Automated Assembly Time Analysis Using a Digital Knowledge Based Approach

Y. Jin[1] and R. Curran[2] and J. Butterfield[3]
[1,3]School of Mechanical & Aerospace Engineering, Queen's University Belfast, UK BT9 5AH [2]Aerospace Management & Operations, Delft University of Technology,2629 HS Delft, The Netherlands

and

R. Burke[4] and B. Welch[5]
Bombardier Aerospace Belfast, Airport Road, Belfast, UK BT3 9DZ

The implementation of effective time analysis methods fast and accurately in the era of digital manufacturing has become a significant challenge for aerospace manufacturers hoping to build and maintain a competitive advantage. This paper proposes a structure oriented, knowledge-based approach for intelligent time analysis of aircraft assembly processes within a digital manufacturing framework. A knowledge system is developed so that the design knowledge can be intelligently retrieved for implementing assembly time analysis automatically. A time estimation method based on MOST, is reviewed and employed. Knowledge capture, transfer and storage within the digital manufacturing environment are extensively discussed. Configured plantypes, GUIs and functional modules are designed and developed for the automated time analysis. An exemplar study using an aircraft panel assembly from a regional jet is also presented. Although the method currently focuses on aircraft assembly, it can also be well utilized in other industry sectors, such as transportation, automobile and shipbuilding. The main contribution of the work is to present a methodology that facilitates the integration of time analysis with design and manufacturing using a digital manufacturing platform solution.

I. Introduction

AIRCRAFT assembly is a labor intensive and time consuming process which accounts for around one third of

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[1] Research Fellow, CEIAT, School of Mechanical & Aerospace Eng., Stranmillis Rd, Belfast, UK BT9 5AH, e-mail: y.jin@qub.ac.uk, Tel: +44 (0)28 9097 5657

[2] Professor, Aerospace Management & Operations, Delft University of Technology, 2629 HS Delft The Netherlands

[3] Lecturer, School of Mechanical and Aerospace Engineering, Queen's University Belfast.

[4] Methods Engineering, Bombardier Aerospace Belfast.

[5] Methods Engineering, Bombardier Aerospace Belfast.

total manufacturing cost. The accurate estimation and analysis of aircraft assembly times are important for process planning, cost control and reducing product development lead times. Traditional time estimation requires the methods engineer to calculate assembly times based on assembly books, which are created by process planners. However, these assembly books are mainly focusing on the production plan but are generally not well suited to time generation activities. Methods engineers sometimes have to search through drawings or check with shop floor operators to obtain time information. This in itself, is very time consuming and error prone. More importantly, the process planner may not have an accurate sense of time when he plans the production, so that the assembly times for different sub-assembly modules may not be in the same scale, making line balancing difficult. The gap between methods engineers, process planners and even designers, imposes negative effects on the success of a company in the competitive aerospace industry today. In addition, time consumed on the shop floor may not be traceable, making it difficult to identify the time driver once a big project fails to complete in the pre-assigned schedule. Although there are some CAE tools, such as AutoMOST, to aid engineers for time analysis, each of these tools is only limited to pieces of functions of the whole product life cycle. Furthermore, these CAE tools cannot be seamlessly integrated into a collaborative/concurrent environment, which is imperative to any modern lean enterprises. Therefore, to eliminate the gap and establish a rapid, effective and traceable mechanism has become the prime challenge for an aircraft company to build and maintain a competitive advantage.

Digital methods are now playing a more significant role in process planning activities within the aerospace industry [1]. Digital manufacturing is defined as the ability to describe every aspect of the design-to-manufacture process digitally—using tools that include digital design, CAD, Office documents, PLM systems, analysis software, simulation, CAM software and so on [2, 3]. Digital Manufacturing is an emerging software technology that will become a fundamental and liberating component of Product Lifecycle Management (PLM) [4]. However, such tools cannot be embedded blindly and they often need to be company-specific, which poses new challenges on knowledge capture, data definition and transformation, and the development of effective and efficient decision making tools [5, 6]. Digital manufacturing solutions have to be applied within a framework of carefully developed and deployed closed-loop processes for both manufacturing planning and information management.

Facing these challenges, this paper is to solve following questions.

- How to precisely and rapidly quantify process/production times?

- How to design the software configuration to facilitate process planning, automatic time generation and information management?
- How to store, capture and transfer knowledge for both process planning and time generation in a convenient and efficient manner?
- When, where and what knowledge needs to be captured, saved, transferred and output?
- How to implement the automation of time analysis so that it can be used by a casual end-user without expert knowledge?

The work in this paper focuses on the most import module of a big project for implementing lean enterprises through digital manufacturing, i.e., assembly time analysis. This paper considers the development of a digital design and manufacturing modeling platform with integrated time analysis capabilities, providing a truly collaborative methodology and concurrent engineering tool for shortening aircraft assembly time, so as for reducing aircraft life cycle cost. A structure oriented, digital knowledge based approach is proposed for the automated time analysis of aircraft assembly processes. The structure is object oriented, standard, repeatable and extendable. It facilitates not only process planning but also time estimation, and it can be seamlessly integrated into a digital manufacturing environment. Intuitive interfaces, function modules supported by expert systems and algorithmic links are designed and developed mapping to the different phases of production. This paper consists of five sections. Section 2 reviews literatures. Section 3 addresses the proposed methodology and its integration within a digital manufacture environment. Section 4 presents an exemplar study. Section 5 concludes this paper.

II. Literature Review

Time and cost metric are very important throughout design, planning and production. It is reported that around seventy percent of the manufacturing cost is determined at the design phase [5]. Many companies and researchers have put their great efforts on developing design for manufacturing/production tools by integrating time/cost metrics [7-14]. However, most of their works are only piece of the simulations or function modules, which cannot cover the whole product life cycle, so that a comprehensive design environment is imperatively required. More and more manufacturing companies, such as Airbus, Boeing and Bombardier, have recently started utilizing digital design and manufacturing tools to implement truly lean enterprises [16 - 19]. And many researcher groups are currently looking at developing a more integrated approach to design and digital manufacturing [5, 7, 9, 16, 17]. Freedman [5] compared the engineering process of traditional “physical” engineering and modern virtual engineering, and discussed the benefits of digital manufacturing, such as collaborative engineering and simulation based design resulting in significant cost/time reduction. He also mentioned the challenges of implementing a fully digital enterprise, including the establishment and management of product, process and resource knowledge base across the whole enterprise. Curran et al. [16] proposed a concurrent approach for integrating cost capabilities into digital design and manufacturing modeling at the conceptual design phase. This approach offers the user to readily exploit the digital manufacturing simulation capabilities to get optimal solutions within the context of the whole aircraft life cycle cost. Herrmann and Chincholkar[8] introduced a design-for-production tool based on a queuing network model for assessing the capability requirements and manufacturing cycle time to provide feedback to the product design team. Maropoulos et al. [20] discussed the major problem in a large and complex product design and integration, i.e. design is separated from the manufacturing and assembly planning & control within an enterprise. The aggregate process planning method and large-scale laser metrology approach was introduced for collaborative design and production engineering under a digital enterprise framework. Butterfield et al. [17] has investigated the benefits of using digital manufacturing tools by a case study on the assembly process optimization of aircraft fuselage. It clearly shows that digital manufacturing can bring many advantages, such as accelerating process and production planning, providing prerecorded simulations for operation training, reducing the number of design iterations. It also admits that various functional modules and tools are urgently required to be customized and developed for a unique company. This requires much collaboration between IT engineers, manufacturing engineers, and university researchers. In summary, knowledge and intelligence has become the key challenges to evolve the manufacturing enterprises to modern lean enterprise, which requires an effective, rapid and accurate time/cost assessment throughout the whole product life cycle [10].

