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Intelligent Assembly Time Analysis Using a Digital Knowledge-Based Approach

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The implementation of effective time analysis methods which are both fast and accurate, in the era of digital manufacturing, has become a significant challenge for manufacturers hoping to build and maintain a competitive advantage. This paper proposes a structure oriented, knowledge-based approach for intelligent time analysis for complex, engineering assembly processes within a digital manufacturing framework. The approach combines three important aspects: hierarchical object oriented structure, knowledge modeling, and implementation within a digital manufacturing framework. The hierarchical structure facilitates the capture of work breakdown structure, automated time analysis, and effective information management. Knowledge modeling enables the intelligent generation of manufacturing cycle times from design parameters. The implementation of a digital design and manufacturing platform with integrated time analysis capability through intuitive graphical user interfaces and configured functionalities, provides a truly collaborative methodology and concurrent engineering tool for productivity improvement. An exemplar study using an aircraft panel assembly from a regional jet is presented. Although the method currently focuses on aerospace assembly, it can also be applied to many other industry sectors including automotive, railway carriage, and large scale marine manufacturing. The main contribution of the work is to present a methodology that facilitates the integration of time analysis with product design and assembly process definition using a digital manufacturing solution.

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I. Introduction

AIRCRAFT assembly is a labor intensive and time consuming process which accounts for around one third of total manufacturing cost [1]. The accurate estimation and analysis of aircraft assembly times is important for process planning, cost control, reducing product development lead times, and ultimately commercial success. All modern enterprises are pursuing continuous productivity improvement to achieve a real lean production [2]. Precise time prediction will provide baseline information for assessing potential business opportunities at the bid stage, evaluating simulated, conceptual performance, and monitoring real-time production. Traditional time estimation based on manual methods, calculates assembly times based on assembly books, which are created by process planners. However, these assembly books mainly focus on the production plan based on build order but are generally not well suited to time generation activities. Methods engineers may have to search through hard copy drawings or check with shop floor operators to establish likely timing information. This in itself, is very time consuming and error prone. More importantly, the process planner may not have access to accurate timing data, making resource planning and allocation difficult. The gap between methods engineering, process planning and even product design, due to the current absence of predictive timing/costing technologies, imposes negative effects on the potential success of any aerospace company operating under current economic conditions. 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 preassigned schedule. Although there are some CAE tools, such as AutoMOST (a computer-aided tool based on Maynard operation sequence technique (MOST), which is a predetermined time standard system, for effective time analysis), to aid engineers for time analysis, each of these tools is only limited to pieces of functionality within the whole product life cycle. Furthermore, these CAE tools have not been integrated into a collaborative/concurrent environment. Therefore, the elimination of this technology gap and the establishment of a rapid, effective, and traceable time estimation mechanism has become a prime challenge for any aircraft company hoping to build and maintain a competitive advantage.

Digital methods are now playing a more significant role in process planning activities within the aerospace industry [2]. 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, product lifecycle management (PLM) systems, analysis software, simulation, CAM software, and so on [3,4]. Digital Manufacturing is an emerging software technology that will become a fundamental and liberating component of PLM [5]. 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 [6,7]. 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 seeks 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?

This paper considers the development of a digital design and manufacturing modeling platform with integrated time analysis capabilities, providing a collaborative methodology and concurrent engineering tool for shortening aircraft assembly time and reducing aircraft life cycle cost. A structure oriented, digital knowledge-based approach is proposed for the automated time analysis of an aircraft panel assembly process. 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 II reviews current literature. Section III addresses the proposed methodology and its integration within a digital manufacture environment. Section IV presents an exemplar study. Section V concludes this paper.

II. Literature Review

Time and cost metrics are very important throughout product design, process planning, and final production. It is reported that around 70% of the manufacturing cost is determined at the design phase [6]. Many companies and researchers have put significant effort into developing design for manufacturing/production tools by integrating time/cost metrics [8–16]. However, most of their work consists of standalone simulation or function modules, which do not currently cover the whole product life cycle integrating all engineering functions. A comprehensive, integrated process design environment is therefore required. More and more manufacturing companies, such as Airbus, Boeing, and Bombardier, have recently started utilizing digital design and manufacturing tools to implement lean enterprises [17–20]. Additionally, many researcher groups are currently looking at developing a more integrated approach to design and digital manufacturing [6,8,10,17,18,21]. Freedman [6] 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 a product, process, and resource (PPR) knowledge base across the whole enterprise. Curran et al. [17] proposed a concurrent approach for integrating cost capabilities into digital design and manufacturing modeling, at the conceptual design phase. This approach offers the user readily exploitable digital manufacturing simulation capabilities to get optimal solutions within the context of the whole aircraft life cycle cost. Herrmann and Chincholkar [9] 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. Butterfield et al. [18] has investigated the benefits of using digital manufacturing tools by a case study examining the assembly process optimization of a regional jet fuselage section. It clearly shows that digital manufacturing can bring many advantages, such as accelerating process and production planning, providing prerecorded simulations for operator training and reducing the number of design iterations. It also admits that despite recent improvements in the predictive methods available to production planners, integrated company specific functional modules and tools are still required. This requires collaboration between IT engineers, manufacturing engineers, and university researchers. In summary, knowledge and intelligence has become the key challenges to evolve the manufacturing enterprises into modern lean enterprises, which require an effective, rapid, and accurate time/cost assessment throughout the whole product life cycle [11].

