Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 104 (2021) 1143–1148

www.elsevier.com/locate/procedia

54th CIRP Conference on Manufacturing Systems

An efficient cost estimation framework for aerospace applications using Matlab/Simulink

Konstantinos Bacharoudis[a], Heather Wilson[a,*], Stephen Goodfellow-Jones[b], Atanas Popov[a], Svetan Ratchev[a]

[a]*Institute for Advanced Manufacturing, Faculty of Engineering, University of Nottingham, Jubilee Campus, Nottingham, NG8 1BB, United Kingdom*
[b]*GKN Aerospace, London Luton Airport, Percival Way, Luton LU2 9PQ, United Kingdom*

* *Corresponding author. Tel.: +44(0)1157484376; fax: +0-000-000-0000. E-mail address: heather.wilson@nottingham.ac.uk*

Abstract

The ability to estimate costs and process times at the early stage of a design phase is of great importance to the product development process, enabling selection of the most suitable design and manufacturing concepts. Therefore, herein an efficient framework is developed, utilising appropriate process and feature based cost modelling techniques in a MATLAB/SIMULINK environment. The sophisticated structure of the cost tool, using the drag and drop approach of predefined SIMULINK blocks, enables the rapid cost modelling of complex aerospace assemblies. The capabilities of the developed framework are demonstrated through analysis of a novel air-intake structure for single aisle aircraft.

Keywords: Cost modelling; Manufacturing costs; Cost estimation

1. Introduction

It is already known that, in the aerospace and automotive industry, approximately 70% of the cost of a product is committed by decisions made at the early stage of the design process [1]. At this stage of the design, there is unlimited freedom for selection of alternative materials, designs, manufacturing and assembly processes whilst the actual incurred costs are quite low. As the design progresses, and the design process moves towards the production phase, any change in the design of the product or the processes can be very expensive. For this reason, it is important to enable and perform trade-off studies at the early stage of the design based on more quantitative analytical evidence rather than based exclusively on experience and engineering judgement. Cost estimation is one of the key elements that should be worked out at this preliminary stage in order to make optimized, informed decisions.

Several cost estimation methods have been developed for the estimation of manufacturing and assembly costs for aircraft structures, among them, analogous, parametric, activity and technical based methods [2]. Every method has advantages and disadvantages and should be carefully selected to fit the purpose.

At the conceptual phase of the design, in which several concepts should be tested and down selected and depending on the available data, analogous and parametric methods have been mainly used e.g. in [3]. Despite their fast estimation, these models are calibrated against specific cost data, product based and thus, their applicability and accuracy can be dubious for different or new products. Technical or process-based cost modelling (PBCM) [4] is a very efficient cost estimation method capable of capturing differences in the material, design concepts and manufacturing processes for new products, focusing on the processes to fabricate the product. However, it needs the knowledge of an expert to build a suitable model.