Time analysis and work measurement are important building block of modern lean enterprises. However, the ability to utilize the vast information database available during the creation of standards associated with the optimal design of the production system has more potential impact. In addition, the fidelity and accuracy of analysis that is then available is crucial to the precision of the final assembly time estimation. This is critical to the scheduling and planning of each project or contract.

In practice, there are several different systems available for time estimating, such as Work-Factor system (WFS), Design For Assembly (DFA) [14], Methods-Time Measurement (MTM) [21] and Maynard Operation Sequence

Technique (MOST) [22]. WFS [23] is one of the pioneer methods for establishing standards based on the motion of human body members, such as head, arms and legs. A work factor is used as an index for the extra time required above the basic time. Depending on the application requirements, WFS is classified into three systems, named Detailed WFS, Ready WFS, and Brief WFS. The WFS is mainly utilized in Japan. For the original DFA method, the estimates of assembly time were based on a group technology approach in which the design features of parts and products were classified into broad categories and, for each category, average handling and insertion times were established. Clearly, for any particular operation, these average times may be considerably higher or lower than the actual times but are likely to converge on a nominal cumulative value that is of sufficient accuracy. Essentially, for assemblies containing a significant number of parts, the positive and negative differentials tend to cancel out so that the total time is reasonably accurate. In fact, application of the DFA method in practice has shown that assembly time estimates are reasonably accurate for small assemblies in low-volume production where all the parts are within easy arm reach of the assembly worker. However, the main contribution of the DFA method was to improve the assembly efficiency, or so called assemblability, in terms of reducing part counts and the number of assembly operations; time analysis being an assessment metric rather than an absolutely accurate time prediction. Therefore, DFA is mainly used in the design stage other than planning stage for aerospace industry.

The Methods-Time Measurement (MTM) approach was proposed in the 1940's by Maynard, Stegemerten and Schwab [21]. MTM is a procedure that analyzes any series of manual operations in accordance with the basic motions required to perform it. It assigns to each motion a pre-determined time standard that is determined by the nature of the motion and the conditions under which it is performed. MTM has evolved into versions referred to as MTM-2 and MTM-3 that further its application. The modern version of MTM is termed MOST, being a simplified system firstly developed by Zandin [22]. For different application areas, the MOST system is then further classified into three independent systems: BasicMOST®, for general applications; MiniMOST®, for repetitive and short cycle operations; and MaxiMOST®, for non-repetitive and long cycle operations. The MOST system makes use of similarities in the sequence of MTM-defined motions to lay out the foundation for the basic activity models; so that the MOST system is fast, accurate, easy to learn and simple to use. Consequently, it aims to be the fastest method with the required relevant accuracy. It has been reported that the application speed of BasicMost system is up to eight times faster than MTM-2; which tends to be utilized by aerospace, considering their associated factory practice. In implementation, a top-down analysis is carried out for analyzing the shop floor operations; where these are then broken down into sequences of sub-ops, each sub-op being further decomposed into a sequence of basic MOST motions, as illustrated in Figure 1.

Although some software systems are available to help the user estimate times automatically, many interactions are required and the user must be a trained expert. In addition, these software systems cannot be integrated into a digital manufacturing environment easily to bridge the design and production. The integration of time analysis with design and manufacturing in a PLM environment is currently out of literature, and our work will present a solution to fill into this position.