Time analysis and work measurement are important building blocks 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 time estimates for final assembly. 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) [15], methods-time measurement (MTM) [22], and MOST [23]. WFS [24] is a pioneering method for establishing time standards based on the motion of human body members, such as the head and limbs. A work factor is used as an index for any extra time required above the basic time, for the effects of the variables of manual control and weight. Depending on the application requirements, WFS is classified into three systems, namely Detailed WFS, Ready WFS, and Brief WFS. The WFS is mainly utilized in Japan. For the original DFA method, 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, with time analysis being an assessment metric rather than an absolutely accurate time prediction. Therefore, DFA is mainly used in the design stage prior to the planning stage for aerospace industry. The MTM approach was proposed in the 1940s by Maynard et al. [22]. MTM is a procedure that analyzes any series of manual operations in accordance with the basic motions required to perform them. It assigns to each motion a predetermined time standard that is

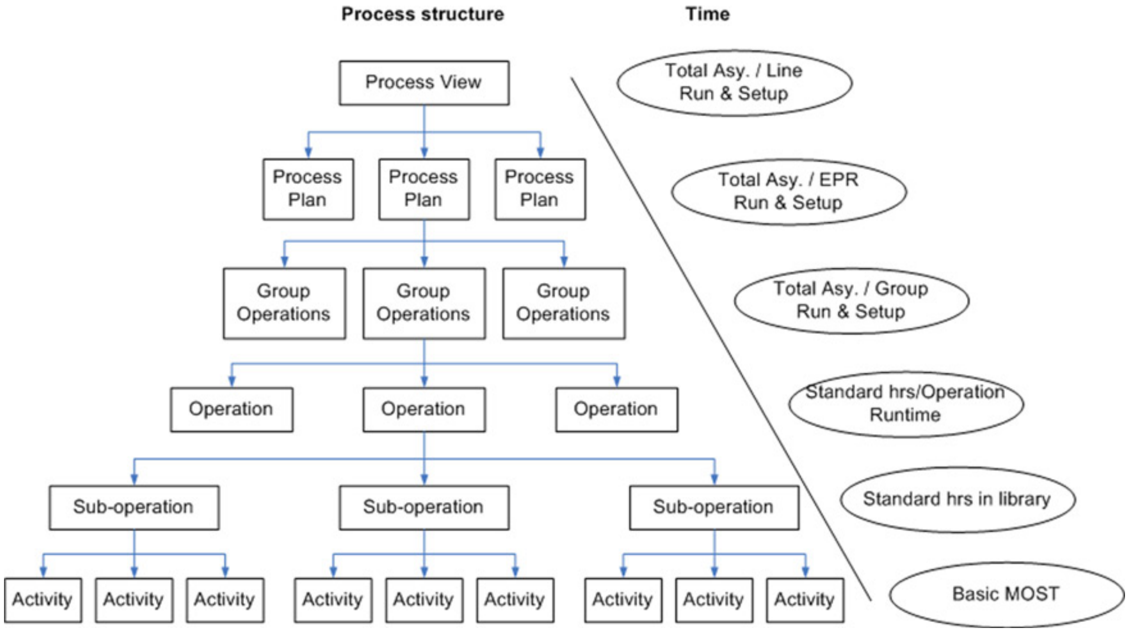


Fig. 1 Architecture of the work breakdown structure utilized for the time analysis.

determined by the nature of the motion and the conditions under which it is performed. The modern version of MTM is termed MOST, being a simplified system first developed by Zandin [23]. 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 nonrepetitive 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. Therefore, the MOST system has been selected for this work. 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-operations (sub-ops), each sub-op is then further decomposed into a sequence of basic MOST motions, as illustrated in Fig. 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 easily integrated into a digital manufacturing environment to bridge the design and production disciplines. The integration of automated time analysis with design and manufacturing planning in a PLM environment is currently out of literature. This work will present a solution to fill into this position.

III. Proposed Methodology

A. Process Structure

To facilitate the automatic generation of assembly times for the different levels mapped to the various 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, manipulated, and output. To implement automated assembly time analysis, the structure must be able to capture all assembly breakdown information and time consumption procedures for completing the assembly. With current 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 method explained below. The lowest level of this structure is the human activities associated with the MOST motions and their associated standard times. As the speed of MOST modeling 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 are referred to in the work instructions and are equated to operational objects. These become the basic units for process planning, where generally only the run-time 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 for 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 for time analysis, all domain knowledge needs to be analyzed, extracted and modeled carefully, based on the proposed process structure. The domain knowledge comes from the following resources: *predetermined basic activity time information* (i.e., the basic building block—associated with activity objects on the lowest level); *expert domain knowledge* (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); and *learning curve knowledge* (used for time analysis for the whole production of a number of sets of products). More details will be explained later.

1. Modeling of Sub-operations and Operations

As mentioned before, a top-down analysis needs to be carried out for analyzing shop floor operations for the purpose of modeling the assembly time. Each operation is broken down into a sequence of sub-operations which

