Complexity Based Cost Estimation Model for Composite Aerospace Structures.

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SUMMARY: This paper outlines a new approach to determining the effect of part complexity on the cost of manufacturing a composite part. It also describes a methodology for predicting cost based on complexity that uses the techniques of Method Time Measurement (MTM). The proposed methodology offers a relatively simple method to predict the fabrication time of a complex component. It is based on the theory of acceleration and deceleration for every movement of action; therefore, the developed model has physical interpretations. In addition this paper describes a computer-based system for estimating time/cost to manufacture a complex composite part. The cost model has been implemented in a Relational Database Management System (RDBMS) with Access 97. The time estimated for hand lay-up compares very well with the industrial data. This concept of estimating fabrication time for a complex part appears to be applicable to many other composite manufacturing processes.

KEYWORDS: Computer Aided Design and Manufacture, Cost Estimation, Design.

1. INTRODUCTION

Advanced composite materials have shown the potential to achieve improved performance on aircraft structures. Their unique mechanical properties, such as low weight and high strength, make it possible to engineer structures at a lower weight than alternative designs made of aluminium. However, their use is restricted due to high material and fabrication costs. Considerable research has been carried out in an attempt to reduce the high cost of manufacturing composite structures. The general consensus is that revised manufacturing techniques are needed as a tool for increasing cost effectiveness. It is very important that the designers design composite structures with manufacturing cost effectiveness in mind. Knowledge acquired in concurrent design and concurrent engineering (CD/CE) indicates that a large percentage of the final cost of a product can be determined at the design stage itself.

Studies indicate that one of the major cost drivers in composite manufacturing is the complexity of the part. Therefore, the cost model for composite manufacturing should incorporate measures of complexity that a designer can abstract from the design with readily available design tools. The ACCEM (Advanced Composite Cost Estimating Manual Program) [2] model is one of the earliest to predict the costs associated with composite manufacturing. It is a purely an empirical model; the resulting power law equations and constants lack physical significance though they do incorporate part complexity. Therefore, the accuracy of this method of estimation will depend largely on the quality of the data used to determine the coefficients. There is also no physical interpretation of the ACCEM model, so it is very difficult to extrapolate it to new kinds of parts or processes.

An information theoretic approach was developed at MIT [1],[3] to identify complexity metrics. This was used to estimate the impact of complexity on the time and cost of

manufacturing with manual machining [3] and hand lay-up [1]. Neoh [1] developed a costing framework based on this approach. However, its use has not been verified in automated processes and other manufacturing processes such as RTM (Resin Transfer Mould) and RFI (Resin Film Infusion). The framework has in fact been applied only to two different composite fabrication processes (Automatic Tow Placement (ATP) and hand lay-up).

The MIT complexity model [1] was used to estimate the time of manufacturing complex components. These estimates were analysed and compared with the data gathered from Australian industry. The MIT data and industrial data were mapped for every set of processes; the mapping was based on process time and cost driver. It was found that for small values of cost drivers, the MIT data seemed to agree with the industrial data. However, for larger values of cost drivers, the time estimates were not consistent with the Australian industry data. The detailed study is presented in [7].

It is primarily for these reasons that a methodology based on the MTM technique was developed at RMIT to estimate complexity metrics. This methodology has been verified on the basis of data from the Australian composites industry. A computer-based system has been developed using the MTM technique. This system can be used to evaluate the complexity of a part and to estimate the fabrication time of different manufacturing processes, such as Prepreg, RTM and RFI. This system stores process information related parameters and the complexity metrics in an RDBMS. These information can be retrieved at any point during the product development.

This paper describes the method and theory involved in defining part complexity, and it illustrates how complexity metrics are calculated to estimate fabrication time. It also gives results with respect to model verification.

2. PROPOSED THEORY

Every action encompasses acceleration, movement and then deceleration if it encounters a change in direction of the movement. This is depicted in Fig. 1. To perform any task on a given part or component, initially there will be constant acceleration till the action reaches steady state velocity V_0. The action will then continue with the same velocity until it experiences a change in direction of the movement. Then the manual action starts to decelerate with constant deceleration for a certain time period, which mainly depends on the angle of bend. After the bend or change in direction is passed, the action again starts to accelerate. This sequence is repeated if another change in direction is encountered, until the task is completed.