10.1016/j.procir.2021.11.192

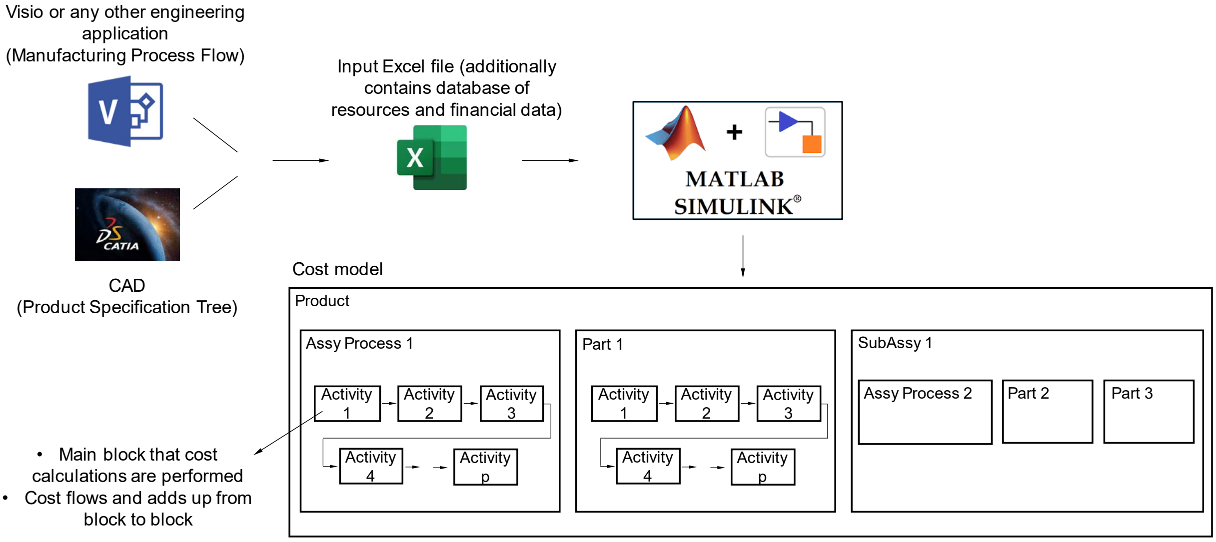


Fig. 1. Overview of the developed cost framework structure

The input accumulation for a PBCM model can prove to be a very demanding and difficult task. Often, customized interfaces, usually in spreadsheet software, have been used to build PBCM models. It is clear that the cost model for a complex assembly with many parts and subassemblies with a large number of activities is difficult to be managed by spreadsheet files, whilst a graphical approach depicting the structure of the cost model would be more helpful. Commercial software exist and try to deal with these issues. More specifically, SEER Aerostructures by Galorath Incorporated is based on the PBCM technique and substitutes the expert's knowledge by offering a variety of cost estimation relationships for many aerospace processes. Regarding improvement on the management and clear representation of the cost model, the OPLYSIS by CONBILITY cost tool has been developed.

From the listed commercial tools and the open literature, there is a systematic effort to introduce advanced cost methods at the earlier stages of the design process to improve cost estimations. However, a major element in cost calculations based on the PBCM technique is the estimation of the resources, e.g., the number of machines, workers, tools etc. needed to run the fabrication process and produce the necessary number of products in the given time period. From this perspective, optimisation of the resources by implementing line balancing techniques should be included in the cost estimations for better accuracy of the output. Although there is a branch in the assembly line balancing field that deals with the optimisation of the line with respect to the cost, nevertheless according to [5] there is a lack of tools that combine cost and line balancing analyses.

Therefore, this work seeks to develop this framework that will facilitate the PBCM technique to be implemented at earlier stages of the design process, as well as improving the cost estimations by optimising the processes performing line balancing. The first step to achieve the stated target is to establish this framework. Therefore, a cost estimation framework has been developed in a Matlab/Simulink environment. The improved cost framework provides a user-friendly interface for the modeller by the drag and drop approach of predefined blocks in Simulink and thus, a graphical representation of the cost model is possible. The input of the Simulink cost model can be provided either directly to each block or by a structured way in an Excel format as presented in Fig 1. The latter, in combination with the logic of the PBCM technique, as well as the capabilities of the Matlab/Simulink environment, enables the Simulink cost model to be built automatically. Moreover, gives the possibility in the future to reorganize the various activities and reshape the structure of the cost model performing line balancing techniques. Additionally, in the era of the Industry 4.0 in which simulation and digital manufacturing become more and more important for the product development with more connected and integrated solutions [6]-[7], the existence of a structured input Excel file opens the way to the connectivity with other engineering applications similar to what was presented in [8] and thus, to facilitate the input accumulation by retrieving necessary data from any application where that data exists, based on VBA scripting. The effectiveness of the framework is demonstrated by studying a specific subassembly of the latest generation of an air intake for single aisle aircraft developed by GKN for two different manufacturing concepts.