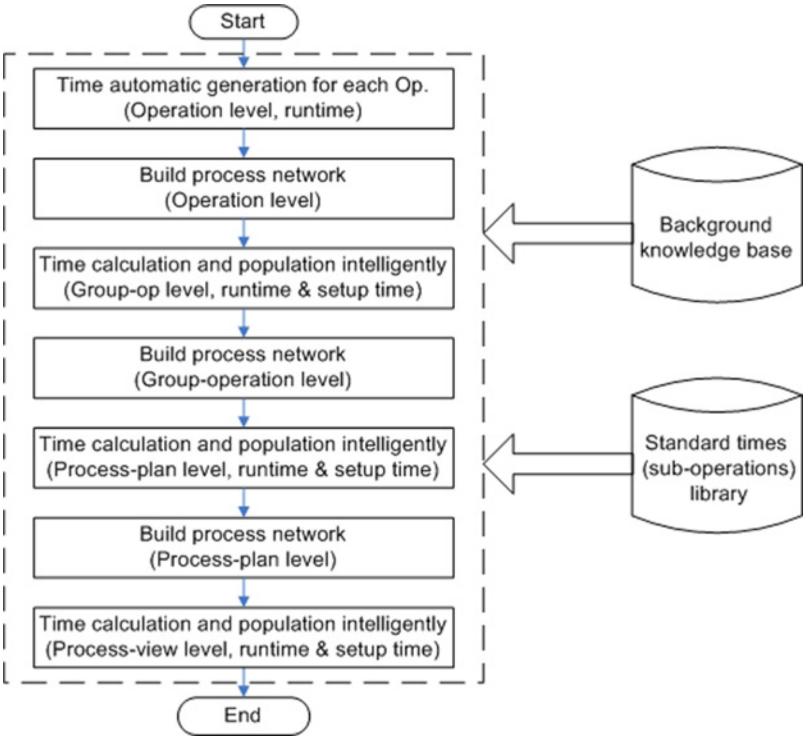


Fig. 2 Procedure for time estimation across different process levels.

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

consist of motion sequences which are compatible with MOST. MOST certified instructors (methods engineers) observe and document the procedure 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 associated with a standard time and a unique identity (ID). For example, the operation "Drill" on alloy parts is further classified into seven different types, such as drill 3/32 inch hole. The "drill 3/32 inch hole" (ID 2000, Time required: 0.1362 min) operation is composed of following sub-operations.

a) ID 1000, drill hole, 0.111 min.
b) ID 1001, bending allowance, 0.0060 min.
c) ID 1002, move platform, 0.0192 min.

And the sub-operation "Drill hole (ID 1000, 185 TMUs $=$ 0.111 min)" is built up by following activities.

a) Hold and 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 (Sequence Model: A1 B0 G1 A3 B0 P1 A0, 15 TMUs).

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

2. *Modeling of Reasoning Method*

The modeling procedure includes analysis, extraction and classification stages. For aircraft assembly, operations are generally classified as locate, drill, dismantle, deburr, sealing and coating, reassemble, install fasteners, and special operations. Figure 3 shows a forward inference mechanism to reason from existing knowledge to the corresponding conclusions. The existing knowledge includes part design information such as part material, size and weight, and operation process knowledge such as operation type. For instance, the standard time for a locate operation can be obtained with part material and size/weight information. An inference mechanism of this type can be easily symbolized into a rule-based system. Note that, setup time is also required for some operations for instance, before a drilling operation, the drill gun must be connected to an air pipe and the specified drill bit must be inserted. Therefore, an inference mechanism for estimating setup times must be included.

3. *Modeling of Learning Curve*

Learning curve theory 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.

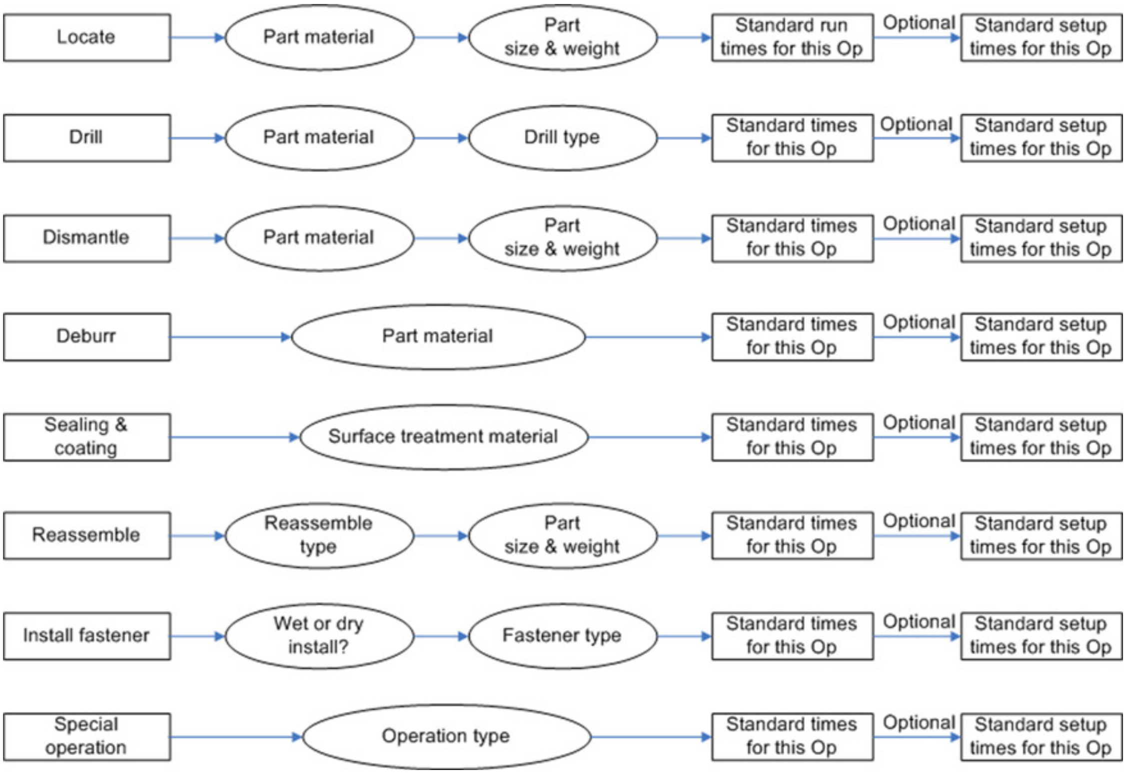


Fig. 3 Forward inference mechanism for operation times.