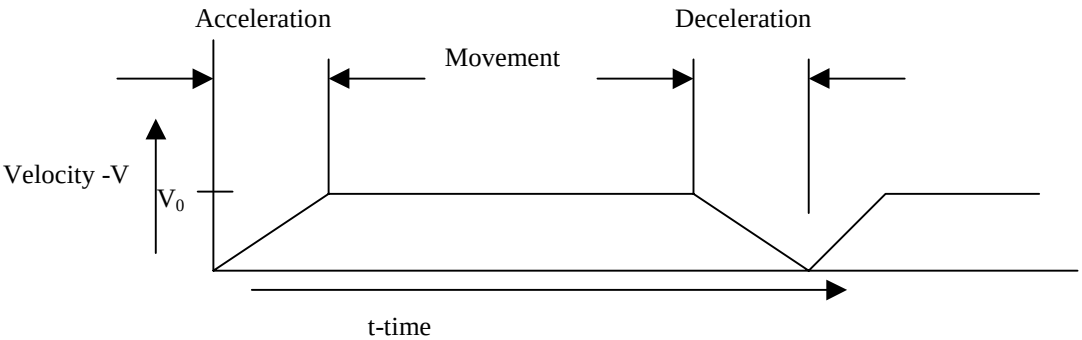


Fig. 1: Velocity profile with constant acceleration, movement and deceleration.

This hypothesis can be applied to estimate the time to do a task if the part is a flat surface. This is shown in Fig. 2. Initially there will be acceleration for length L_1, till it reaches the steady state velocity V_0 in time t_1 (which is the dynamic time constant), then the action continues with the same velocity and completes the task in time t_f for the remainder of the length L_2.
From Fig. 2 it can be seen that
Integrating Eqn 1 and Eqn 2 within the specified limits, the lengths L_1 and L_2 result as shown in Eqn 3 and Eqn 4.

$$V = V_0 \, t/t_1 \qquad 0 < t < t_1 \qquad \text{where } t_1 = \tau \text{ dynamic time constant} \qquad (1)$$

$$V = V_0 t \qquad t_1 < t < t_f \qquad (2)$$

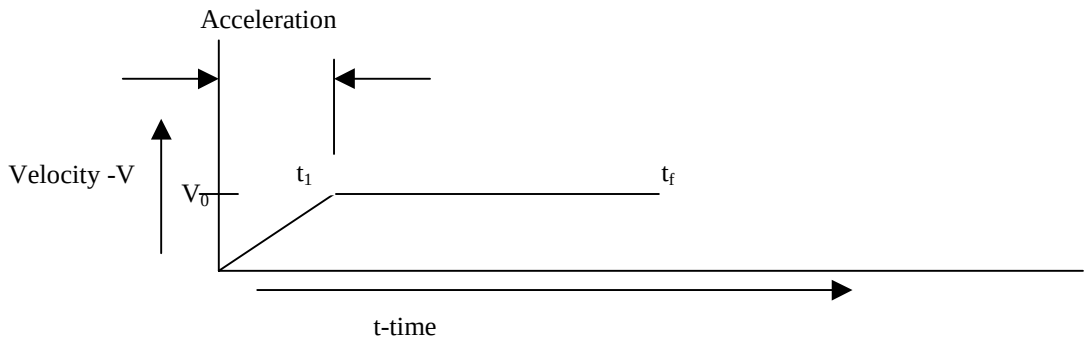


Fig. 2: Velocity profile of a flat surface part

$$L_1 = \tfrac{1}{2} V_0 t_1 \qquad (3)$$

$$L_2 = V_0 \left(t_f - t_1 \right) \qquad (4)$$

Adding Eqn 3 and Eqn 4 the total length L of the component is obtained. On re-arranging the terms, Eqn 5 results to estimate the time for a flat part.

$$t = \frac{L}{V_0} + \frac{\tau}{2} \qquad (5)$$

In Eqn 5, t is the time in hours and L is the design variable directly obtained from the design (it could be area or length or volume). V_0 is the steady state velocity and τ is the dynamic time constant. Vo and τ are based on process parameters and these values are adapted from the MIT model [1].