Therefore, in section 2, the basic characteristics of the suggested framework are described including a brief presentation of the PBCM technique. In section 3, the necessary automation that allows connectivity with other engineering applications and facilitates the input accumulation is detailed. The case study and some preliminary results are given in section 4 and 5. Useful conclusions are drawn in section 6.

2. Proposed cost estimation framework

The PBCM method is based on the estimation of recurring and non-recurring costs for every operational step (or activity) of a manufacturing/assembly process. The main steps to estimate costs using the PBCM technique are:

- to have an initial product specification tree (parts and subassemblies) of the product under investigation
- to specify preliminary manufacturing and assembly activity sequences for preferred manufacturing and assembly processes for the various parts and subassemblies
- to estimate the activity time and the number of resources needed based on necessary design, process and industrial input data
- to find fabrication costs based on estimated resources, times and financial data

It is highlighted that the cost estimation of a product can be thought as the flow of various cost streams that add up to the final product cost. Thus, a Matlab/Simulink environment was selected to develop the suggested framework taking advantage of the graphical programming environment of Simulink.

2.1. Structure

An overview of the structure of the developed framework, namely CAMcost, is presented in Fig. 1. The developed structure in Matlab/Simulink immediately reflects the product specification tree and the manufacturing and assembly plan of the product analyzed and thus, offers a good visibility of the developed model for complex assemblies. That is, in Fig. 1, there is the product block that contains all the other blocks (subassembly, part, assembly process and activity blocks). At this level, industrial parameters are defined. Inside the product block exists the subassembly and part blocks as well as the assembly process block necessary to join the parts and subassemblies involved at that level. Subassembly blocks can contain part and other subassembly blocks as well as new assembly process blocks. Part blocks contain manufacturing activity blocks whilst the assembly process blocks contain assembly activity blocks. Necessary design, manufacturing and financial input data are provided for every block at every level in the cost model. All the blocks have been pre-specified in a library and thus, they can be used to model any aircraft component as well as various manufacturing and assembly activities. Cost estimations can be extracted at any block.

2.2. Cost and time equations

Cost flows from block to block and adds up to the top level, the product block. In relation to Fig. 1 and noticing that in every subassembly block there is always one assembly process block reflecting the necessary assembly process to form the subassembly, the total product cost that consists of n_1 parts, n_2 subassemblies is given by

$$C = \sum_{i_1=1}^{n_1} C_{Parts}^{i_1} + \sum_{i_2=0}^{n_2} C_{AssyProcess}^{i_2} \tag{1}$$

where $C_{Parts}^{i_1}$ is the total cost of the i_1^{th} part and $C_{AssyProcess}^{i_2}$ is the total assembly cost of the i_2^{th} subassembly. $C_{AssyProcess}^{0}$ corresponds to the assembly process at the product level. The cost of the i_1^{th} part is associated to the manufacturing cost of the part. Focusing on the manufacturing of one part and the assembly of one subassembly, the total manufacturing cost per part, C_{Parts}, and total assembly cost per subassembly, $C_{AssyProcess}$, are calculated by the sum of recurring and non-recurring costs by

$$C_{Parts/Assy} = C_{Material} + C_{Labour} + C_{Tool\,bits\,\&\,Inserts} + C_{Energy} + C_{Equipment} + C_{Tooling} + C_{Building} \tag{2}$$

Material, labour (direct), inserts and tooling bits (e.g. cutters, drill bits, bolts, nuts etc.) and energy costs are considered as recurring costs in the present cost model. Non-recurring costs are the capital recovery of the machines/equipment/tooling/fixtures necessary for the production, maintenance costs of those machines and tools, as well as the floor-space costs to accommodate the production. To calculate each of these elements (*el*= material, labour etc.) of per piece cost, the annual cost of each element is divided by the target annual production volume (of the part or the subassembly). It is mentioned that the annual costs for each element are the sum of that element's costs calculated for each stage/activity of the manufacturing process. The formulas for the calculation of the annual production costs for each element can be found in [9]. The heart of the developed framework is the activity block in which all the cost calculations are performed. Linking one activity block to the other, the cost adds up, and thus total part and assembly process costs are estimated as depicted in Fig. 1. Similar logic is followed to estimate subassembly and product costs by linking the various part, assembly process and subassembly blocks.

