 1. Labour time estimation/collections are conducted on each process step level. The driving parameters for the time analysis are not limited on weight/mass but parameters more closely linked with the process steps based on physics and/or statistics. Once the labour times of the detailed process steps are obtained, cost time analyses are implemented to accumulate the LCC. The general formulations of the process step cost time evaluations are highlighted in Eqs. (4)-(7).

$$t_{i,k,j} = f_{i,k,j}\left(x\right) \qquad \text{[when } j \text{ refers to labour cost]} \tag{4}$$

$$C_{i,k,j} = r_{i,k,j} t_{i,k,j} \qquad \text{[when } j \text{ refers to labour cost]} \tag{5}$$

$$C_{i,k,j} = r_{i,k,j}\left(\Delta W\right) \qquad \text{[when } j \text{ refers to material/fuel cost]} \tag{6}$$

$$C_{LCC} = \sum_i C_i = \sum_i \sum_k C_{i,k} = \sum_i \sum_k \sum_j C_{i,k,j} \tag{7}$$

Where, f represents the equation evaluating the labour time (t) for each process step in the aircraft life cycle. Generally, the expression is obtained from statistical data analyses based on design and process parameters (x) using power law models or physical approximations. For example, the composite manufacturing process are approximated by first order law models and further adapted to hyperbolic function models [10]. r, i and j are the same as they are in the high level costing. The added footnote k represents process steps derived based on the process meta models. ΔW is the A/C weight (or the fuel weight in a flight trip operating process) increase or decrease during the operation of each process step.

2. Case study-A330 flight trip operating cost example

2.1. Trip operating process

Figure 4 illustrates a typical aircraft mission profile for a trip of flight operating. Time and fuel consumption are deployed on each operating process segment. The Reserve fuel required includes the contingency trip fuel, alternative fuel and the final reserve fuel. Three operating cost items, *viz.*, the crew cost, the airport charge fee and the fuel cost are estimated for the flight mission profile.

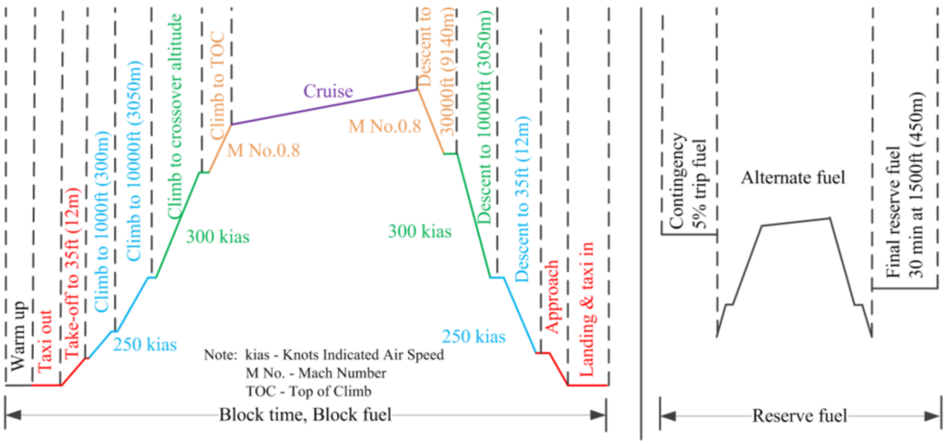

Figure 4 Aircraft mission profile [11-14]

2.2. High level model

The operating relevant items in the DOC + I method [15] are adapted for high level trip operating cost estimation, see Eqs. (8)-(12). Less than 20 parameters are required for this estimation.

$$t_{operating,crew} = \frac{R}{V} \tag{8}$$

$$C_{operating,crew} = \left[482 + 0.590(MTOW/1000) + \left(n_{seat}/30\right)78\right] t_{operating,crew} (1 + r_{\inf lation})^{y-y_0} \tag{9}$$

$$C_{operating,fee} = \left[4.25\left(MTOW/1000\right) + 0.136 \times 500\sqrt{MTOW/1000}\right](1 + r_{\inf lation})^{y-y_0} \tag{10}$$

$$W_{fuel} = MTOW\left(\frac{W_{fuel}}{MTOW}\right) \tag{11}$$

$$C_{operating,fuel} = r_{operating,fuel} W_{fuel} \tag{12}$$

Where, operating time for crew cost ($t_{operating,crew}$) is obtained from range (R) and speed (V). Operating crew cost ($C_{operating,crew}$) is calculated based on Maximum Take Off Weight ($MTOW$) and seat capacity (n_{seat}). Operating fee ($C_{operating,fee}$) is based on $MTOW$. The fuel weight is the production of the jet fuel price ($r_{operating,fuel}$) and fuel weight (W_{fuel}), which is related to the fuel weight fraction ($\frac{W_{fuel}}{MTOW}$). Since DOI + I adopts the mid-1993 money, which is converted to 2015 money by applying the constant inflation rate $r_{\inf lation}$ from the reference fiscal year (y_0) to the fiscal year (y) in Eqs. (8) and (9). The total operating cost is then the summation of crew, fee and fuel expenses.