The process parameters can be established using four different approaches: i) dynamic models, ii) physical limits, iii) comparison to similar processes, and iv) experimental/measurement methods. The use of dynamic models necessitates an accurate physical description of the system. Two examples of dynamic models are considered in [1] to determine the parameters. The physical limit approach to derive the process parameters involves an understanding of the principle rate-governing phenomenon in the process. Comparing similar processes allows one to utilise data that are available across different fields and is particularly useful in estimating the time for new processes. A master chart representing the velocities for different processes across various fields is given in Neoh [1]

2.1 Definition of a complex part

A part's complexity depends on the shape of a part. Most of the processes in the aircraft industry are affected by part complexity. For example, layup, bonding tool (tool's complexity) and debulking or bagging all involve complexities. According to proven study and experience at the CRC-ACS' industrial partners, if a part has a bend greater than 30 degrees, then

complexity is involved. Therefore, a part is categorised as complex if it has one or more bends that exceeds 30 degrees. In reality, the amount of effort and time needed to do any task on a part having a bend less than 30 degrees is identical to that of a flat part. This is because the curvature of bend along the surface is small, and the change in direction of the movement (of the task) is negligible. Parts that are flat or have bends of less than 30 degrees are termed as zero complexity.

Complex parts are differentiated into two types. Parts with bends along one direction are classified as simple curvature parts, and parts with curvature along two directions are double curvature parts. Simple curvature parts consist of one or more bends along one direction. Moreover, the time needed to do a task on a simple curvature part is less compared to the time needed for double curvature part.

3. MTM methodology

This section focuses on the development of an MTM methodology. It discusses MTM techniques that can be applied to estimate the fabrication time of a complex part. MTM is a procedure-, which analyses any manual operation. It breaks the operation into all of the individual motions required to perform it, such as reaching, grasping, moving and positioning. It also assigns to each motion a predetermined time standard [4] [5], which is determined by the nature of the motion and the conditions under which it is made. The detailed approach used to calculate the time standard for different sets of motions is elaborated in [4]. Each motion has different degrees of influence. For example, length of motion, condition of motion, type of motion and effort all influence the Move motion (element).

Although all these motions have predetermined time standards assigned to them, only the Move motion is considered in the MTM methodology. This is because we are concerned only with the change in direction of the path when a task is carried out on a complex part.

3.1 Degrees of influence on the Move motion

The following describes degrees of influence on a Move motion:
a) Length of motion:- The length of motion is the distance actually covered between the start and end of the motion in centimetres.
b) Condition of motion:- The accuracy of location or positioning, and the condition of the destination to which the object is being transferred governs the condition of motion. There are three different cases of motion:-, case A, case B and case C. Case A is to move an object to the other hand or against a stop. The characteristic of this move is that little or no attention is required to carry out the motion. Case B is to move an object to an approximated or indefinite location. The feature of this move is that it does not require any special care or precaution. Case C is to move to an accurately determined location. Hence visual and mental concentration is necessary for this careful move. Out of these three different conditions of motion, we have considered Case A motion in this MTM study, because it does not involve visual and mental concentration, or precautionary measures.
c) Type of motion:- Most of the motion starts and ends with zero velocity. Any preceding or succeeding motion, however, can influence the motion.
d) Effort:- The last one is the effort required to move an object. The effort needed depends on the weight of the object and the frictional force of sliding.
The MTM data for a Move motion given in Table 1 has been established after considering the above mentioned different influences except the effort (depends on the weight of the object). Comparatively, the factor that affects the move motion due to the effort influence is very

small [4]. Additionally, the study is carried out to estimate the increase in time to do a task dependent on the distance moved and the amount of directional changes encountered.

3.2 The MTM time standard data

Originally the MTM was developed from an analysis of many hundred feet of motion-picture films. The qualified operators performing industrial operations in many of the geographical areas were filmed. Simultaneous equations and statistical methods were employed to determine the published time standard data.

The MTM time standard data for Case A move motions are expressed in Time-Measurement Units (TMU). The time values of this standard table are based on the normal degree of effort. The value of 1 TMU is equivalent to 0.00001 hours or 0.0006 minutes. In the normal standard table the distances are given in centimetres and the time in TMU. This is shown in Table 1.