Different time periods exist in the production process and thus, in the proposed framework, the scheduled operation time, the cycle time, the yield capacity and several time losses are considered. These different types of time are further used to estimate resources. More specifically, the cycle time for every activity can be provided directly by the user and thus, a general activity block has been created in the Simulink library. On the other hand, cycle time is estimated based on industrial equations, e.g. adopting the equations in [10] or on theoretical formulas using specific parameters of the component analyzed as well as of the process under study. Thus, dedicated activity blocks have been created, e.g. pilot drilling block as presented in [11]. In this work, the cycle time for all the activities has been provided by GKN as specific values and thus, only the general activity block is used.

Finally, the number of resources is important and is derived from a time-based estimation by calculating a scaling factor given by

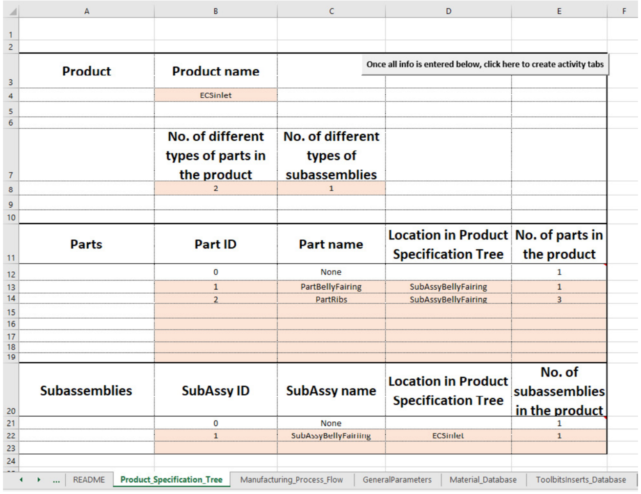
$$NR^{j} = \frac{PV_{effective}^{j+1} \cdot CT^{j}}{YC^{j}} \tag{3}$$

Where $PV_{effective}^{j+1}$, is the effective production volume necessary to feed the next activity, CT^j is the cycle time of the activity and YC^j is the yield capacity.

It is imperative that the number of resources are estimated and improved on the basis of activities organized in workstations, in which the idle time of these resources has been minimized. This is, however, the next step of improvement for the suggested framework and therefore is not further studied herein.

3. Introducing automation

There are two, time consuming activities related to the cost model development of complex products using the PBCM technique. The first activity concerns the build of the model itself and the second the accumulation of the input and its assignment to the developed cost model. Although the developed framework in Matlab/Simulink environment facilitates the fast creation of the cost model and gives good flexibility and customization, it does however, take time to build the structure of Fig. 1 as well as to assign all the input parameters to the various blocks for complex products such as aerospace components. To address both issues, a structured way of capturing the necessary input data was devised based on an Excel file. Every spreadsheet corresponds to a different type of input information, for example, product specification tree, manufacturing process flow, activity tabs, as well as various databases e.g. materials, tools, machines.



	A	B	C	D	E
3	Product	Product name			
4		ECSinlet			
7		No. of different types of parts in the product	No. of different types of subassemblies		
8		2	1		
11	Parts	Part ID	Part name	Location in Product Specification Tree	No. of parts in the product
12		0	None		1
13		1	PartBellyFairing	SubAssyBellyFairing	1
14		2	PartRibs	SubAssyBellyFairing	3
20	Subassemblies	SubAssy ID	SubAssy name	Location in Product Specification Tree	No. of subassemblies in the product
21		0	None		1
22		1	SubAssyBellyFairing	ECSinlet	1