Taking the Wright's cumulative average model for instance, as shown in Fig. 4, the learning curve function is defined as follows [15,25].

$$Y = mX^n$$

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. If the cumulative average time per unit decreases

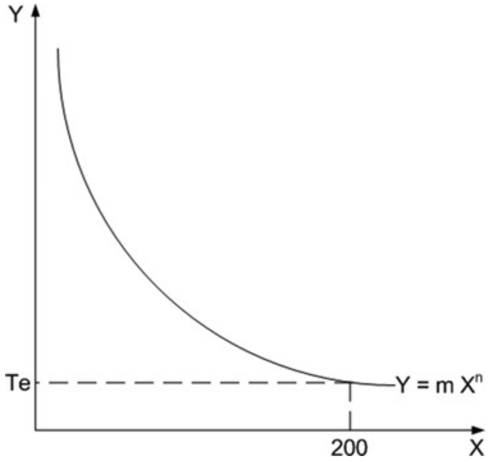


Fig. 4 Wright's learning curve model.

by 20% over double quantity, then this is referred to as an 80% learning curve. Generally speaking, leaning curves can be represented by an exponential function, which decreases steeply at the beginning and becomes flat as the level of experience in the workforce increases. Note that the time estimates obtained from the section above is the optimal time with the "best" method, because the MOST system provides predetermined time standards that are determined by the trained operators using best methods, i.e., standard hours which assume that all learning is complete and the curve has consequently, flattened out. 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 Te be the time estimate obtained 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.

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

Thus, we have

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

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

C. Implementation within Digital Manufacturing Tools

Although digital manufacturing has many advantages for manufacturers, digital planning solutions have to be applied within a framework of carefully developed and deployed closed-loop processes for both manufacturing planning and information management [4]. The architecture must be carefully tailored to suit the requirements from the different departments within the organization. In addition, the architecture must be well defined to ease data capture and transformation so that the functional modules can be perfectly defined and developed.

1. Integration of Process Structure into Digital Manufacturing Tools

One popular software tool which has been designed to deliver digital manufacturing capability to the aerospace industry among others, is Delmia process engineer (DPE), which helps process planning by integrating PPR information from the conceptual design phase through to the process planning phase and on to the production phase. It utilizes an object-oriented PPR tree structure which is capable of modeling complete project planning structures

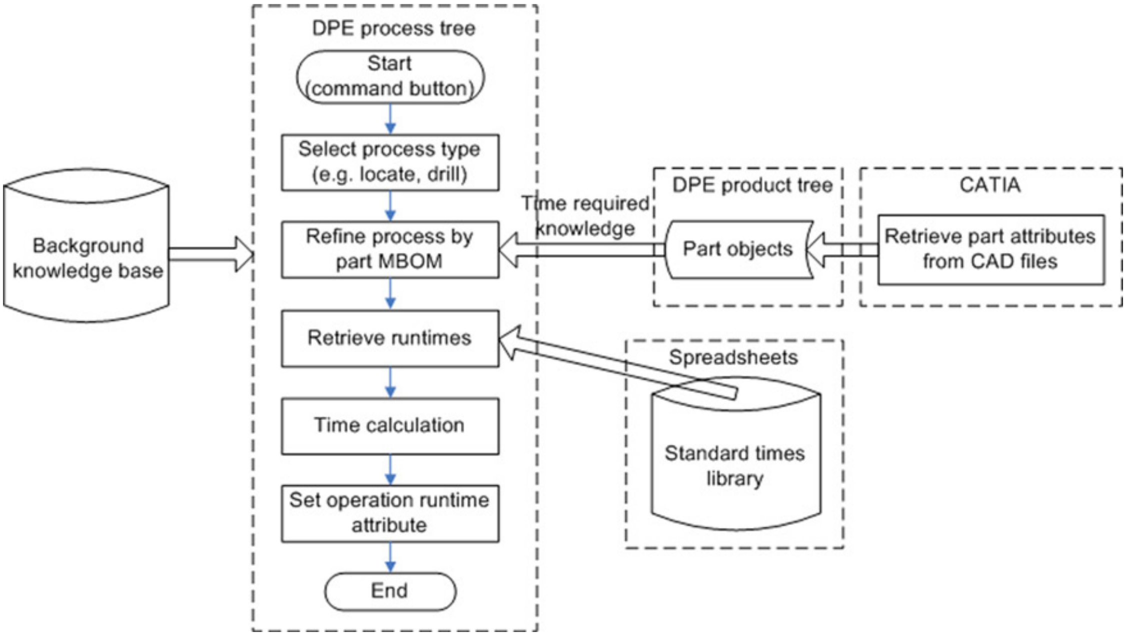
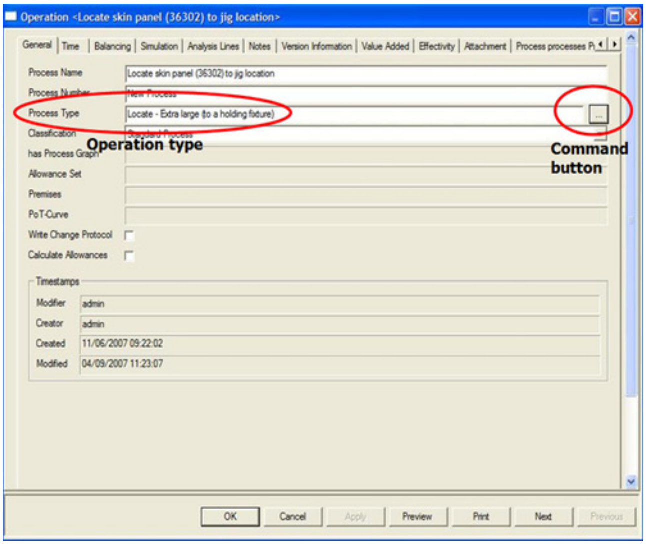


Fig. 5 Intelligent time generation for individual operations within a process.

and all logical relationships between the PPR data. More importantly, DPE can be fully integrated with other digital manufacturing modules, such as CATIA and Delmia digital process manufacturing (DPM). In this project DPE V5R17 (Version 5.17) 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 of the default V5R17 plantype sets (plantype refers to an object type in DPE), 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.