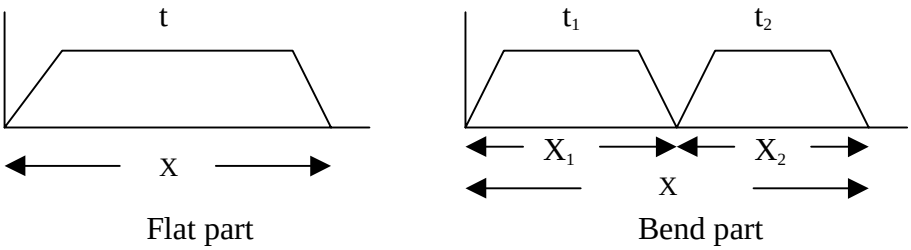
Table 1: MTM Time standards for the MOVE motion

Distance moved in centimetres	Normal time in TMU	Distance moved in centimetres	Normal time in TMU
2	2.0	28	12.1
4	3.1	30	12.7
6	4.1	35	14.3
8	5.1	40	15.8
10	6.0	45	17.4
12	6.9	50	19.0
14	7.7	55	20.5
16	8.3	60	22.1
18	9.0	65	23.6
20	9.6	70	25.2
22	10.2	75	26.7
24	10.8	80	28.3
26	11.5		

3.3 Percentage calculation

We use the MTM standard shown in Table 1 to estimate the percentage increase in time required to do a task on a complex part. To evaluate the percentage increase, two parts of the same size, one with a bend and the other without a bend, are considered. This is depicted in Fig 3. A part with a bend is regarded as two parts of length X_1 and X_2 and the time to do the task for the bend part results by adding the corresponding two TMU ($T = t_1+t_2$) values. With the TMU value 'T' of the bend part and the TMU value 't' of the flat part, the percentage difference in time is calculated. Likewise, after considering all different combinations of lengths and taking averages, it was found that variations in percentage difference for widths up to 40 centimetres were not significant for each bend considered separately.

Consequently, Table 2 was created with two groups of percentage differences (for parts having width less than 40 centimetres and for parts having width greater than 40 centimetres) for each of the directional changes, such as two bends, three bends, and four bends, etc. On examining the last two columns in Table 2 (simple curvature) and Table 3 (for double curvature as described in the next section), it can be seen that the percentage increase in time required to do the task is less in last column than it is in the second column.



$$\text{Percentage difference} = \frac{T-t}{t} \times 100$$

Fig 3: Profile of the lengths and corresponding MTM values for flat and bend parts

This is due to the fact that when parts are larger in size, it will be easier and faster to do the task at the bend portion. This is graphically illustrated in Fig 4.

Table 2: Percentage increases for different directional change for small and large widths

Simple curvature parts	Small widths	Large widths
Number of directional changes	Average percentage increase (%)	Average percentage increase (%)
1	21	14
2	37	28
3	49	38
4	61	50
5	70	59
6	82	69

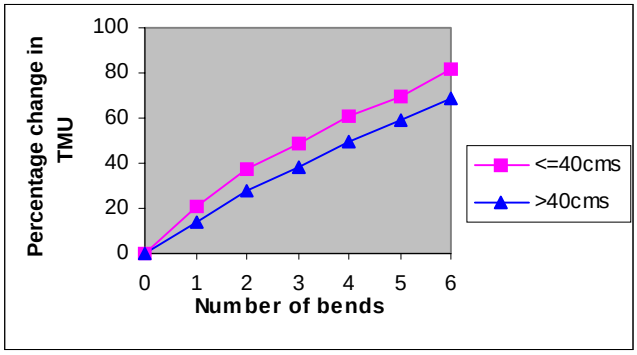


Fig: 4 Comparison of percentage difference for small and large widths

3.4 Complexity calculation

The MTM concept from the previous section can be used to estimate the time to perform the tasks on complex parts. Simple curvature parts are discussed in section 3.4.1, with double curvature parts in section 3.4.2.

3.4.1 Simple curvature parts

A simple bend or simple curvature part has one to many bends along one direction. Depending on the number of bends in a given component, the percentage increase evaluated

$$t = \left(\frac{L}{V_0} + \frac{\tau}{2} \right) \times \text{sb\_percent} \tag{6}$$

using MTM analysis is used in combination with Eqn 5 to estimate the fabrication time of a simple curvature part. Thus, the Eqn 6 gives the time taken to do a task on a simple curvature part. In the Eqn 6, sb_percent is obtained from the percentage column of Table 2.

