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Composite Aircraft Components Maintenance Cost Analysis

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Abstract. Maintenance cost of composite aircraft components are generally estimated based on the actual maintenance practices. The estimate is only available for the operating group while not for the design and manufacturing engineers. Moreover, the influence of component attributes are not considered, missing the link from component to maintenance task scheduling, till cost estimation. In this paper, a detailed maintenance cost estimation method is presented. Rules related to component maintenance are extracted to simulate the rationale behind the task scheduling process. Analyses based on a set of maintenance intervals and statistical maintenance times are carried out to determine maintenance cost. In order to identify the influence of composite material, maintenance labor cost for composite component is highlighted in particular. A study case is applied on the A330 composite rudder. The result shows that composite maintenance has a major influence on the overhaul of aircraft component. This research illustrates the capability to perform maintenance cost estimation by linking the component design to the maintenance operations. Assisted by the knowledge based engineering techniques and genetic-causal cost modeling, the influences of sub-assembly design to life cycle implications are identified.

Keywords. Maintenance program generation, maintenance cost estimation

Introduction

Started from 1968, the maintenance process is evolved from the Maintenance Steering Group (MSG)-1 to the MSG-2 in 1970, till the MSG-3 for current use. The MSG-3 is accepted by the airworthiness authorities, the commercial airplane manufacturers and most of the major business manufacturers [1, 2]. Currently, MSG-3 is employed as a standard to determine the essential scheduled maintenance for new airplanes. MSG-3 is based on a rigorous knowledge based decision tree analysis concerning the failures of the parts to the failures of the aircraft system [3]. Along with the evolution of maintenance programming, maintenance cost estimation models are developed accordingly, ranging from Liebeck's maintenance cost model based on airframe weight, engine thrust and trip time to Dhillon's maintenance cost estimation based on components' reliabilities [4, 5].

Although airlines adopt the flexible MSG-3 program, the logic behind the maintenance planning mostly relies on part failures and operating rules. Therefore, to perform maintenance cost estimation during the design phase, automation can be applied on the maintenance scheduling for designers. Furthermore, current cost estimation mainly emphasizes the total maintenance cost for the airline, whereas the

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maintenance cost of each component or system, especially component cost for those of composite materials, is not focused. Moreover, the cost distributed on each maintenance task is not identified. This leads to less understanding of the relation between a component's attributes and its maintenance cost, which is seen as the characteristic of the disconnect between design and operations. This research aims to build a maintenance cost model that links the aircraft design parameters and the operating parameters with the maintenance scheduling process, and eventually to the maintenance cost estimation. A methodology of detailed maintenance cost analysis for aircraft component is presented. By adding the capability of maintenance scheduling and cost analysis based on Knowledge Based Engineering (KBE) techniques, it enables rule/knowledge extraction, analysis process automation and acceleration.

1. Methodology

The method is established on the basis of Knowledge Based Engineering (KBE) techniques and Genetic-causal cost modeling approach. KBE emphasizes the automation of repetitive activities typically encountered in the product development process, involving KBE techniques such as knowledge extraction, formalization and reuse [6]. Similar with component design, operating processes like aircraft maintenances are also repetitive, rule-based activities, where the KBE techniques are adopted. The component breakdown as well as the maintenance program generation for maintenance cost estimation are elaborated in sections 1.1 and 1.2. The maintenance cost estimation, especially the scheduled maintenance labor cost estimation method, is followed in section 1.3. Genetic-causal cost modeling is employed for the analysis. This modeling approach stresses the causality between the cost driving parameters and its induced cost, therefore, it focuses on connecting the product itself and the relevant cost [7]. Since the natural causes of the maintenance cost is actually the tasks performed on each maintenance item based on their failure conditions, the product design and maintenance cost are associated when the Genetic-causal approach is applied. With the assistant of KBE and Genetic-causal cost modeling, this research is able to link the product sub-assembly design and its life cycle effect in terms of maintenance cost.