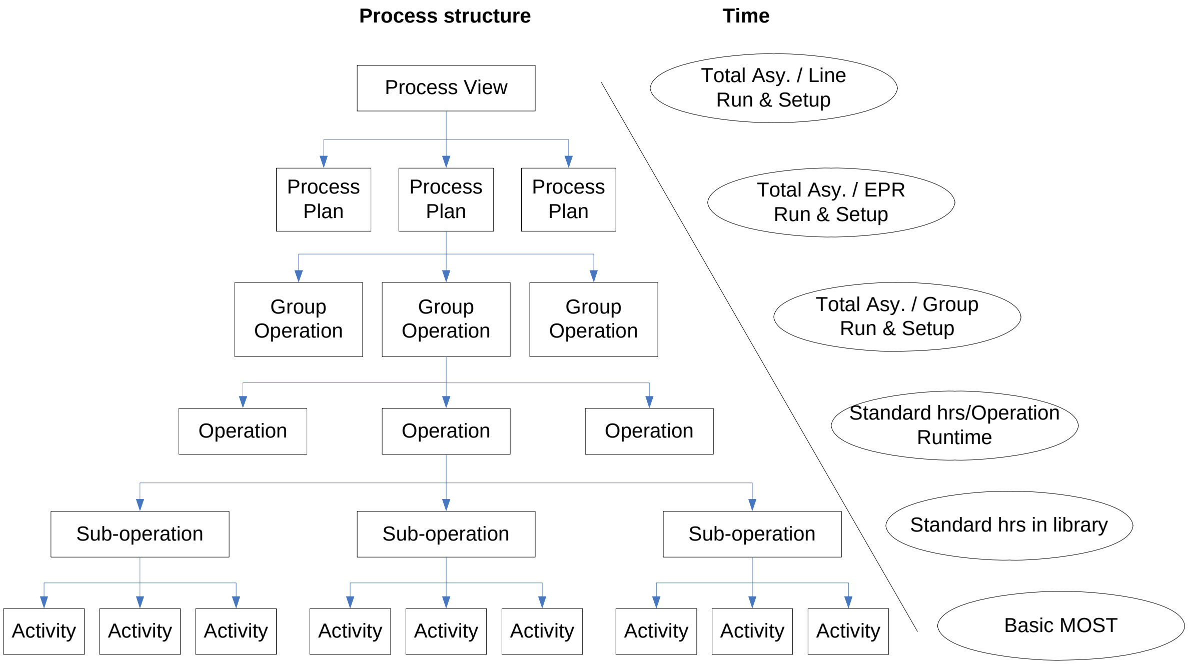


Fig.1 Architecture of work breakdown structure utilized in time analysis

III. Proposed Methodology

A. Process structure

To facilitate the automatic generation of assembly times for the different levels mapped to the different production phases, a suitable structure is required to support effective information management and functionality development, so that all required information can be efficiently and effectively captured, utilized and manipulated. To implement automated assembly time analysis, the structure must be able to capture all assembly breakdown information and time consumption procedure for produce the assembly. With the shop floor practice in mind, a structure orientated methodology is proposed as shown in Fig. 1. The structure follows a top-down approach where each parent object is composed of several child objects in the level below. Such a structure or template will facilitate both the process planning and the time generation explained below. The lowest level of this structure is the human activity associated with MOST motions and with their associated standard times. As the speed of MOST is far from sufficient to compute every time standard economically on a direct basis, a level of sub-operation, which is built up by the activities, is required. The operation level is defined by the type of assembly operation and relates to the basic ergonomic operations carried out on the shop floor. These basic elements that are referred to in the work instructions are equated to operational objects. These become the basic units for process planning, where generally only the runtime is associated with each operation. Subsequently, sequential operations are designated as forming a group-operation, with the setup time being input at this level. Each process plan consists of a sequence of group-operations with an associated setup time; relating to the time taken to prepare tooling, etc. and review instructional materials. Similarly, a sequence of process plans make up a process view, where the setup time for building workstations will be taken into account. Finally, at each level the user has the ability to build the network for the next higher-level assembly. In summary, the procedure of time analysis on different production levels is shown in Fig. 2 and the functional requirements for each level are listed in Table 1.

B. Knowledge acquisition and modeling of the reasoning method

To realize an effective approach of time analysis, all domain knowledge need to be analyzed, extracted and modeled carefully based on the proposed process structure. The domain knowledge comes from following resources: predetermined basic activity time information, which is the basic building block and associated with activity objects of the lowest level; expert domain knowledge, which is for modeling sub-operations by rolling up the basic activities, and modeling operations by rolling up sub-operations, and time allowance accounting for the personal, fatigue, and auxiliary delay allowances; domain process knowledge, used to find the corresponding time to an operation, and to assign the according setup time, from operation level to the top level; learning curve knowledge, which is used for time analysis for the whole production of a number of sets of products. More details will be explained later on.

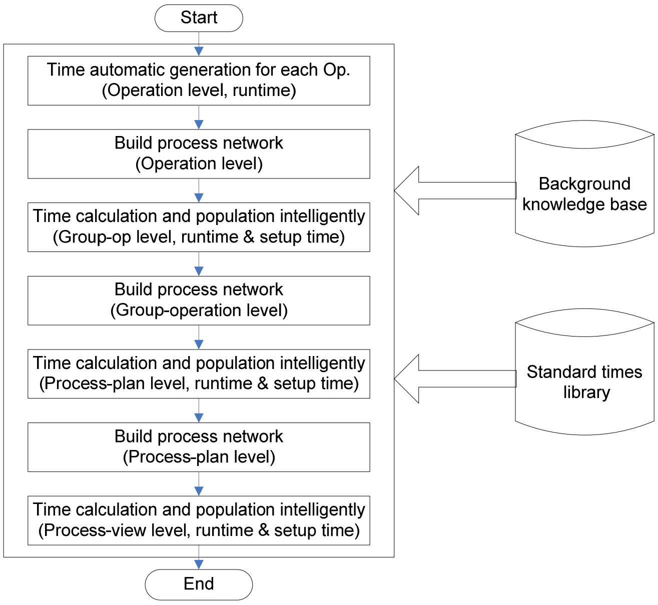


Fig. 2 Procedure of time estimation in different process Levels

Table.1 Functional requirements in each level

Process level	Required functional modules
Process View	• Add setup time for the production line • Calculate assembly time/cost
Process Plan	• Add setup time for the plan • Calculate assembly time/cost • Build up network • Model learning curve
Group Operation	• Add setup time for the sequence of operations • Calculate assembly time • Build up network
Operation	• Establish links with sub-ops • Automatic time population • Build up network
Sub-operation	• Generation of sub-ops with standard activity times • Store all sub-ops in a library
Activity	• MOST standard times

B.1 Modeling of sub-operations and operations

As mentioned before, a top-down analysis needs to be carried out for analyzing shop floor operations to model the assembly time. Each operation will be broken down into a sequence of sub-operations which consist of MOST motion sequences. MOST certified instructors (methods engineers) observe and document the method for each different work activity. They then consult the technical team to establish a reasonable and fair standard practice for different work activities and standardize each sub-operation with a standard time and a unique ID. For example, the operation “Drill” on alloy parts is further classified into seven different types, such as drill 3/32" hole and ream. The “drill 3/32" hole” (ID 2000, 0.1362 mins) operation is composed of following sub-operations.

a) ID 1000, drill hole, 0.111 mins

b) ID 1001, bending allowance, 0.0060 mins

c) ID 1002, move platform, 0.0192 mins

And the sub-operation “Drill hole (ID 1000, 185 TMUs = 0.111 mins)” is built up by following activities.

a) Hold & place drill gun from operator to hole (Sequence Model: A0 B0 G0 A1 B0 P3 A0, 40 TMUs)

b) Push trigger on drill gun at part (Sequence Model: A1 B0 G1 M1 X10 I0 A0, 130 TMUs)

c) Move 1/4 step to next group of holes (Seq. Model: A1 B0 G1 A3 B0 P1 A0, 15 TMUs)

Based on this method, various operations on shop floor can be accurately modeled and quantified, so that the standardization on shop floor can be realized. In the era of digital manufacturing, all these standard operations with standard times will be stored in a digital library and seamlessly integrated into the central database shared by all functional division in a company.

B. 2 **Modeling of reasoning method**

The modeling procedure is a process of analysis, extraction and classification. For aircraft assembly, operations are generally classified as locate, drill, dismantle, deburr, sealing & coating, reassemble, installing fasteners and special operations. Fig. 3 shows a forward inference mechanism to reason from existing knowledge to the corresponding conclusions. The existing knowledge includes part design knowledge such as part material, size and weight, and operation process knowledge such as operation type. For instance, with part material and part size/weight information of a locate operation, the standard time for this operation can be obtained. Such an inference mechanism can be easily symbolized into rule-based systems. Note that, setup time is required for some operation. For instance, before drilling operation, preparing a drill gun and connecting an air hose to air tool are required. Therefore, an inference mechanism for estimating setup times needs to be built up.