2.3. Detail level model

Time and fuel calculations for the segments of the mission profile are adopted for the detail level trip operating cost model. More than 60 parameters are needed for this estimation.

Warm-up: Warm-up crew cost ($C_{operating,warm-up,crew}$) is estimated based on an average operating time ($t_{operating,warm-up,crew}$) [14], the hourly rates ($r_{operating,warm-up,flight-crew}$, $r_{operating,warm-up,cabin-crew}$) and the numbers of flight and cabin crew ($n_{flight-crew}$, $n_{cabin-crew}$), see Eq. (13). The fuel cost is obtained from the fuel rate ($r_{operating,warm-up,fuel}$) and the consumed fuel mass ($W_{operating,warm-up,fuel}$) according to empirical weight fraction, see Eqs. (14)-(15).

$$\begin{aligned} C_{operating,warm-up,crew} &= r_{operating,warm-up,flight-crew} t_{operating,warm-up,crew} n_{flight-crew} \\ &+ r_{operating,warm-up,cabin-crew} t_{operating,warm-up,crew} n_{cabin-crew} \end{aligned} \quad (13)$$

$$W_{operating,warm-up,fuel} = \Delta W_{warm-up} = \left(1 - \frac{W_{warm-up}}{MTOW}\right) MTOW \quad (14)$$

$$C_{operating,warm-up,fuel} = r_{operating,warm-up,fuel} W_{operating,warm-up,fuel} \quad (15)$$

Taxi-out and take-off: Since the time of a smooth taxi-out and take-off is very little, the crew cost due to this operation segment can be neglected. The fuel weight fraction is employed for the fuel cost evaluation by adopting $\frac{W_{TO}}{MTOW}$ in Eq. (14) and corresponding fuel weight ($W_{operating,TO,fuel}$) in Eq. (15). In addition, the take-off charge is assessed as part of this segment cost. Based on the airport charge report [16], Eq. (16) shows that the cost including the weight based take off charge ($r_{operating,TO,fee} W_{TO}$), and the service charge ($r_{service} n_{seat} r_{occupancy}$), security fee ($r_{\sec urity} n_{seat} r_{occupancy}$) and Passengers with Reduced Mobility (PRM) levy ($r_{PRM\_levy} n_{seat} r_{occupancy}$), which all based on the number of available seat ($n_{seat} r_{occupancy}$).

$$\begin{aligned} C_{operating,TO,fee} &= r_{operating,TO,fee} W_{TO} + r_{service} n_{seat} r_{occupancy} \\ &+ r_{\sec urity} n_{seat} r_{occupancy} + r_{PRM\_levy} n_{seat} r_{occupancy} \end{aligned} \quad (16)$$

Climb: According to the typical climb law, three climb segments are considered (Figure 4): from 0ft (0m) to 10000ft (3050m) at constant 250 knots Indicated Air Speed (IAS); from 10000ft to crossover altitude above 30000ft (9140m) at constant 300 knots (IAS); from 30000ft to the Top of Climb (TOC) 36000ft (11000m) at constant 0.80 Mach [17]. The climb IAS should be converted to Ground Speed (GS) [14]. Therefore, the time to climb ($t_{operating,c\lim b,crew}$) is the aggregation of the time ($\left(\Delta t_{operating,c\lim b,crew}\right)_l$)

for each climbing segments l, which is the integral of altitude (h) over the Rate of Climb (R/C), also represents the vertical velocity [11], see Eqs. (17) and (18).

$$t_{operating,c\lim b,crew} = \sum_{l} \left(\Delta t_{operating,c\lim b,crew} \right)_l \tag{17}$$

$$\left(\Delta t_{operating,c\lim b,crew} \right)_l = \int_{h_{initial}}^{h_{final}} \frac{dh}{R/C} \tag{18}$$

Assume the R/C changes linearly with the change of the altitude, then

$$\left(\Delta t_{operating,c\lim b,crew} \right)_l = \frac{h_{l+1} - h_l}{R/C_{l+1} - R/C_l} \ln \left(\frac{R/C_{l+1}}{R/C_l} \right) \tag{19}$$