2. *Implementation of Knowledge-Based System of Time Analysis*

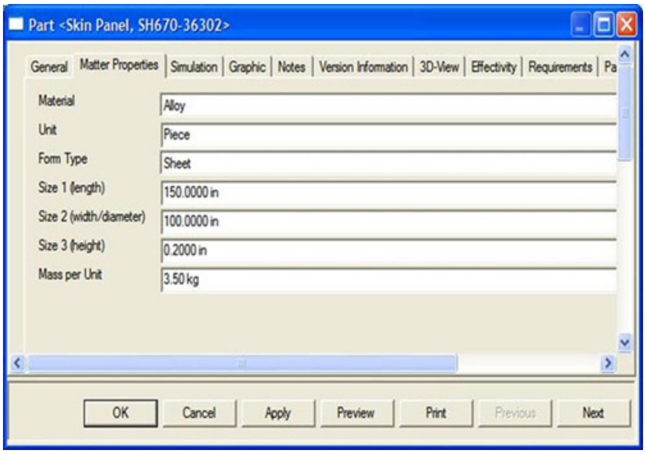
The first step in establishing intelligent time estimation within the digital manufacturing environment is to automate the time generation process so that it requires minimum interaction from casual end-users who may not have expert knowledge. To achieve this goal, an expert system is developed by using DPE scripting as shown in Fig. 5, and it is executed by clicking a command button that is configured through the property dialog box of the operation plantype, as shown in Fig. 6. Time generation is implemented in the DPE process tree for every operation object


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

Process Name: Locate skin panel (36302) to jig location
Process Number: New Process
Process Type: Locate - Extra large (to a holding fixture)
Classification: Standard Process
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 interface within DPE for operation plantype.

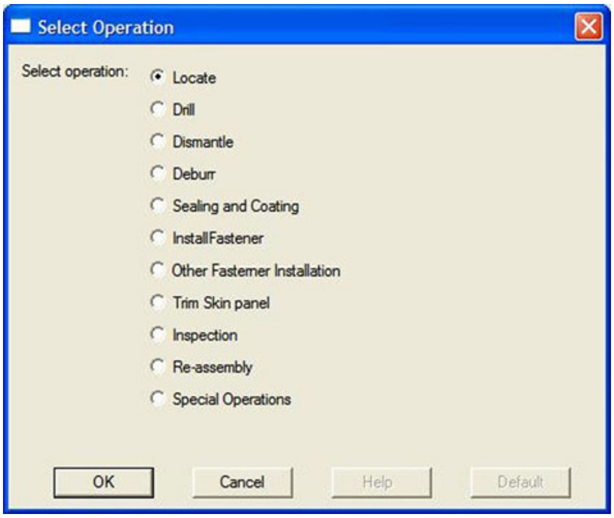

Part <Skin Panel, SH670-36302>

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 Graphical user interface showing time required information.

which is in turn, 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 CATIA models 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 naming 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 box 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 using quantified information based on predefined algorithms. Finally, the run-time of the operation is set as one of its attributes through the customized interface as shown in Fig. 9.

With standard run-times 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

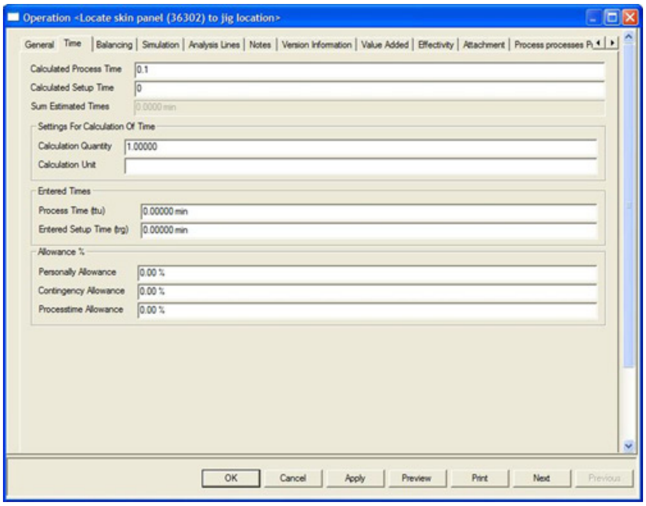


Select Operation

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.



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

Calculated Process Time: 0.1
Calculated Setup Time: 0
Sum Estimated Times: 0.0000 min

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

Entered Times
Process Time (ttu): 0.00000 min
Entered Setup Time (trg): 0.00000 min

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

Fig. 9 Configured interface for time population within DPE.

establishing a network, in which each object is represented by an icon and relationships between object instances (precedences) 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. The algorithm can capture the relationships and retrieve related object instances to extract their associated attributes, such