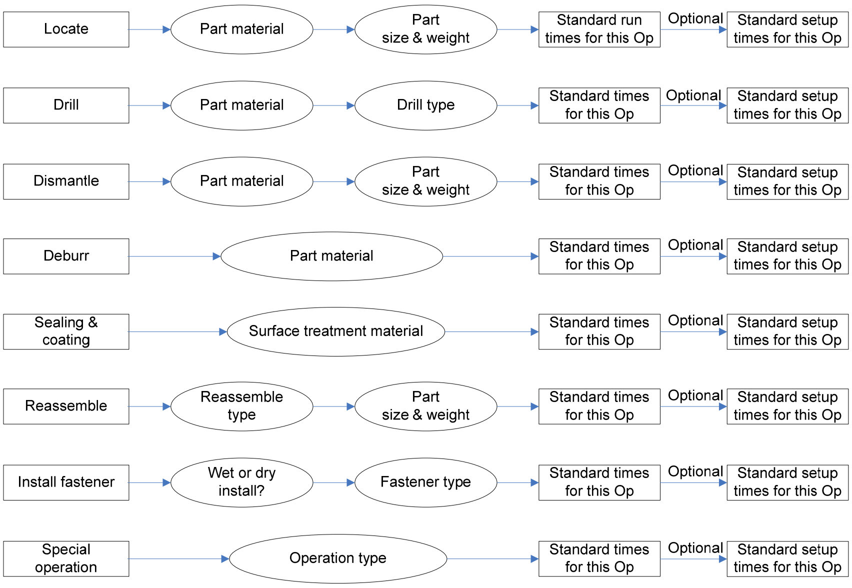


Fig. 3 Forward inference mechanism for operation times

B. 3 **Modeling of learning curve**

Learning curve is based on the fact that the time required to perform a repetitive task decreases as one gains experience. Learning curves are useful for time/cost estimates, production planning, control and evaluation. Taking the Wright's cumulative average model, as shown in Fig. 4, the leaning curve function is defined as follows [14, 24].

$$Y = m X^n$$

Where Y represents the cumulative average time per unit; X the cumulative number of units produced; m time required to produce the first unit; n the ratio of log of learning rate to log of 2. An 80% leaning curve refers to that the cumulative average time per unit will decrease by 20% over double quantity. Generally speaking, leaning curves always follow an exponential curve, which decreases steeply at the beginning and becomes flat with the experience increased. Note that the time estimates obtained from above section is the optimal time with the "best" method, therefore, the time estimate is equal to or close to the minimum time consumed, mapping to a point with larger X value on the flat area of the learning curve. Let's say the time estimate Te obtained is at the 200th unit and the operators follow an 80% curve, then the time consumed for making the first unit can be calculated by following equation.

$$Te = Y(200) * 200 - Y(199) * 199 = m * 200 * 200^{\log 0.8/\log 2} - m * 199 * 199^{\log 0.8/\log 2} \quad (1)$$

So we have

$$m = 8.11 * Te \tag{2}$$

With initial time available, time estimates for any lot size of units can be calculated easily according to Eqn. (1).

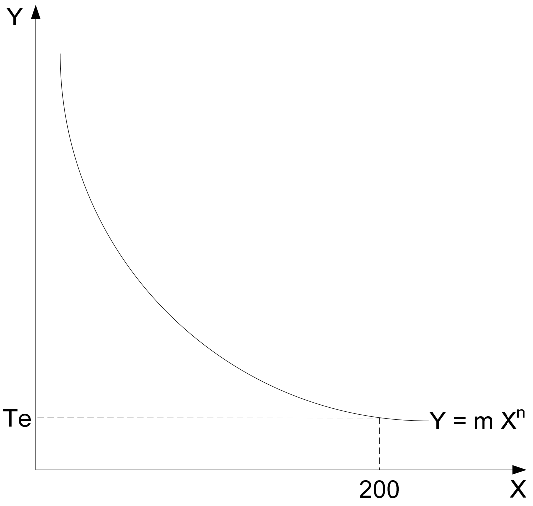


Fig. 4 Wright’s learning curve model

C. Implementation within digital manufacturing tools

Although digital manufacturing has many advantages for the manufacturers, digital planning solutions have to be applied within the framework of carefully developed and deployed closed-loop processes for both manufacturing planning and information management. The architecture must be carefully tailored to suit the requirements from different departments within the organization. In addition, the architecture must be well defined to ease data capture and transformation so that the function modules can be perfectly defined and developed [3].

C.1 Integration of process structure into digital manufacturing tools

One popular software tool to realize digital manufacturing within the aerospace industry is Delmia Process Engineer (DPE), which helps process planning by integrating product, process and resource (PPR) information from the conceptual design phase through to the process planning phase and on to the production phase. It utilizes object oriented PPR tree structures capable of modeling the entire planning contents and all logical relationships between the process, product and resource data. More importantly, DPE can be seamlessly integrated with other digitized manufacturing modules, such as CATIA and digital process manufacturing (DPM). In this project DPE V5R17 is employed. Considering the functionality of the DPE process tree and ease of its application, from the operation level to the top level of the process structure will be implemented in DPE. The sub-operations with standard hours will be saved in a library. As there is no group operation level in the process tree for the default V5R17 plantype (configuration), one more assembly level is created to align with our proposed structure. The configuration can be customized to conform to any company's unique structure.

C. 2 Implementation of knowledge-based system of time analysis

The first step to establishing intelligent time estimation within the digital manufacturing environment is to automate the time generation process so that it requires minimum interaction from casual end-users who may not have expert knowledge. To achieve this goal, an expert system is developed by DPE scripting as shown in Fig. 5, and it is executed by clicking a command button that is configured through the property dialog of the operation plantype, as shown in Fig. 6. The time generation is implemented in the DPE process tree for every operation object which is supported by the DPE product tree with all associated part objects, time required knowledge and a sub-operation library containing standard times. In order to store the design knowledge for each part object in DPE, a transformation tool is developed for retrieving design knowledge from CAD files in CATIA and transferring them to corresponding part objects in the DPE product tree. Therefore, the part plantype in DPE is configured, and a graphical user interface is developed to store, visualize, and edit these part attributes, as shown in Fig. 7. A name convention mechanism should be established for knowledge transfer. Once the expert system is started, the user can select an operation type through an option dialog as shown in Fig. 8. The operation type will be further refined by its associated part attribute knowledge. The corresponding standard times can then be retrieved and calculated with quantity information based on predefined algorithms. Finally, the runtime of the operation is set as one of its attributes through the customized interface as shown in Fig. 9.