Fig. 2. Cost model input: Product specification tree

The logic behind the PBCM technique is that the costs add up from activity to activity to estimate total cost of a part and assembly process cost. Furthermore, these costs add up from part to part and subassembly to subassembly to the final product. The way that blocks added and linked together to capture this flow is universal and applicable to any product. Based on this observation and taking advantage of the Matlab capabilities in which a Simulink model can be created using only Matlab commands, the automatic creation of the Simulink cost model can be achieved based on the preliminary input data captured in the Excel file. An example is depicted in Fig 2 for information related to the product specification tree. Using this preliminary information, the Simulink cost model is built automatically and thus, the cost model exists as a separate entity in a graphical way for further processing.

3.2. Input accumulation and assignment

Focusing on the input data depicted in Fig. 2, information related to the product specification tree usually exists in a preliminary CAD model. Therefore, this type of information can be directly retrieved from a CAD model, linking for example CATIA v5 software with the specific Excel file as depicted in Fig. 1. The link has been realized, herein, by programming simple VBA scripts in CATIA, whilst a customized cost toolbar has been created in the CATIA environment to enable cost estimations directly from the CAD tool, and therefore accelerate the input accumulation and assignment. As a future work, the necessary input to build the cost model, e.g. manufacturing process flow, will be retrieved from other applications that could be used to capture this information, for example a preliminary process flow diagram created in VISIO Microsoft or in a PowerPoint. Finally, databases have been created capturing information related to the materials, tools, machines and equipment. The more that the cost framework is utilized, the richer those databases become.

4. Case study

The case study concerns the advanced air-intake product depicted in Fig. 3. The product is being developed in the frame of AISA project under GKN leadership. The aim of the AISA project is to develop a new, high production rate capable, ice-protected air-intake for aerospace applications. The advanced air intake will have several novel characteristics such as intelligent control and efficient power-management of the ice protection system whilst the manufacturing rates of the product must meet the next-generation single aisle commercial aircraft production rates. This is roughly estimated as 150 air-intake products per month.