Where, the R/C can be evaluated according to force equilibrium during climb [13], Eq. (20) applies. It is calculated by applying formulas of thrust (T) and density (ρ) at altitude h, converting IAS to GS as V_∞ ([13] and [17]), and substituting average weight during climb (W), reference area (S), zero-lift drag coefficient (C_{D_0}) and drag due to lift coefficient (K). Thereafter, the operating climb crew cost can be obtained by employing Eq. (13) while using $t_{operating,c\lim b,crew}$ for the time term.

$$R/C = V_\infty \left[\frac{T}{W} - \frac{1}{2} \rho V_\infty^2 \left(\frac{W}{S} \right)^{-1} C_{D_0} - K \frac{2}{\rho V_\infty^2} \left(\frac{W}{S} \right) \right] \tag{20}$$

The operating climb fuel cost is estimated by accumulating fuel consumption for each climb segment based on the average Specific Fuel Consumptions ($(SFC)_{ave,l}$), the thrust (T_l) and the segment time ($\left(\Delta t_{c\lim b} \right)_l$), see Eq. (21). With the combination of Eq. (15) while adopting $W_{operating,c\lim b,fuel}$ in the calculation, the fuel cost is obtained.

$$W_{operating,c\lim b,fuel} \approx \sum_{l} \left(\Delta W_{c\lim b} \right)_l = \sum_{l} (SFC)_{ave,l} T_l \left(\Delta t_{c\lim b} \right)_l \tag{21}$$

Cruise: Assume the aircraft cruises at altitude 36000ft (11000m) at Mach 0.8. The crew cost is calculated based on the time to cruise by Eq.(8) from the high level cost model while employing cruise range (R_{cruise}) and cruise speed ($V_{\infty,cruise}$), and substituting $t_{operating,cruise,crew}$ in Eq.(13). The Breguet range equation (Eq.(22)) is adopted to estimate the fuel consumption, where the lift drag ratio (L/D) is needed, see Eqs. (23) and (24). The fuel cost is again obtained by utilizing $W_{operating,cruise,fuel}$ in Eq.(15).

$$R_{Cruise} = \frac{L/D}{SFC} \frac{V_\infty}{g} \ln \frac{W_{cruise,initial}}{W_{cruise,final}} \tag{22}$$

$$W_{cruise,final} = W_{cruise,initial} \exp \frac{-R_{Cruise} SFCg}{V_{\infty}(L/D)} \tag{23}$$

$$W_{operating,cruise,fuel} = \Delta W_{cruise} = W_{cruise,initial} - W_{cruise,final} \tag{24}$$

Descent: A descent process is a reversed process of climb. Three descent segments are considered: from the Top of Descent (TOD) 39000ft (11890m) to 30000ft (9140m) at constant 0.80 Mach; from 30000ft to 10000ft (3050m) at constant 300 knots IAS; from 10000ft (3050m) to 35ft (300) at constant 250 knots [17]. During descent, the engine thrust is normally set to flight idle, *i.e.* the thrust is close to zero, and the speed is controlled by the aircraft altitude [13]. Similar to R/C, the rate of descent (R/D) is applied for crew cost evaluation (Eqs. (25) and (26)), while the empirical weight fraction ($\frac{W_{descent}}{MTOW}$) is adopted by fuel cost calculation using Eqs. (14) and (15) while replacing the corresponding weight parameter ($W_{operating,descent,fuel}$) for descent segment.

$$\left(\Delta t_{operating,descent,crew}\right)_l = \frac{1}{a}\int_l^{l+1} \frac{1}{R/D} d(R/D) = \frac{h_{l+1} - h_l}{R/D_{l+1} - R/D_l} \ln\left(\frac{R/D_{l+1}}{R/D_l}\right) \tag{25}$$

$$R/D = -\frac{1}{C_L/C_D} V_{\infty} = -V_{\infty}\left[C_{D_0}\left(\frac{1}{2}\rho V_{\infty}^2\right)\left(\frac{W}{S}\right)^{-1} + K\left(\frac{1}{2}\rho V_{\infty}^2\right)^{-1}\left(\frac{W}{S}\right)\right] \tag{26}$$

Approach, landing and taxi-in: Similar to taxi-out and take-off segment, the time of a smooth approach, landing and taxi-in is negligible. The fuel cost is based on the weight fraction ($\frac{W_{landing}}{MTOW}$), Eqs. (14) and (15) with the counterpart parameters apply. The airport landing fee is considered for this segment including the weight based landing fee ($r_{operating,landing,fee} MTOW$), the government noise levy ($r_{gov\_noise/insulation\_levy}$) and weight based planning compensation levy ($r_{gov\_planning\_levy} \times MTOW$)[16] (Eq. (27)).

$$\begin{aligned} C_{operating,landing,fee} &= r_{operating,landing,fee} MTOW + r_{gov\_noise/insulation\_levy} \\ &+ r_{gov\_planning\_levy} \times MTOW \end{aligned} \tag{27}$$

Reserve: It is assumed the reserve fuel is carried but not used, therefore, the crew cost due to the time for reserve is zero. According to Raymer [11], 5% reserve fuel and 1% trapped fuel are considered.