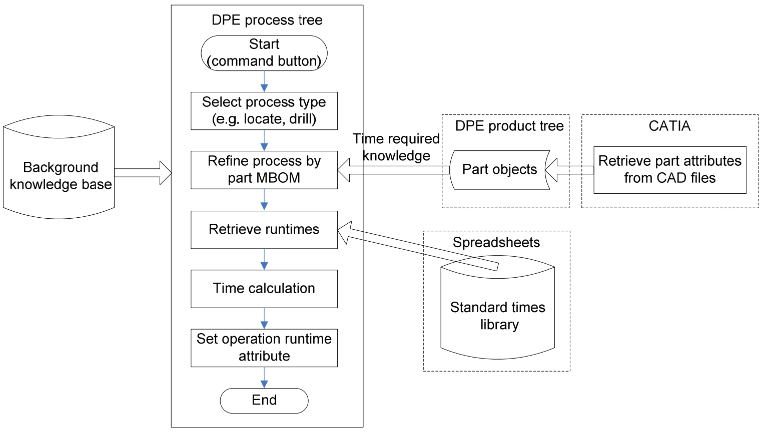
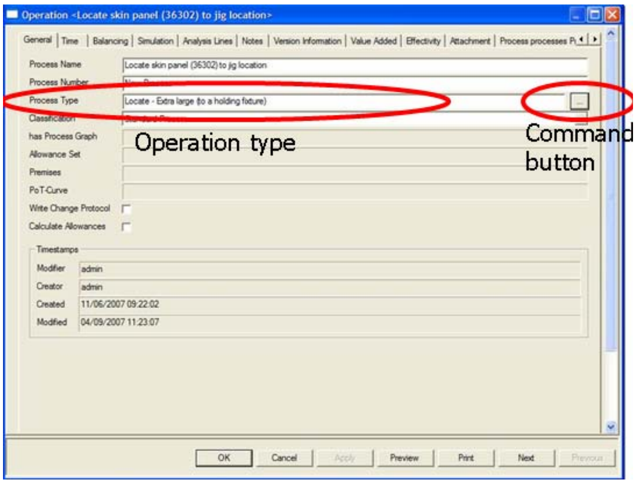


Fig. 5 Time generation intelligently for each operation



Operation <Locate skin panel (36302) to jig location>

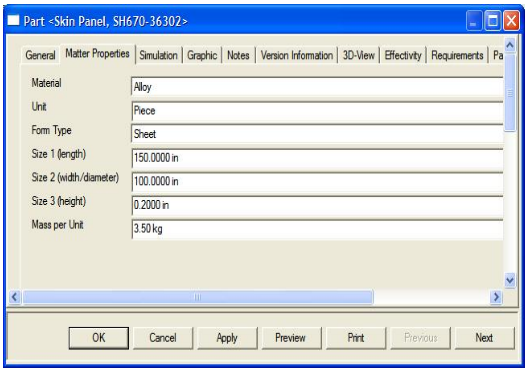
Process Name	Locate skin panel (36302) to jig location
Process Number	
Process Type	Locate - Extra large (to a holding fixture)
Classification	
has Process Graph	
Allowance Set	
Premises	
PoT-Curve	

Write Change Protocol ☐
Calculate Allowances ☐

Timestamps

Modifier	admin
Creator	admin
Created	11/06/2007 09:22:02
Modified	04/09/2007 11:23:07

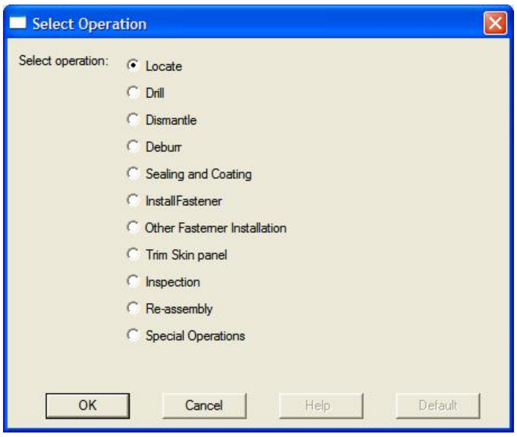
Fig. 6 configured plantype for an operation



Part <Skin Panel, SH670-36302>

Material	Alloy
Unit	Piece
Form Type	Sheet
Size 1 (length)	150.0000 in
Size 2 (width/diameter)	100.0000 in
Size 3 (height)	0.2000 in
Mass per Unit	3.50 kg

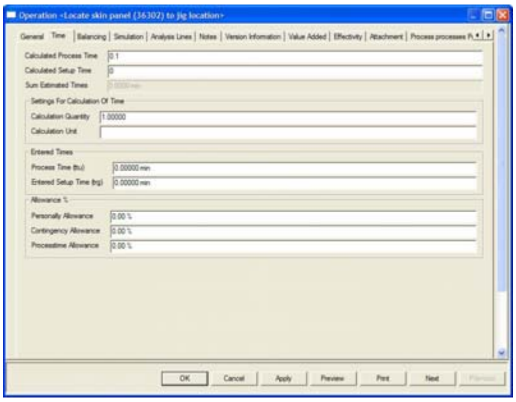
Fig. 7 GUI of time required knowledge



Select operation:

- ● Locate
- ○ Drill
- ○ Dismantle
- ○ Deburr
- ○ Sealing and Coating
- ○ InstallFastener
- ○ Other Fastemer Installation
- ○ Trim Skin panel
- ○ Inspection
- ○ Re-assembly
- ○ Special Operations

Fig. 8 User interface used to select a process type for an operation



Calculated Process Time: 0.1
Calculated Setup Time: 0
Sum Estimated Times

Settings For Calculation Of Time
Calculation Quantity: 1.00000
Calculation Unit:

Entered Times
Process Time (tu): 0.00000 min
Entered Setup Time (tg): 0.00000 min

Allowance %
Personally Allowance: 0.00 %
Contingency Allowance: 0.00 %
Processtime Allowance: 0.00 %

Fig. 9 Configured interface for time population

With standard runtimes for all operations available, both the duration and cycle time (man hours) can be calculated after the network is established at operation level. DPE provides a convenient process graph environment for establishing a network, in which each operation is represented by an icon and relationships between operations can be easily set up in a drag-and-drop way as shown in Fig. 10. A generic algorithm, which can cope with both serial and parallel process networks as well as application to other production levels, is developed. Figure 11 shows the logic for calculating both the duration and cycle time for each object of Group-operation. The domain knowledge of methods engineers is also captured and modeled in the DPE process tree, so that the setup time can be automatically calculated and populated on different production levels. Similarly, the functional modules for the upper assembly level can be implemented.