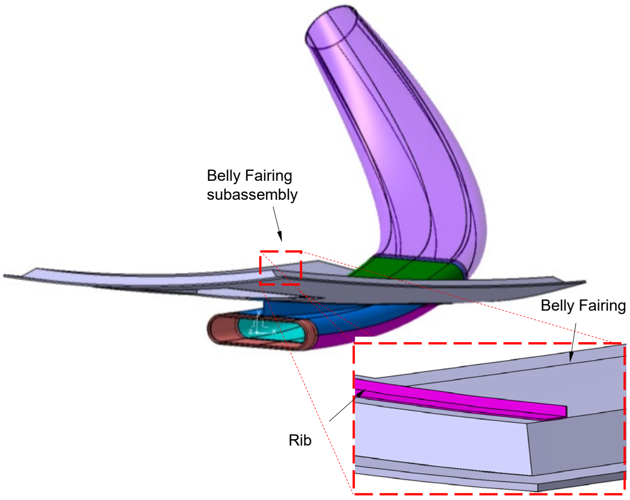


Fig. 3. Air intake scoop, with detail of the belly fairing subassembly

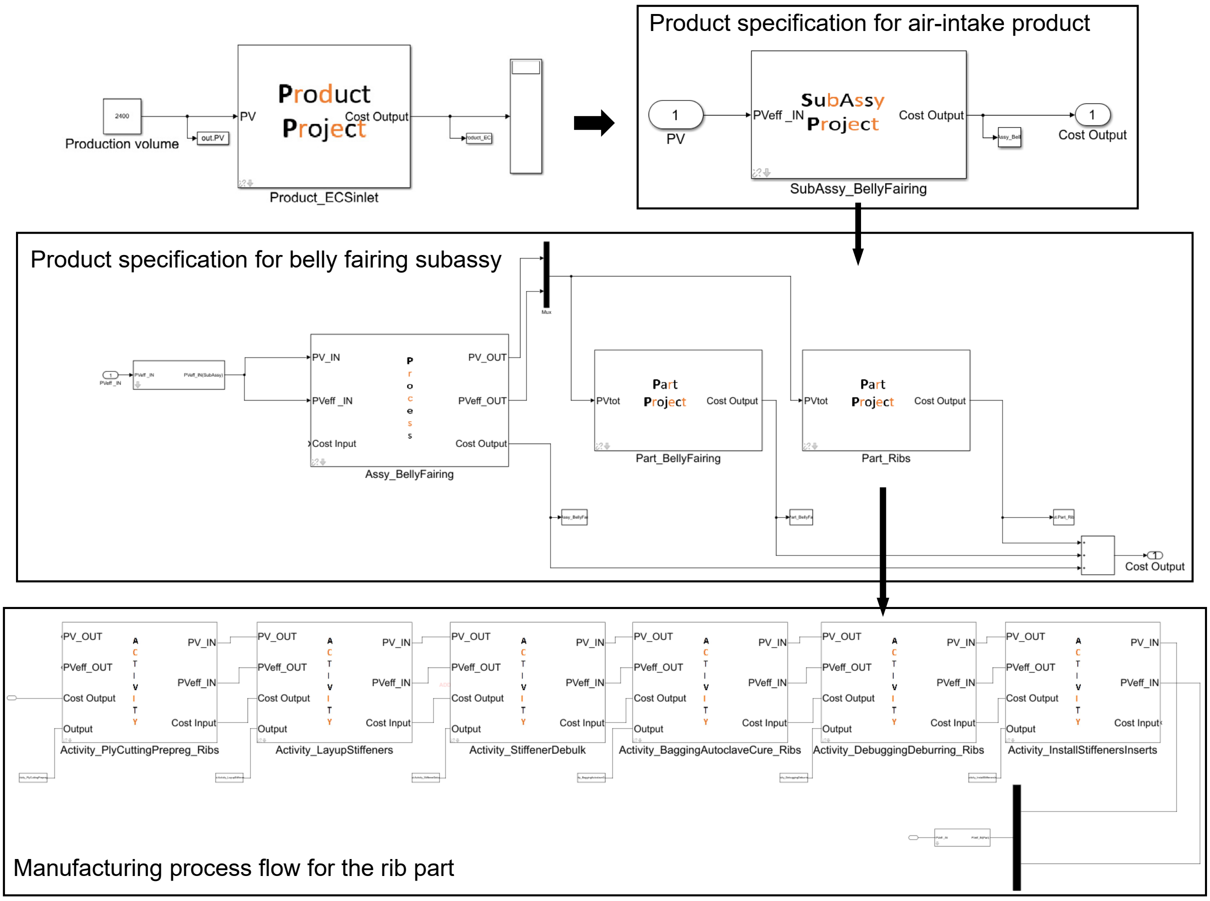


Fig. 4. Simulink cost model for the air-intake product assuming prepreg lay-up manufacturing techniqueTo assess and quantify the specified KPI for various design and manufacturing concepts of the air-intake and furthermore, to compare the various concepts to each other, numerical process models are needed that are capable of taking into account differences in the materials and in the manufacturing and assembly processes. The suggested cost estimation framework has been developed to perform these trade-off analyses.

Preliminary screening to identify Key Performance Indicators (KPI) has been performed and captured by GKN. One of these KPIs is the cost of the product.