1.1. Component Breakdown for Maintenance

The component breakdown is required for the scheduling of the maintenance process, since the tasks are applied due to the item failures. An aircraft is divided into numbered zones by the manufacturers according to the standard ATA iSpec 2200 [8]. An example of aircraft zones is shown in Figure 1. A component is covered by one or more zones, which can be further divided into functional parts, connections and relevant systems, see Figure 2. At least one functional part is located in one zone. A part is a generalization of the main structure such as skin, spar, rib and the miscellaneous part including fastener, fitting and attachment. A connection mainly refers to the interface between two or more parts. Relevant system represents the hydraulic system or the electrical system, which keeps the component functioning properly. Large parts and complex systems are distributed in one or more zones. Then the maintenance tasks are scheduled for each item allocated in different zones.

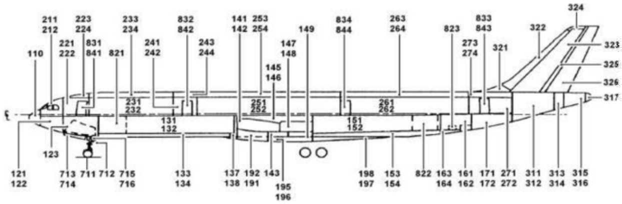

Figure 1. Example of aircraft zones [9].

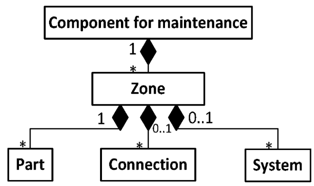

Figure 2. Component class diagram.

1.2. Maintenance Program Generation

1.2.1. Maintenance steering Group-3

The summarized MSG-3 maintenance program is shown in Figure 3. Its objective is to produce scheduled maintenance tasks performed by the Maintenance Working Groups (MWG). The causality of the maintenance program is based on the part/component's function, its failure modes, the failure effects, and the failure causes [10]. MSG-3 considers three maintenance program groups: systems & powerplant maintenance program, structures maintenance program and zonal maintenance program. The system & powerplant group provides maintenance program for aircraft systems and engines. The structural group focuses on the maintenance program of airframes. The zonal inspection group deals with maintenance program for items in each pre-divided zone area. Depending on the safety, operational and economic aspects of failures, maintenance tasks with specific actions, intervals and durations are assigned. The tasks are listed in a sequence considering its difficulty and cost from lower level to higher level.

program	MSG-3 maintenance program								
maintenance program groups	structural program	system &power plant program							zonal program
		hydraulics & flight controls	environmental	powerplant & APU	avionics	fuel system	landing gear	interior	
tasks	• Lubrication / Servicing (LU / SV or LUB / SVC) • Operational / Visual Check (OP / VC or OPC / VCK) • Functional Check /Inspection (FC / IN* or * / FNC), including General Visual Inspection (GV or GVI), Detailed Inspection (DI or DET), Special Detailed Inspection (SI or SDI), Scheduled Structural Health Monitoring (S-SHM) • Restoration (RS or RST) • Discard (DS or DIS)								

Figure 3. MSG-3 maintenance program (Summarize according to [1,2,11-13]).

1.2.2. Maintenance task scheduling

1) Predict the number of times each maintenance task is performed

According to the task thresholds (the deadline for the first maintenance) and intervals, the number of times n_i the maintenance task i performed in a Fiscal Year (FY) can be predicted. Extracted rules for planning are incorporated. For the maintenance task with a threshold value and a check interval, Eq.(1) is applied.