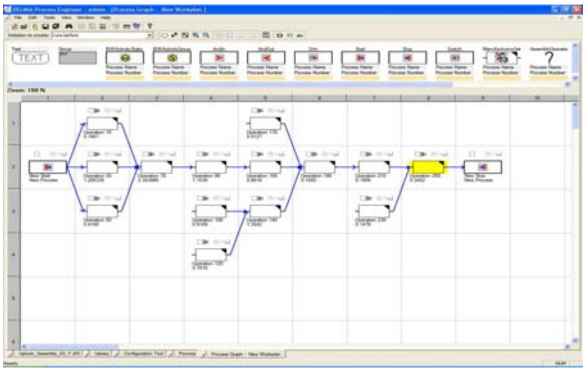


Fig. 10 Process network built in process graph environment

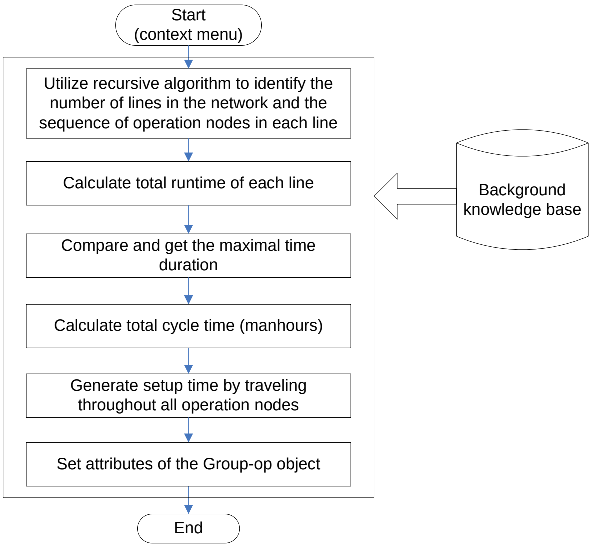


Fig. 11 Time generation logic in Group-operation level

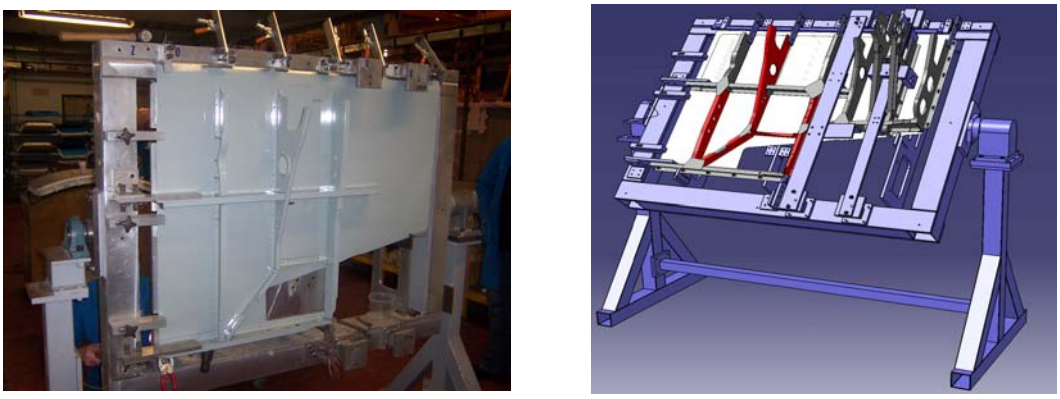


Fig. 12 Uplock & Apron Assembly and its CAD model

IV. Exemplar Study

An exemplar study is carried out using the Uplock & Apron Assembly for one of Bombardier's current regional passenger jets as shown in Fig. 12. The original assembly book for this panel composed of 250 operations associated with 148 parts, is written by a process planner based on experience, without considering assembly time. Methods engineers then need to manually calculate the time for each operation based on the assembly book which contains twenty pages of text with drawing references but no graphical illustrations. This is a very time consuming and error prone process, and rework is often required on the assembly book due to the unbalanced line, where different modules have quite different times making it difficult to balance. Based on the proposed process structure mentioned before, the assembly book can be easily modeled, and the objects of different production level can be easily established as shown in Fig. 13. The assembly book maps to the process plan level, and the next lower level, such as Operation 10 and Operation 30, maps to the Group Operation level. Each Group Operations is consisted of a number of operations, such as "locate skin panel". These required functional modules on each level are implemented by VB scripts in Bombardier Aerospace in Belfast.

The reasoning rules are established according to the shop floor practice, and some of them are shown as follows.

if Op = "Locate" and Size = "Small (length < 6 inches)", then OpId = 0001

if Op = "Locate" and Size = "Medium (length 6 – 12 inches)", then OpId = 0002

if Op = "Locate" and Size = "Medium Large (length 1 – 5 feet)", then OpId = 0003

if Op = "Locate" and Size = "Large (length 5 – 8 feet)", then OpId = 0004

if Op = "Locate" and Size = "Extra Large (length >= 8 feet)", then OpId = 0005

if Op = "Drill" and Material = "Aluminum alloy" and Drill 3/32" hole, then OpId = 0006

if multiple "Drill" Ops in one Group-Op, then only one "Drill" setup will taken into account

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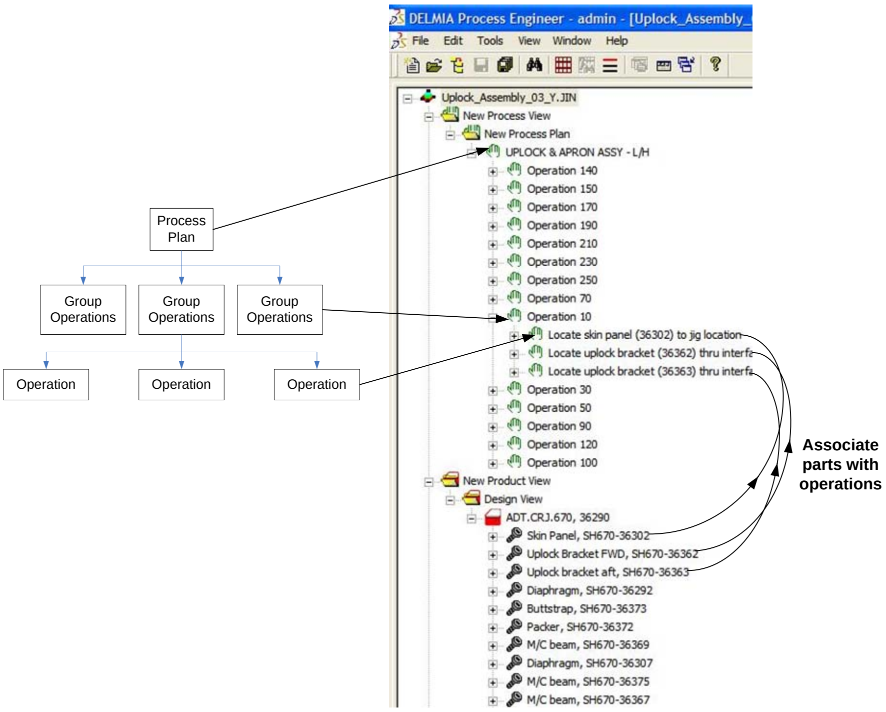