Two manufacturing methods namely the prepreg layup and the resin transfer molding (RTM) manufacturing methods are analyzed herein for one subassembly of the air-intake product. More specifically, the work focus on the analysis of the belly fairing (BF) subassembly consisting of a sandwich curved panel namely the BF panel and three composite ribs/stiffeners for additional structural rigidity as depicted in the detail of Fig. 3. The prepreg lay-up method for the BF subassembly is realized in two stages. In the first stage, the two faces of the sandwich panel as well as the ribs are laid up and cured separately. In a second stage, core, faces and ribs are assembled and bonded together followed by machining and inspection operations. Similar logic is followed when the RTM method is used. The developed Simulink model for the prepreg lay-up process can be seen in Fig. 4. Because only one subassembly is assumed in this analysis, the air-intake product contains only one subassembly block. Furthermore, two part blocks are used to capture the two different types of parts existing in FB subassembly as well as one assembly process block capturing the necessary assembly activity. It is highlighted that 'assembly process' is used herein with a wider sense, and thus, assembly activities are not restricted necessarily to typical aerospace assembly activities, e.g. drilling, shimming etc. Each part and assembly process block contains the list of activities to manufacture/assemble each component. The activities for the first manufacturing stage exist in the two part blocks and are partially presented for the ribs in Fig. 4. The assembly process block contains the activities related to the second manufacturing phase. A similar cost model was created for the RTM manufacturing process.

5. Results and discussion

Preliminary results related to the two manufacturing concepts are depicted in Fig. 5. Due to confidentiality reasons, the necessary input for each Simulink model has been slightly modified so they are not presented herein. The results concern the percentage of the total cost allocated per activity. It is obvious that different manufacturing methods involve different activities and thus, different cost allocations. It is highlighted that the suggested framework has accelerated the cost estimation process compared to the traditional PBCM implementation in an excel spreadsheet. That is, once the input Excel file has been filled in, the cost model is created and estimated in few seconds. Part of the necessary input data was extracted directly from the preliminary CAD model of the analyzed product. Additionally, Simulink implementation offers a graphical representation of the cost model for further processing and customization as depicted in Fig. 4.

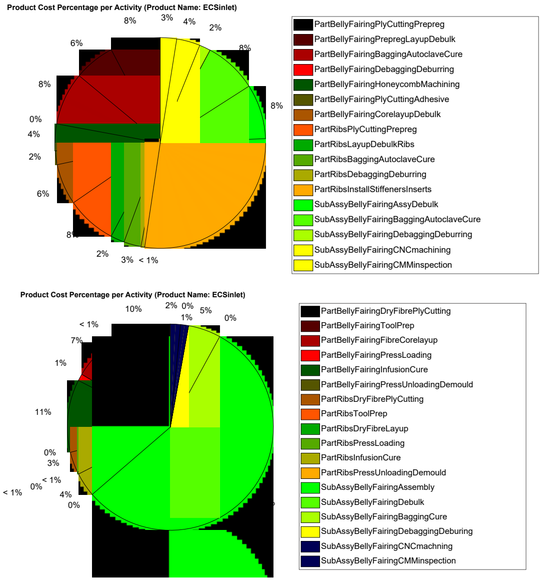
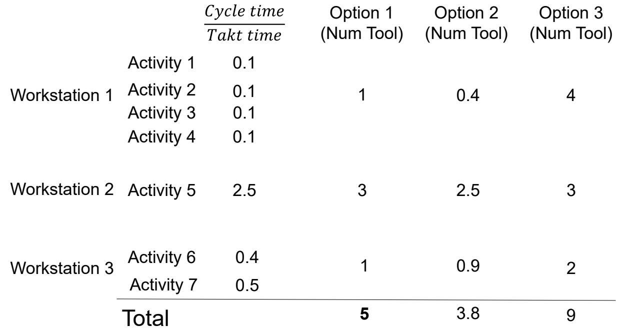


Fig. 5. Percentage of product cost allocated to each activity

It is pointed out that the number of workstations necessary to achieve the annual production volume is not estimated in the current version of CAMcost. Therefore, activities are not grouped into workstation and thus, the cost tool cannot estimate accurately the necessary number of tools, machines and/or workers needed to run the production when these resources are shared among the various activities.