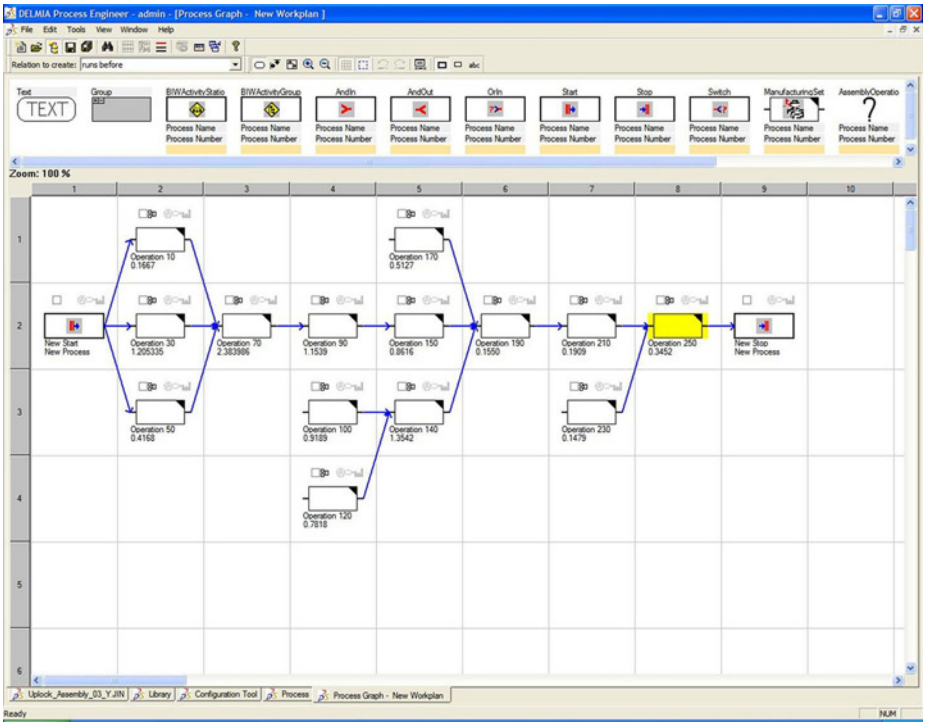

Relation to create: runs before

Fig. 10 Process network built in process graph environment.

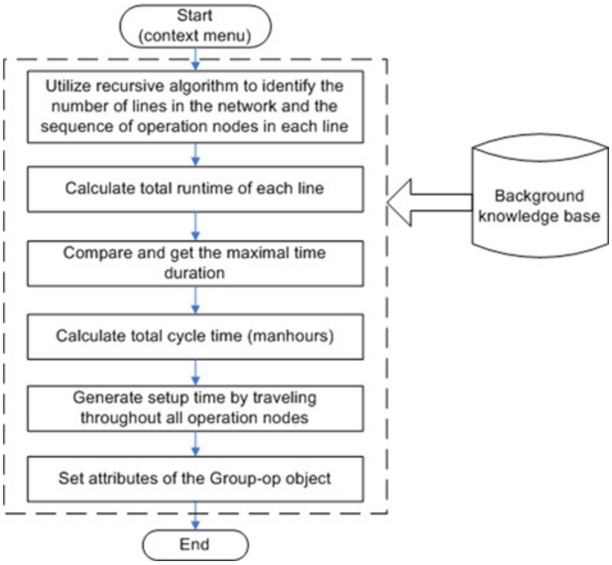


Fig. 11 Time generation logic at group-operation level.

as cycle time. Figure 11 shows the logic for calculating both the duration and cycle time for each object of group operation. The domain knowledge of the methods engineer 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.

IV. Exemplar Study

An exemplar study is carried out using the Uplock and Apron assembly for one of Bombardier's current regional passenger jets as shown in Fig. 12. The original assembly book for this panel which included 250 operations consuming 148 different parts, was written by a process planner based on experience. Methods engineers then manually calculate the time for each operation based on the assembly book which contains 20 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 in each of the different production levels can be easily identified 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 operation consists of a number of operations, such as "locate skin panel". These required functional modules found on each level, are implemented by VB scripts in Bombardier Aerospace in Belfast.

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

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

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

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

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

if Op = "Locate" and Size = "Extra Large (length $\geqslant 8$ ft)", then OpId = 0005

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

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

...

After each part in the Product node is linked to its corresponding operation in the process node, the operation process time can be intelligently populated by the expert reasoning system which is 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

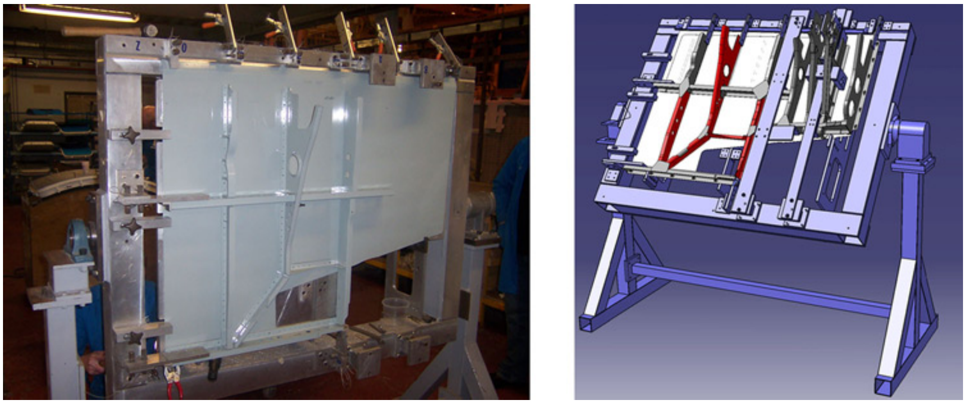


Fig. 12 Uplock and Apron assembly (with fixture) and its CAD model.