Fig. 13 Implementation of the object oriented process structure

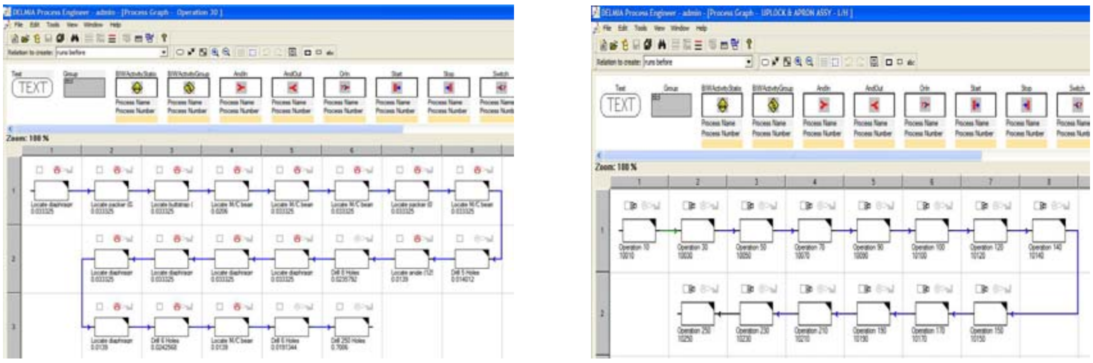


Fig. 14 Networks of the Operation 30 and the Process Plan

After each part is associated with its corresponding operation, the operation process time can be intelligently populated by the expert reasoning system executed by clicking the command button shown in Fig. 6. Taking the operation “Locate skin panel (36302) to jig location” as an example, the expert system is started by asking the user to choose the operation type through the user interface shown in Fig. 8, followed by retrieving part length information (12 feet in this case) for refining the operation type, so as to find the standard time by the "OpId 0005" in the library for the operation "Locate – Extra large". Once the standard time/unit is obtained, the process time is calculated by multiplying it to the quantity (1 in this case), and is then populated on the time property page of this operation, as shown in Fig. 9. With all operation times populated for each operation, the process time of Group operation, such as Operation 10 and Operation 30, can be calculated based on the process network shown in Fig. 14 by executing algorithms through context menu as shown in Fig. 15. Figure 16 shows the output reports of the Group-operation 30 and the Process Plan respectively for the Uplock & Apron Assembly with all data replaced by "**". With the assembly time results and pre-obtained part costs for the process plan, the total assembly costing functionality is developed for calculating the total assembly cost, which includes both the assembly time costing and part costing.

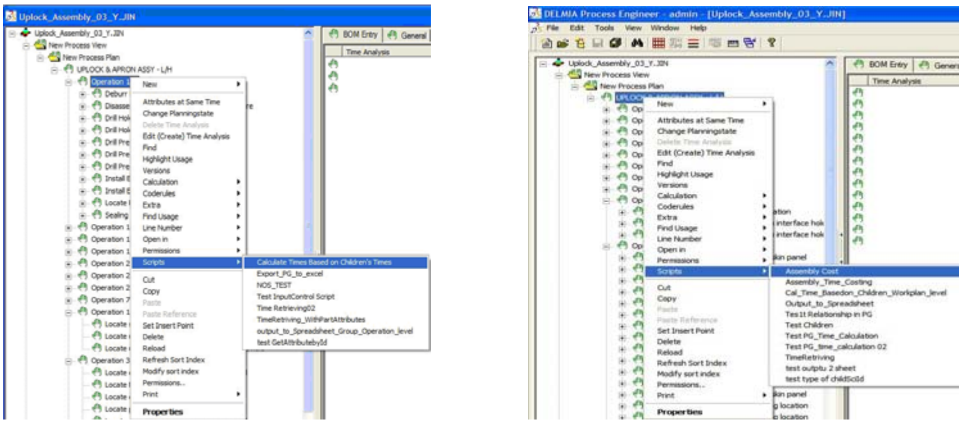
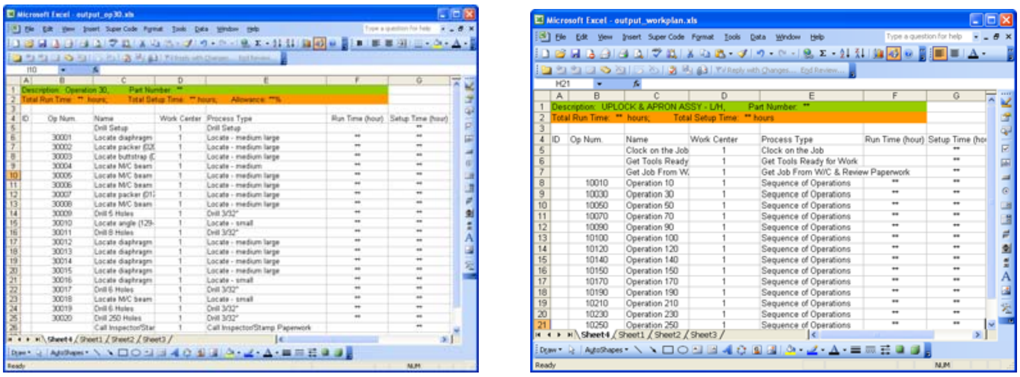


Fig. 15 Context Menus at Group-Operation and Process Level

The learning curve is resulted from the shop floor practice by using graphical work instructions and highlighted 3D simulations through advanced digital manufacturing tools. As it is confidential, the 80% learning curve of White model is employed here for the first 200 sets, 90% curve for the following 200 sets, and 100% curve thereafter. With the obtained assembly time "7 hours (for example)" which consumed by the 200th set of assembly, the initial time consumed by the first assembly can be calculated by Eqn. (2), and all production times for this assembly can be generated automatically in a spreadsheet for ease of planning as shown in Fig. 17.

As a result, methods engineers can carry out time analysis when they are making production plans. They are very happy to use this tool, which help reduce the analysis time from several days to a couple of minutes, apart from its benefits for the automated generation of work instructions. A standard time scale is defined for every sub-assembly module for ease of line balancing. Design engineers can obtain the assembly time cost estimates before releasing their designs. A part attributes template is defined for information transfer from design through process, to the production phase. This clears the responsibilities of the designer, planner and methods engineer, and productivity has been significantly improved. Moreover, this digital approach will fit seamlessly into the lean model of the whole factory production, which will be our next step.