3.4.2 Double curvature parts

In double curvature complex parts, the path of bend changes along two different directions, and this makes any kind of task very difficult. Therefore the time required to perform any task on a double curvature part is much greater relative to the time required for a part with a simple bend. This is reflected by modifying Eqn 6. Since the direction of bend is along two different directions, the percentage needs to be doubled in each direction. Therefore, for every directional change, the percentage difference listed in Table 2 is multiplied by a factor of four to generate Table 3. As a result the percentage in Table 3 is four times the sb_percent (simple curvature percentage). Table 3 gives values for db_percent (double curvature components).

$$t = \left(\frac{L}{V_0} + \frac{\tau}{2} \right) \times \text{db\_percent} \tag{7}$$

Table 3: Percentage increase for various directional changes for double curvature parts

Double curvature parts	Small widths	Large widths
Number of directional changes	Average percentage increase (%)	Average percentage increase (%)
1	84	56
2	148	112
3	196	152
4	244	200
5	280	236
6	328	276

Eqn 7 can be used to estimate the fabrication time of double curvature parts. Thus far, the time calculated is for each ply of the given component. If there is more than one ply, accordingly the number of plies needs to be factored into Eqn 6 or Eqn 7.

However, if the part is too long (say length greater than 100 centimetres) and very big (even the width greater than 80 centimetres), the manual tasks need more than one person. Therefore, in practice, for larger components, the total time required to do the task will be a multiple of the value that could be predicted theoretically depending on the size of the component. This hypothesis was tested and the result seems to agree with the actual values from industry.

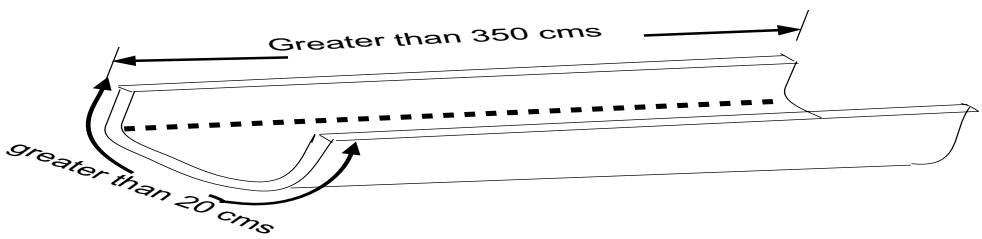


Fig. 5: One of the largest component tested for hand lay-up process.

4 System Overview

The computer-based system is depicted in Fig. 6 in a use case representation. A use case diagram indicates use cases (the way the system can be used), actors (users in certain roles), and relationships between the use cases and the actors.

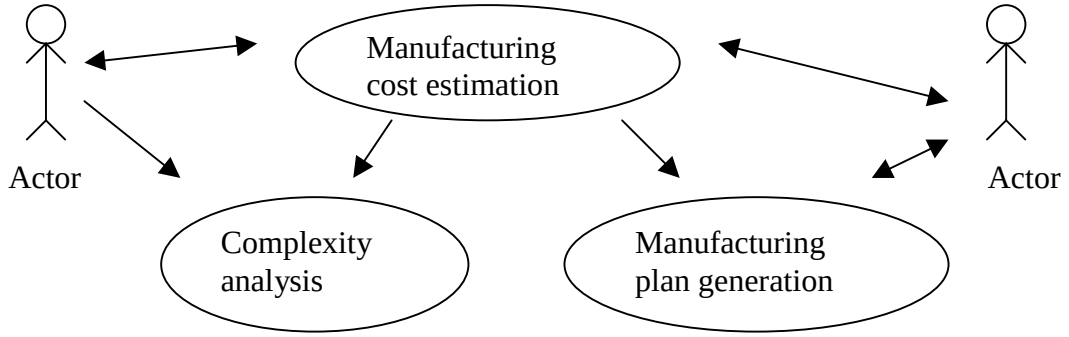


Fig. 6: The use case representation of the computer system

Interaction between the external actor (designer) and the sub-system

Use Case: A way to represent the system

Relationship between the Use Cases

4.1 Relational Database Management System (RDBMS)

The full system is implemented in Microsoft Access 97 (a relational database) using Visual Basic. The system has a user-friendly Graphical User Interface (GUI) that the user can employ to interact with the cost model. Access has the features of creating forms and reports using the object based language such as Visual Basic for Access (VBA) and the macro programming, which is based on the events that occur during data processing. The detailed approach is described in Kumar [7].