$$n_i = \begin{cases} floor\left[\dfrac{FH_{post}}{interval_i}\right] - floor\left[\dfrac{FH_{pre}}{interval_i}\right]\left(FH_{pre} < FH_{post} < threshold_i\right) \\ 1 + floor\left[\dfrac{FH_{post} - threshold_i}{interval_i}\right]\left(FH_{pre} < threshold_i \le FH_{post}\right) \\ floor\left[\dfrac{FH_{post} - threshold_i}{interval_i}\right] - floor\left[\dfrac{FH_{pre} - threshold_i}{interval_i}\right]\left(threshold_i \le FH_{pre} < FH_{post}\right) \end{cases} \quad (1)$$

where, $floor[\,]$ rounds down to the nearest integer. i represents the maintenance task i, $i = 1,2,3,\ldots,k$. n_i is the number of times the maintenance task i is performed in a FY. FH is the aircraft flight hours in a FY, where $FH = FH_{post} - FH_{pre}$. FH_{post} is the cumulative aircraft flight hours since the aircraft is new after the end of a FY (equal to the average fleet age in this research). FH_{pre} is the cumulative aircraft flight hours since the aircraft is new before the start of a FY. $threshold_i$ stands for the threshold interval for the maintenance task i. $interval_i$ is the maintenance interval for the maintenance task i.

For the maintenance task with a threshold value and two check intervals, the interval expiring first shall apply. It is interpreted in Eq. (2). Both intervals are considered. The number of times to perform the maintenance task i is the summation of the number of times based on each maintenance intervals after eliminating the duplicated operations.

$$n_i = n_{i,1} + n_{i,2} - n_{i,duplicate} \tag{2}$$

where, $n_{i,1}$ is the number of times the maintenance task i is performed in a FY based on $interval_{i,1}$. $n_{i,2}$ is the number of times the maintenance task i is performed in a FY based on $interval_{i,2}$ (referencing Eq.(1) for the calculation of $n_{i,1}$, $n_{i,2}$). $n_{duplicate}$ refers to the number of duplicated operations when applying both intervals. When $l_{i,1} \times interval_{i,1} = l_{i,2} \times interval_{i,2}$, then $n_{i,duplicate} = n_{i,duplicate} + 1$, where $l_{i,1} \in \left(floor\left[\frac{FH_{pre}}{interval_{i,1}}\right], floor\left[\frac{FH_{post}}{interval_{i,1}}\right]\right)$, $l_{i,2} \in \left(floor\left[\frac{FH_{post}}{interval_{i,2}}\right], floor\left[\frac{FH_{post}}{interval_{i,2}}\right]\right)$.

During the calculation, the unit of the time variables should be consistent in hours (hr) or years (YE).

2) Allocate maintenance task to maintenance packages

The most commonly used work packages are A-check, C-check and D-check. Table 1 shows the letter check descriptions, the intervals and the durations, which formulates the rules of allocation.

Table 1. Maintenance letter checks (adapted according to [2,14,15]).

Check	Description	Duration	Interval	Location	Operation
A	General inspection of the interior / exterior of the airplane with selected area opened, example tasks: LU / SV, OP / VC	≈24 man-hours	biweekly to monthly /500-800 FHs/ 200-400flight cycles	At gate/ Hanger	In service
C	The whole aircraft is inspected: structural inspection of airframe, opening access panels. Example tasks: LU / SV, OP / VC, FC / IN*	Up to 6000 man-hours/ ≈3 days to 1week	15 to 21 months	Hanger	Out of Service
D	Major structural items are inspected: paint, exterior components, interior and equipment are removed. Example tasks: FC / IN*, RS, DS	Up to 50,000 man-hours/ ≈1month to2 months	6 to 12 years	Hanger	Out of service

In addition, rules for other types of work package classifications are also extracted. According to the task function, preventive maintenance and corrective maintenance are classified [3]: **IF** the task is “departure-oriented”, the task interval is on transit, daily, weekly to monthly basis, and the task is performed from 1 to 24 man hours, **THEN** it is line maintenance. Examples of line maintenance tasks are LU / SV, OP / VC. It covers transit check and some tasks from A check. **IF** the task is “fix-oriented”, **THEN** it is base maintenance. Examples of base maintenance tasks are FC / IN*, RS, DS. It covers some tasks from A check, C check and D check.