In summary, the Total operating trip cost is obtained from the following:

$$\begin{aligned} C_{operating} &= C_{operating,warm-up} + C_{operating,to} + C_{operating,c\lim b} + C_{operating,cruise} \\ &+ C_{operating,descent} + C_{operating,landing} + C_{operating,reserve} \end{aligned} \tag{28}$$

2.4. Results

The trip operating cost (excl. maintenance cost and miscellaneous cost) estimated by the high level model (4.2 cents/ASK (Cents per Available Seat Kilogram (ASK)) and the detail level model (2.9 cents/ASK) are realistic when comparing to the average expenses [18]. The cost shares of cost types estimated by both the high level and detail level models are illustrated in Figures 5 and 6 separately. The fuel cost accounts for the major part of a flight trip, which is agreed by both models. The crew cost estimated from the low level model are lower than that of the detail model, this is because the operating time considered by the detail level model tends to reach the lower bound based on the assumption of a time-efficient flight trip, while the airport charge per flight has increased compared with the mid-90s when the parametrical equations of the high level model were generated.

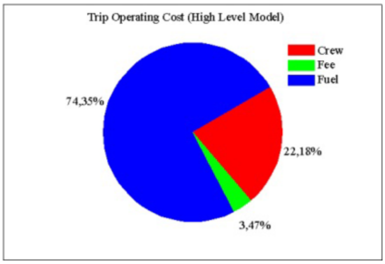

Figure 5 High level model trip operating cost

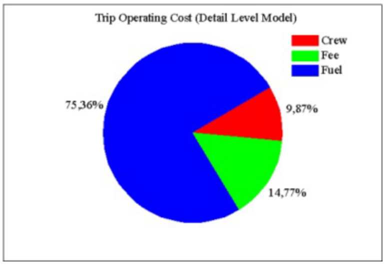

Figure 6 Detail level model trip operating cost

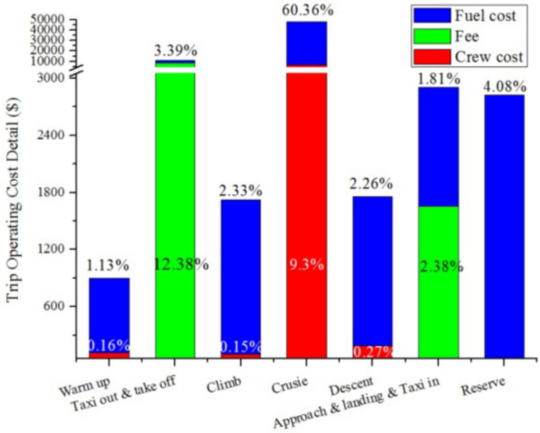

Figure 7 Detail level model trip operating cost by operating segments

Figure 7 shows the cost allocation on each segment of a flight operation. The actual percentages are shown on each of the cost type. The airport charges are allocated on the take-off and landing segments separately. A break point is applied on the figure to zoom in to the shares of crew and fee expenses. This gives a detailed overview of the actual cost distribution over a flight trip, which can be used for trip operating optimization studies. It can be seen that the fuel and crew costs are consumed mostly during cruise, climb and the descent segments. Moreover, fuel consumption is generated during the whole process, which also explains its major impact on flight operating cost and even the whole LCC.

3. Conclusions and future work

This research established a generalized LCC estimation methods in both high and detail levels on the basis of data accessibility in aircraft design phase. High level cost estimation adopts product weight as cost driving parameters. It is capable of a fast cost evaluation based on limited data within aircraft conceptual design phase. A process layer is introduced between product model and cost model for each of the life cycle phase to facilitate the implementation of the detail level cost estimation. This can be applied along with the conceptual design development with gradually extended availability of design and process properties. It provides an in-depth insight of the cost distributions in an aircraft life cycle. The proposed method is exemplified on the A330 operating cost estimation study case, which shows its practical and significant industrial relevance in a strong sense. The future research will focus on the cost estimation strategies for RDT&E and disposal phases in the life cycle and further development on design optimization studies.

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