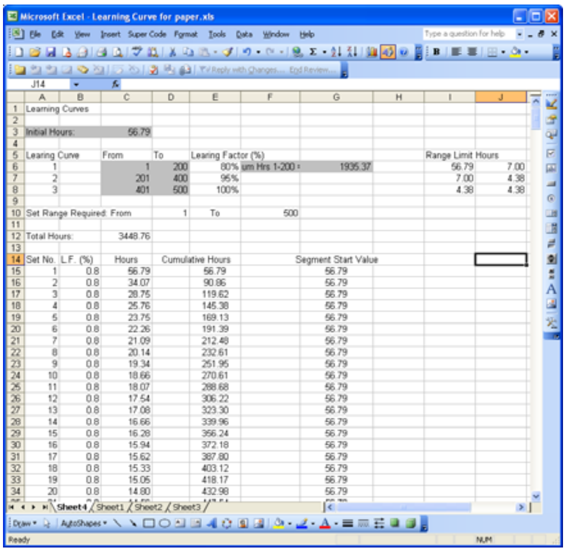
Description: Operation 30, Part Number: **
Total Run Time: ** hours; Total Setup Time: ** hours; Allowance: **%

ID	Op Num.	Name	Work Center	Process Type	Run Time (hour)	Setup Time (hour)
		Drill Setup	1	Drill Setup		**
	30001	Locate diaphragm	1	Locate - medium large	**	**
	30002	Locate packer (02	1	Locate - medium large	**	**
	30003	Locate buttstrap (	1	Locate - medium large	**	**
	30004	Locate M/C beam	1	Locate - medium	**	**
	30005	Locate M/C beam	1	Locate - medium large	**	**
	30006	Locate M/C beam	1	Locate - medium large	**	**
	30007	Locate packer (01	1	Locate - medium large	**	**
	30008	Locate M/C beam	1	Locate - medium large	**	**
	30009	Drill 5 Holes	1	Drill 3/32"	**	**
	30010	Locate angle (129-	1	Locate - small	**	**
	30011	Drill 8 Holes	1	Drill 3/32"	**	**
	30012	Locate diaphragm	1	Locate - medium large	**	**
	30013	Locate diaphragm	1	Locate - medium large	**	**
	30014	Locate diaphragm	1	Locate - medium large	**	**
	30015	Locate diaphragm	1	Locate - medium large	**	**
	30016	Locate diaphragm	1	Locate - small	**	**
	30017	Drill 6 Holes	1	Drill 3/32"	**	**
	30018	Locate M/C beam	1	Locate - small	**	**
	30019	Drill 6 Holes	1	Drill 3/32"	**	**
	30020	Drill 250 Holes	1	Drill 3/32"	**	**
		Call Inspector/Star	1	Call Inspector/Stamp Paperwork		**

Description: UPLOCK & APRON ASSY - L/H, Part Number: **
Total Run Time: ** hours; Total Setup Time: ** hours

ID	Op Num.	Name	Work Center	Process Type	Run Time (hour)	Setup Time (ho
		Clock on the Job	1	Clock on the Job		**
		Get Tools Ready	1	Get Tools Ready for Work		**
		Get Job From W.	1	Get Job From W/C & Review Paperwork		**
	10010	Operation 10	1	Sequence of Operations	**	**
	10030	Operation 30	1	Sequence of Operations	**	**
	10050	Operation 50	1	Sequence of Operations	**	**
	10070	Operation 70	1	Sequence of Operations	**	**
	10090	Operation 90	1	Sequence of Operations	**	**
	10100	Operation 100	1	Sequence of Operations	**	**
	10120	Operation 120	1	Sequence of Operations	**	**
	10140	Operation 140	1	Sequence of Operations	**	**
	10150	Operation 150	1	Sequence of Operations	**	**
	10170	Operation 170	1	Sequence of Operations	**	**
	10190	Operation 190	1	Sequence of Operations	**	**
	10210	Operation 210	1	Sequence of Operations	**	**
	10230	Operation 230	1	Sequence of Operations	**	**
	10250	Operation 250	1	Sequence of Operations	**	**

Fig. 16 Output reports for operation 30 and the process plan



	A	B	C	D	E	F	G	H	I	J
1	Learning Curves									
2										
3	Initial Hours:		56.79							
4										
5	Learing Curve		From	To	Learing Factor (%)				Range Limit Hours	
6	1		1	200	80%	um Hrs 1-200 =	1935.37		56.79	7.00
7	2		201	400	95%				7.00	4.38
8	3		401	500	100%				4.38	4.38
9										
10	Set Range Required: From			1	To	500				
11										
12	Total Hours:		3448.76							
13										
14	Set No.	L.F. (%)	Hours	Cumulative Hours			Segment Start Value			
15	1	0.8	56.79		56.79		56.79			
16	2	0.8	34.07		90.86		56.79			
17	3	0.8	28.75		119.62		56.79			
18	4	0.8	25.76		145.38		56.79			
19	5	0.8	23.75		169.13		56.79			
20	6	0.8	22.26		191.39		56.79			
21	7	0.8	21.09		212.48		56.79			
22	8	0.8	20.14		232.61		56.79			
23	9	0.8	19.34		251.95		56.79			
24	10	0.8	18.66		270.61		56.79			
25	11	0.8	18.07		288.68		56.79			
26	12	0.8	17.54		306.22		56.79			
27	13	0.8	17.08		323.30		56.79			
28	14	0.8	16.66		339.96		56.79			
29	15	0.8	16.28		356.24		56.79			
30	16	0.8	15.94		372.18		56.79			
31	17	0.8	15.62		387.80		56.79			
32	18	0.8	15.33		403.12		56.79			
33	19	0.8	15.05		418.17		56.79			
34	20	0.8	14.80		432.98		56.79			

Fig. 17 Production times by integrating learning curve

V. Conclusion

It was found from the literature review that the tedious time analysis work was a big challenge and its integration with a digital PLM environment was still unavailable. The presented work addressed this challenge by proposing a structure-oriented methodology with a process architecture that will facilitate process/production planning, time generation and knowledge management. Such a structure is object oriented, standard, repeatable and extendable, to facilitate maintenance and management. More importantly, it can be seamlessly integrated with the digital manufacturing environment and times are traceable. An approach utilizing MOST techniques to perform time analysis is discussed. It is implemented within the customized configuration of a digital manufacturing environment based on the proposed process architecture and it is equipped with functional modules, expert systems and library support. The system automatically generates a full listing of assembly times for the specific assembly process to be used on the shop floor, including network planning and learning curve impact. The approach is illustrated and validated through the example of an uplock & apron assembly, and has been implemented in Bombardier Aerospace in Belfast with industry standard times. The main contribution of the work is to present a methodology that facilitates the automated integration of time analysis with design and manufacturing using a digital manufacturing platform solution.

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