According to the place of maintenance, it is grouped into preventive maintenance and corrective maintenance: **IF** the task is applied to non-repairable item, **THEN** it is allocated to preventive maintenance package. Examples of preventive maintenance tasks are LU / SV, OP / VC, FC / IN*. It covers transit check, A check, C check and some tasks from D check. **IF** the task is applied to repairable item, **THEN** it is allocated to corrective maintenance package. Examples of corrective maintenance tasks are RS, DS. It covers some tasks from D check.

1.3. Maintenance cost estimation

1.3.1. Maintenance cost driving parameters

The cost driving parameters are divided in two groups: operation relevant parameters and design relevant parameters. The former refers to the parameters on the airline information level, involving fleet type, average active fleet size, fleet/aircraft(AC) Flight Hour (FH) in a FY, fleet/AC Flight Cycle (FC) in a FY, Average fleet age. Besides, the average labor rate for maintenance activities is incorporated in the labor cost estimation. The inventory material purchase price, interest rate, storage facility cost, *etc.*, are adopted for material cost estimation. Moreover, financial factors of currency exchange rate between local currency and report currency is included.

Design relevant parameters are detailed to each of maintenance items and their correspondent maintenance tasks, including the geometry, part type, material. Those parameters influence the labor time usage, which is the intermediate cost driving parameters for labor cost.

1.3.2. Maintenance cost breakdown

Total Maintenance Cost (TMC) is broken down into Direct Maintenance Cost (DMC) and Indirect Maintenance Cost (IMC) [16, 17]. DMC refers to the cost generated directly associated with the maintenance operations. It mainly includes scheduled maintenance cost and unscheduled maintenance cost. The scheduled/unscheduled maintenance cost is the aggregation of the cost for each scheduled/unscheduled maintenance task, which is further divided into labor cost and material cost. IMC is comprised of tooling & equipment cost, spare & inventory material cost and overhead cost, see Figure 4 and Eqs. (3) to (7).

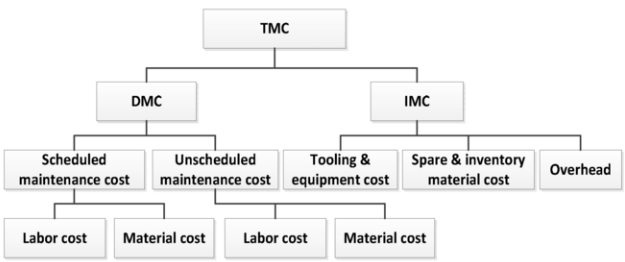

Figure 4. Maintenance cost breakdown.

$$TMC = DMC + IMC \tag{3}$$

$$DMC = C_{scheduled} + C_{unscheduled} \tag{4}$$

$$IMC = C_{tooling\&equipment} + C_{overhead} + C_{spare\&inventory} \tag{5}$$

$$C_{scheduled} = C_{labor,scheduled} + C_{material,scheduled} \tag{6}$$

$$C_{unscheduled} = C_{labor,unscheduled} + C_{material,unscheduled} \tag{7}$$

1.3.3. Maintenance cost estimation model

Under the composition of TMC, a model for labor cost estimation is developed. Based on the maintenance task planning from section 1.2, the scheduled maintenance labor cost is evaluated by two types of cost performance indices.

1) Actual labor cost for a component of an aircraft from a fleet in a FY, see Eq.(8).

$$C_{AC,labor} = \sum_{i=1}^{k} (r_{labor,i} \times n_i \times MT_i \times n_{i,labor}) \tag{8}$$

where, $r_{labor,i}$ is the labor rate for maintenance task i, i.e. maintenance cost per hour ($€/hr$). MT_i refers to the maintenance time required to repair an item by performing maintenance task i (hr). $n_{i,labor}$ is the number of labor forces for maintenance task i.