		$\frac{\textit{Cycle time}}{\textit{Takt time}}$	Option 1 (Num Tool)	Option 2 (Num Tool)	Option 3 (Num Tool)
Workstation 1	Activity 1	0.1	1	0.4	4
	Activity 2	0.1			
	Activity 3	0.1			
	Activity 4	0.1			
Workstation 2	Activity 5	2.5	3	2.5	3
Workstation 3	Activity 6	0.4	1	0.9	2
	Activity 7	0.5			
	Total		**5**	3.8	9

To illustrate this deficiency, another example is presented in Fig. 6 in which the number of tools necessary to fabricate a composite part is estimated for various modelling options. In this specific example, it is assumed that there are seven activities and the same tool is shared by all these activities. Considering that the sum of the cycle time (including losses) of the activities in one workstation should not exceed the takt time of the workstation (or process), then, for this specific example, the activities can be grouped into three workstations. The necessary number of tools to achieve the annual production volume can be estimated by adding the ratios (activity cycle time over activity takt time) of the various activities in a specific workstation and rounding up afterwards, giving 5 tools, Option 1. Another strategy, less accurate, is to consider that the tool is non-dedicated to the activity and can be shared among all the activities, giving 3.8 tools, Option 2. Finally, the tools could be considered alternatively dedicated to the activity and thus, the number of tools is rounded up for every activity resulting in 9 tools, Option 3. Results of Option 2 & 3 are currently the outcome of CAMcost, which depending on the problem under investigation, can be a good or a gross approximation (or provide an upper and lower bound). The specific example highlights the importance of optimizing the resources with respect to time and adopting line balancing techniques.

6. Conclusions

To facilitate the introduction of advanced cost estimation techniques in earlier stages of the design process, a cost estimation framework has been developed. The suggested framework is based upon the PBCM technique and attempts to facilitate the creation of the cost model, the accumulation and assignment of the necessary input data to the model, as well as the visualization of the cost model structure for complex assemblies. Preliminary results indicated the efficiency of the developed framework studying the air intake product developed by GKN. To accelerate cost estimations further, the framework should be linked with appropriate engineering applications to retrieve necessary input information. Finally, resource estimations are of importance in cost modelling and thus, line balancing techniques should be linked with cost estimation methods.

Acknowledgements

The authors gratefully acknowledge the support provided by Innovate UK under AISA (project reference 113250).

References

[1] Roy R. Cost Engineering: Why, What and How? Decision Engineering Report Series, Cranfield University
[2] Hueber C, Horejsi K, Schledjewski R. Review of cost estimation: methods and models for aerospace composite manufacturing. Adv Manuf: Polym & Compos Sci. 2016;2(1):1-13.
[3] Large JP, Campbell HG, Cates D. Parametric Equations for Estimating Aircraft Airframe Costs. R-1693-1-PA&E, 1976.
[4] Kirchain R, Field FR. Process-Based Cost Modelling: Understanding the economics of technical decisions. Encycl Mat Sci & Eng 2000;2:1718-27
[5] Hazir O, Delorme X, Dolgui A. A Survey on Cost and Profit Oriented Assembly Line Balancing. Proceedings of the 19th World Congress, the International Federation of Autotmatic Control, 2014:6159-67.
[6] Mourtzis D. Simulation in the design and operation of manufacturing systems: state of the art and new trends. Int J Product Res. 2020;58(7):1927-1949
[7] Salonitis K, Stavropoulos P. On the integration of the CAx systems toward sustainable production. Procedia CIRP, 20139:115-120.
[8] Zhou W, Wang H, Li H, Tang G. AstroSim: A software framework for aerospace system analuysis and simulation. 2016 IEEE Chinese Guidance, Navigation and Control Conference, 2016:1893-1898.
[9] Johnson MD, Kirchain RE. Quantifying the effects of product family decisions on material selection: A process-based costing approach. Int J Product Econ, 2009;120:653-68.
[10] Northrop Corporation. Advanced Composite Cost Estimating Manual. AFFDL-TR-76-87, 1976;1.
[11] Bacharoudis K, Popov A, Ratchev S. Tolerance allocation: A reliability based optimisation approach. Procedia Manuf, 2020;51:1038-45.