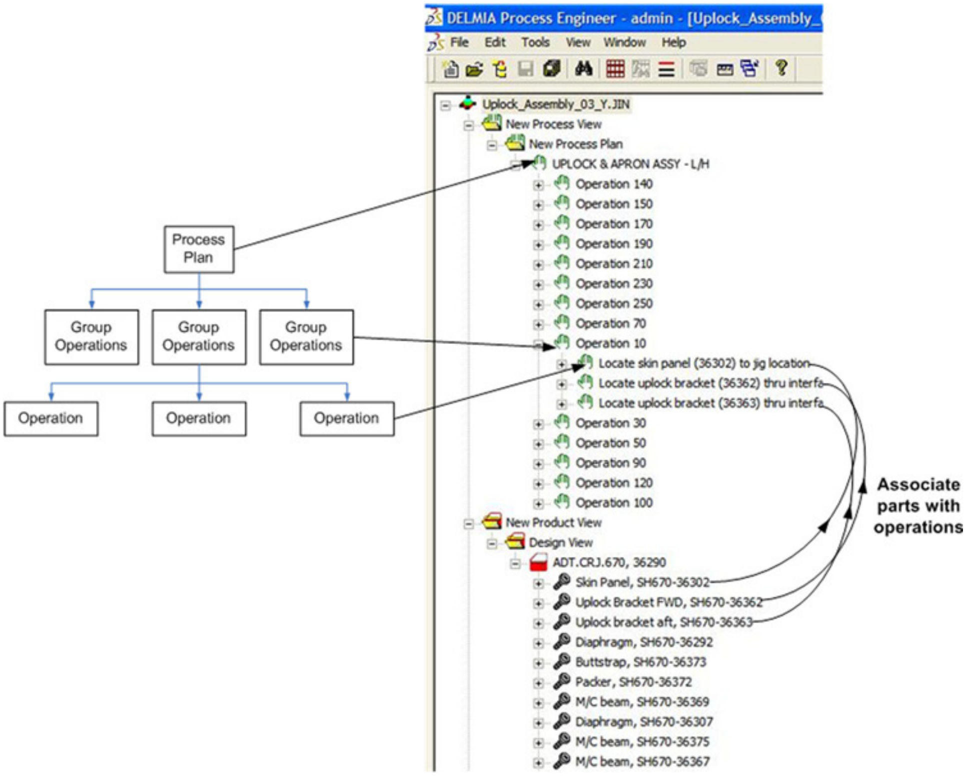


Fig. 13 Implementation of the object-oriented process structure.

by retrieving part length information (12 ft 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 by 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 for the 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 the context menu as shown in Fig. 15. Figure 16 shows the output reports for group operation 30 and the process plan, respectively, for the Uplock and Apron assembly with all data replaced by "**". With the assembly time results and preobtained 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.

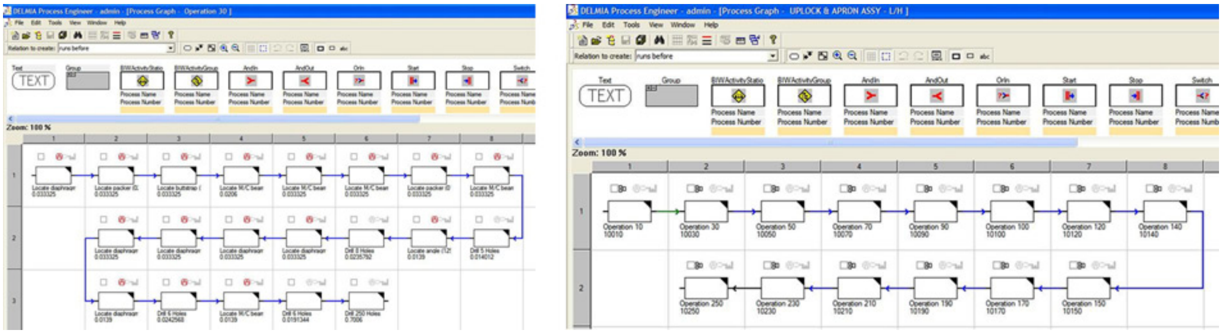


Fig. 14 Network representing operation 30 and the process plan for Apron and Uplock assembly.