2) Mean labor cost for a general maintenance task applied to a component of an aircraft from a certain fleet in a FY, see Eq. (9) to (11) (adapted from[5]).

$$C_{task,labor,mean} = \frac{FH \times r_{labor} \times MTTR}{MTBF} \tag{9}$$

$$MTTR = \left(\sum_{i=1}^{k} \lambda_i \times n_i \times MT_i \times n_{i,labor} \right) / \sum_{i=1}^{k} \lambda_i n_i \tag{10}$$

$$MTBF = \sum_{i=1}^{k} \lambda_i \times n_i \times interval_i \,/ \sum_{i=1}^{k} \lambda_i n_i = \sum_{i=1}^{k} n_i \,/ \sum_{i=1}^{k} \lambda_i n_i \tag{11}$$

where, $MTTR$ is mean time to repair, meaning the average repair time including the influence of the failure rate for a component. $\lambda_i = \frac{1}{interval_i}$ refers to the failure rate of an maintenance item, which can be repaired by maintenance task i. It is relevant to the reliability of an maintenance item. $MTBF$ is mean time between failures, the average time interval including the influence of the failure rate for a component.

$MTTR$, λ_i and $MTBF$ are applicable to corrective maintenance package, when the task is allocated to the preventive maintenance package, the position of the three parameters in Eqs. (9) to (11) will be replaced by mean preventive maintenance time ($MPMT$), frequency of task (f_i) and mean time to failures ($MTTF$) correspondingly. In this research, MT_i and $interval_i$ are based on a set of statistical data from the Maintenance Planning Document.

2. Case study-A330 rudder maintenance labor cost

A330 is a wide-body, twin-engine aircraft type known by its low operating cost for long-haul operations. Around 11% composite material has been used, resulting in more than 10 tonnes of light weight composite airframe structure [18]. The A330-200 rudder, as a typical composite component from an A330 shorter fuselage variant, is chosen for this case study.

2.1. Operation and design properties

By considering KLM A330-200 fleet condition[19] and IATA summary of world A330-200 fleet [20], the operation parameters are listed in Table 2. Average labor rate is assumed to be $42.5€/hr$ (FY2013 Euro) [21]. A330-200 rudder is made from composite sandwich structure, the rudder material distribution and rudder structure are shown in Table 3 and Figure 5 respectively.

Table 2. Airline operation parameters.

Fleet AC type	Airline	AC No.	Avg Age (YE)	FH/FC ratio	Daily Utilization $(\frac{FH}{AC\ No.}\frac{1}{365})$	FH/AC (hr)	FC/AC (hr)
A330-200	KLM	12	5.9	4.3	11.2	4088	951

Table 3. Rudder material distribution.

Part		Material	Remark
Side Shell	Inner skin	CFRP	LH & RH
	Core	Nomex Honeycomb	LH & RH
	Outer skin	GFRP	LH & RH
Spar		CFRP	front
Rib		CFRP	Lower &upper
Hinge, actuator		Non-composite	hinge/ actuator arm, fitting

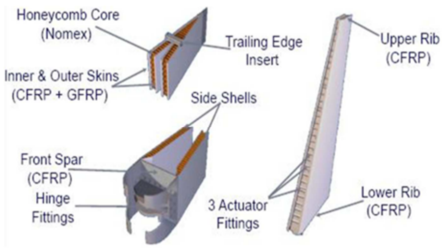

Figure 5. Rudder structure [22].