Fig. 7 illustrates a few of the screen images that support the estimation of manufacturing time for complex components. The first image (Fig. 7) displayed to the user allows them to choose the type of complexity involved in a component. If the simple bend button is selected, the next image shown in Fig. 7 will be presented to the user to choose the size of a component.

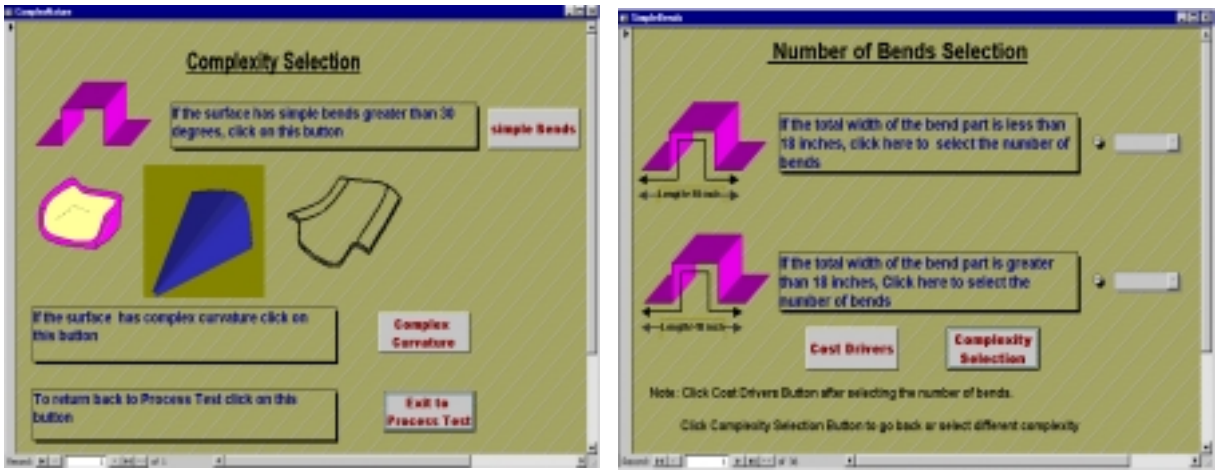


Fig: 7 User Interface to select the type of complexity (Form) and to select the number bends based on the size of the component (Form).

4 Results and Discussion

The proposed complexity based cost model was tested mainly on the hand lay-up process. Only a few parts are shown in Fig. 8, although many simple curvature parts (with one to five bends) and double curvature parts were used to test the developed model.

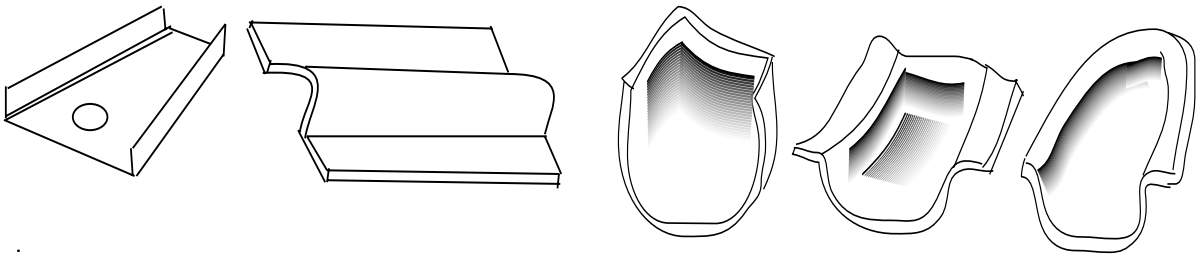


Fig: 8 Simple curvature parts and Double curvature parts.

Fig. 9 shows the comparison of time estimated for hand lay-up process using the proposed method with the industrial data for simple curvature parts. The parts with one, two, three and five bends and having different number of plies were studied. It can be seen in Fig. 9 that the industrial value is very consistent with that of the proposed value for all parts. The graph is not linear because of the fact that the parts considered are of not all of same size and do not have the same number of plies.