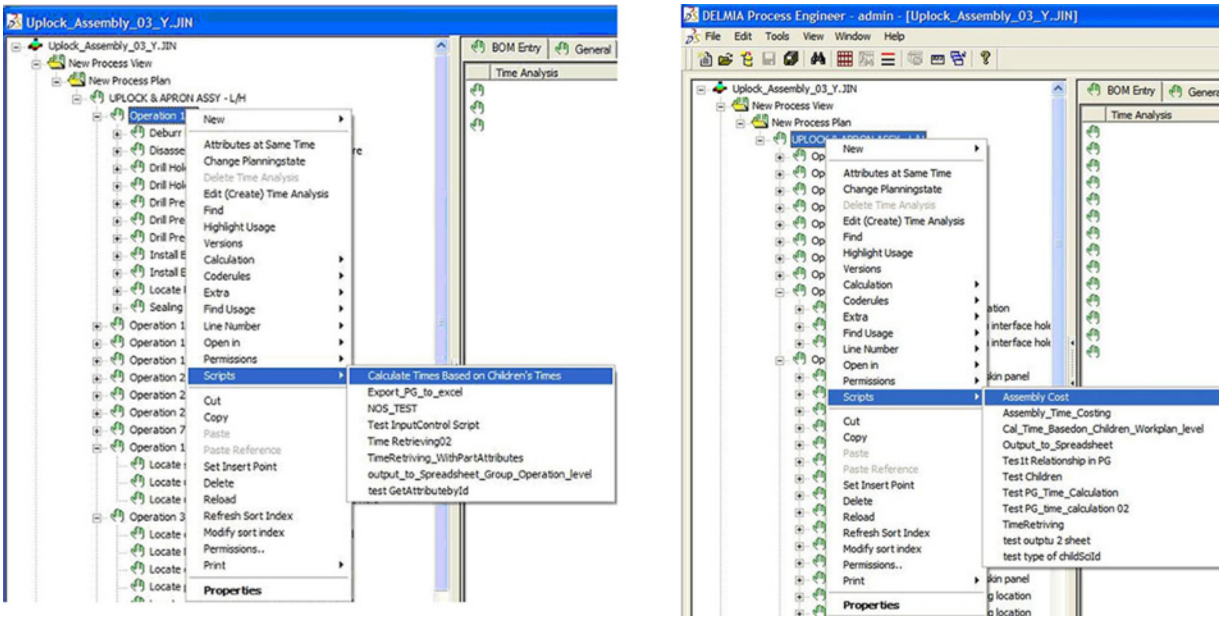
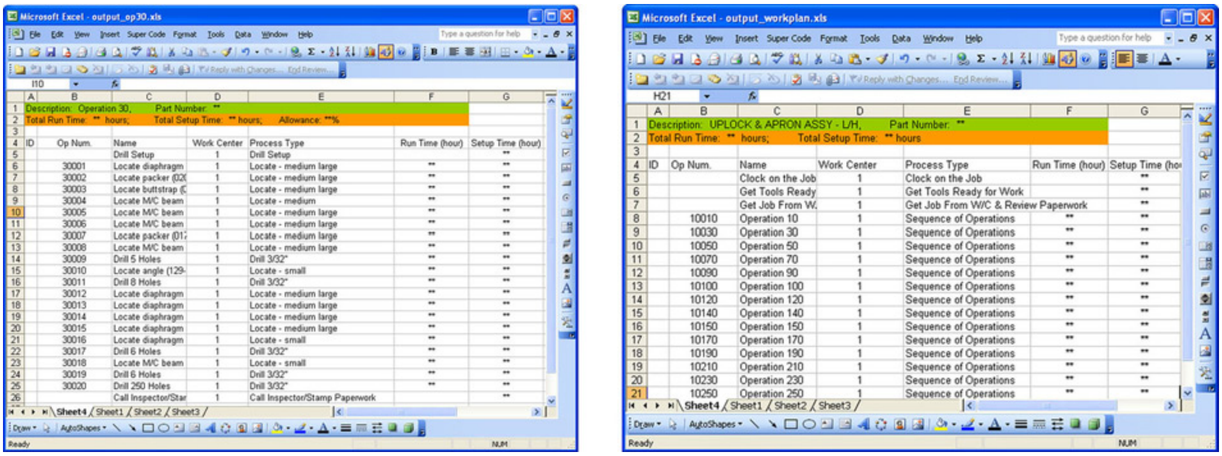


Fig. 15 Context menus at group-operation and process plan level.



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		**

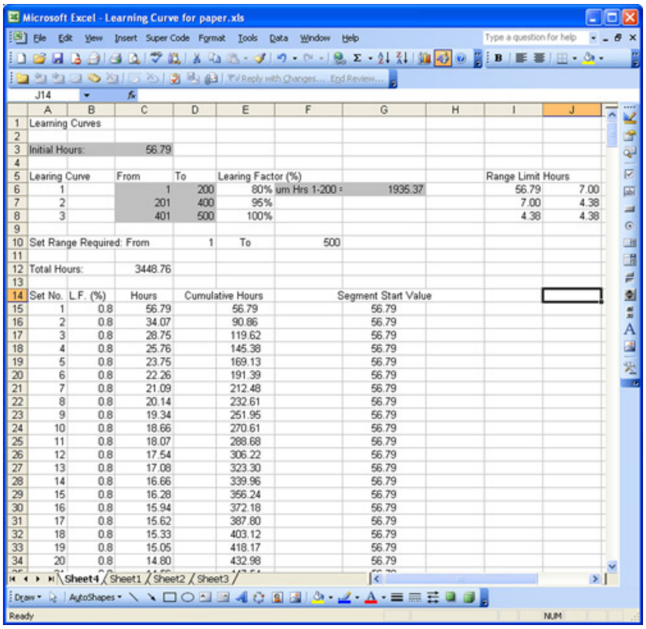
Description: UPLOCK & APRON ASSY - L/H, Part Number: **
Total Run Time: ** hours; Total Setup Time: ** hours

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.

The learning curve is a consequence of shop floor practice where activities are driven by graphical work instructions and highlighted 3D simulations using advanced digital manufacturing tools. The 80% learning curve for the White model is used here for the first 200 sets, a 90% curve is used for the following 200 sets, and 100% curve is used thereafter. With the obtained assembly time "7 hours (for example)" which is arrived at by the 200th set of assembly, the initial time consumed by the first assembly can be calculated by Eq. (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, the methods engineer can carry out time analyzes when they are making production plans. The method presented here, helps to reduce the analysis time from several days to a couple of hours, apart from its benefits for the automated generation of work instructions. A typical assembly process with 250 operations will usually take one day (7.5 h) of a methods engineer's time, to calculate its cycle time with the aid of computer aided tools such as AutoMOST and Microsoft Excel, while only two and a half hours will be consumed by using our digital platform tool.



	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 integrating learning curve.

Therefore the time reduction of time analysis is up to 67%. A standard time scale is defined for every subassembly module for ease of line balancing. Design engineers can obtain the assembly time with their associated cost estimates before releasing their designs. A part attributes template is defined for information transfer from product design through process design, to the production phase which significantly improves productivity. Moreover, this digital approach will fit seamlessly into the lean model of the whole factory production, which will be our next step.

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 and delivering 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 its maintenance and management. More importantly, it can be seamlessly integrated with the digital manufacturing environment and process times are traceable. Design and manufacturing knowledge are captured, analyzed, and modeled to enable intelligent time analysis based on component design parameters and predetermined standard operations. A prototype tool has been 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 data library support. This digital platform tool is capable of automatically generating a full listing of assembly times for the specific assembly process to be used on the shop floor. The approach is illustrated and validated through the example of an Uplock and 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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