2.2. Rudder breakdown and maintenance program generation

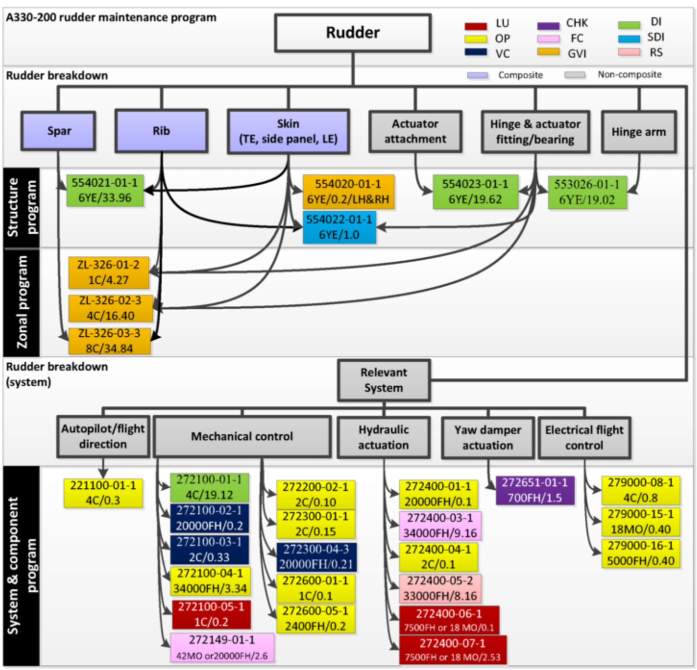

Figure 6. Rudder breakdown structure and maintenance tasks

According to the zonal division of A330-200, the rudder is covered by one physical zone, its relevant systems are distributed in various zones from cockpit, fuselage belly to tail [9]. The component breakdown is shown in Figure 6. Maintenance tasks are assigned to each item based on rules for maintenance program planning. A maintenance task is identified with an unique task number, a task interval and a maintenance time. Task intervals shown as A, C, 2C, 4C, 8C match 600 FH, 18 month, 36 month, 6 year and 10 year operating time respectively [23]. Maintenance times followed after the slash symbol are shown in the unit of man hours.

2.3. Estimation results

Figure 7 to Figure 11 illustrate the results obtained from the rudder scheduled maintenance labor cost estimation. The cost is presented as yearly cost per aircraft from A320-200 fleet. The calculation is based on the high level operation parameters as well as the detailed level task interval and maintenance time resulted from design itself. The cost indices shown in Figures 7, 9 to 12 are referenced to the actual labor cost of the rudder according to section 1.3.3-1), which evaluates the scheduled maintenance cost in each FY based on the rudder breakdown and maintenance task planning and allocation shown in Figure 6. The cost index of Figure 8 is calculated based on the mean labor cost of a general maintenance task according to section 1.3.3-2), which estimates the cost by considering the impact of failure rates (or reliabilities) corresponding to each task. From FY 2012 to FY2022, it is seen from Figure 7 that the cost increases around 26% and 27% in FY2013 and FY2019 compared with the total expense. This predicts the years when the overhauls are taking place. The trend can be seen in the cumulative curve from Figure 7 and in the bar charts from Figures 9 to 12 correspondingly. According to Figure 8 the average cost for a general maintenance task is fluctuating during the period between $94€/task$ to $155€/task$ (FY2013 Euro). It is shown that the mean labor task cost is not influenced by the overhaul but the failure rate (or reliability) of the maintenance items. The composite materials and structural parts maintenance cost are emphasized in this paper. Figure 9 illustrates that the composite structures take a relative small share of the maintenance cost in general, the expenses should be focused during the overhaul period. The composite structures including spar, rib and skin are mostly checked and repaired during overhaul, around 37% in both FY2013 and FY2019 (Figure 10). Correspondingly, in the heavy maintenance period, the maintenance tasks such as DI and GVI, allocated in structure program group and zonal program, are spent nearly 90% of the yearly cost (Figure 11 and Figure 12).