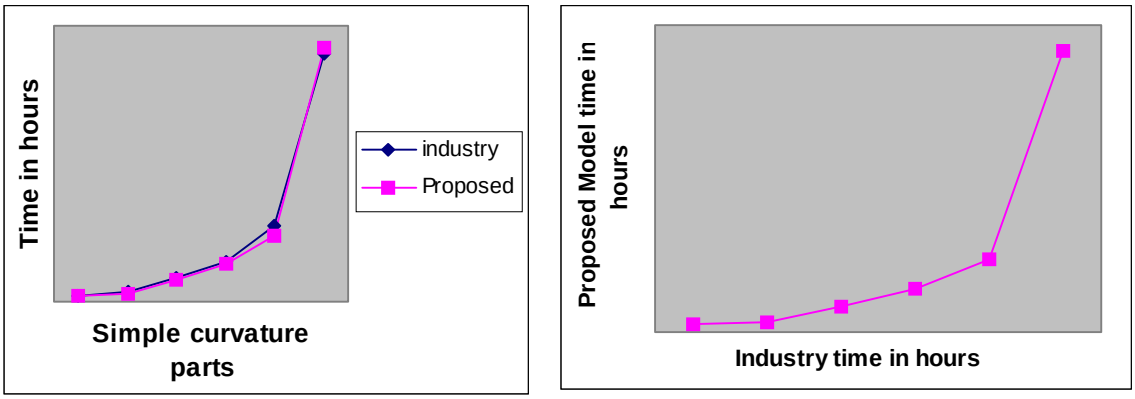


Fig 9: Comparison of Industry data with the proposed model for simple curvature parts

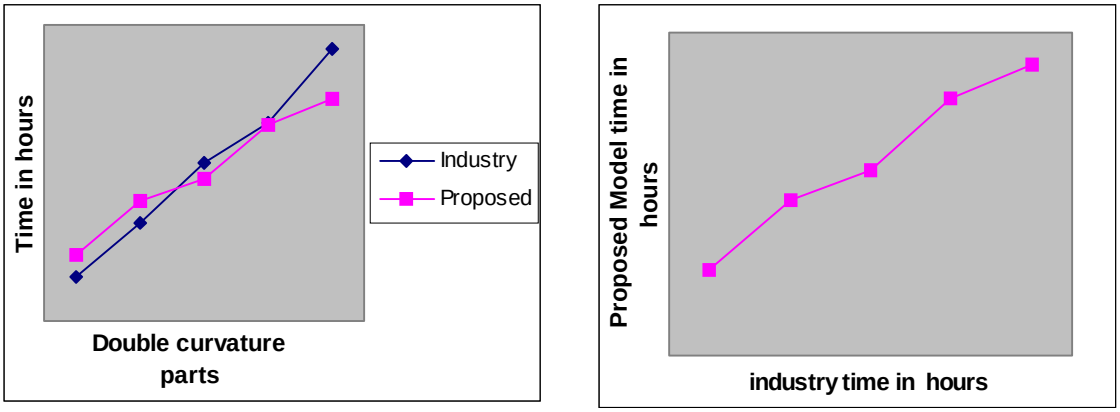


Fig 10: Comparison of Industry data with the proposed model for double curvature parts

Fig 10 shows a comparison of data from the hand lay-up process for double curvature parts. The estimates seem to agree very well with that of the industrial data. In both cases the parts

considered were of different shapes and sizes; they also have different numbers of bends and plies.

Fig. 4 demonstrates that the increase in time required as the number of bends changes is linear. This is comparable with the test carried out on different parts with cumulative bends in Neoh [1]. Please refer to Kumar [7] for more details. It follows that the proposed MTM methodology is simple and has physical significance.

5 CONCLUSION

The proposed methodology is a new approach toward estimating the fabrication time of complex composite components. This concept is very simple and involves time equations, which agree dimensionally. The developed technique can be applied to any composite manufacturing processes. The results obtained for the hand lay-up process have excellent correlation with the industrial data for both simple curvature and double curvature components. The advantages of the proposed model are that the concept is easy to use to identify the complexity; it shows the affect of part complexity on the cost; and it has very good GUI. Finally it is easy to estimate the fabrication time for updated new processes.

6 ACKNOWLEDGEMENT

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