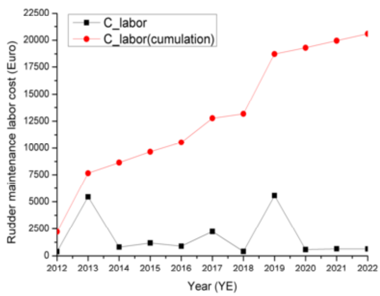

Figure 7. Scheduled maintenance labor cost

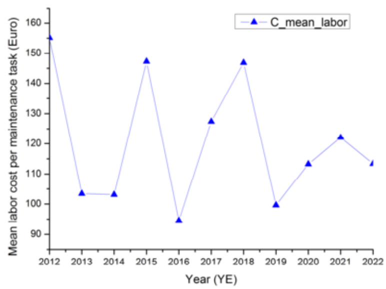

Figure 8. Mean labor cost per maintenance task.

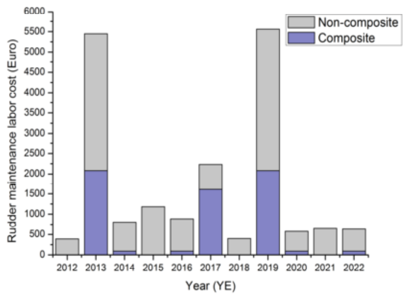

Figure 9. Scheduled maintenance labor cost by material types.

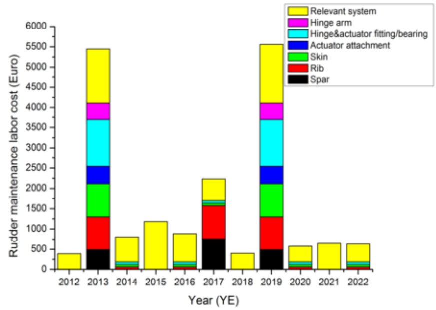

Figure 10. Scheduled maintenance labor cost by part types.

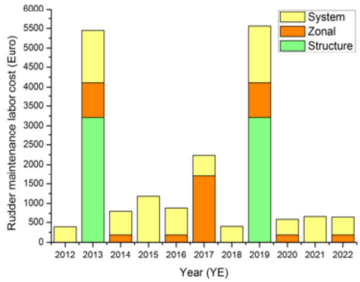

Figure 11. Scheduled maintenance labor cost by program groups.

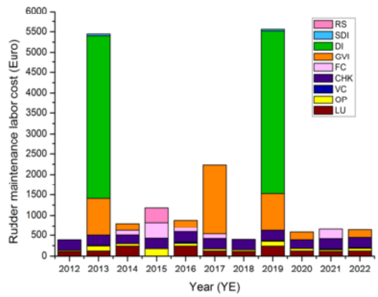

Figure 12. Scheduled maintenance labor cost by task types.

3. Conclusions and future work

This research focused on maintenance cost estimation of composite components. It outlined the cost estimation methodology, which uses a component breakdown structure and maintenance program planning procedures to perform the cost calculation. Based on KBE techniques and Genetic-causal cost modeling approach, this method is able to link the product sub-assembly design and its life cycle effect from maintenance cost perspective. Scheduled maintenance labor cost was emphasized and presented in the A330-200 rudder case. Repetitive maintenance program rules were extracted for task planning and maintenance package allocations. Comparing to current estimates, the presented method drives the estimation to a more detailed level. It developed a thorough maintenance cost analysis relating structural parts and maintenance tasks. Task numbers and maintenance times generated according to part failure conditions were employed for the calculation. Both the operation and design influences were distinguished and included. This is reflected from the case study, where a detailed cost distribution by material, by part and by maintenance tasks could be made available for both airlines and original equipment manufacturers.

Although the methodology is developed, it is necessary to build an application implementing and automating the entire estimation process. In order to capture the causality between product design and labor time, it is desired to build the parameterized estimation relationship to predict maintenance times and intervals of each maintenance task based on part properties such as geometry and material type. Detailed material cost estimation should be constructed. The cost influence of aging factors, unscheduled maintenance cost should be further included in the model.

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