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# Aircraft maintenance planning and scheduling: an integrated framework

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## Abstract

**Purpose** – The purpose of this paper is to examine how certain limitations of the current approaches to planning and scheduling of aircraft heavy maintenance can be addressed using a single integrated framework supported by unified data structures.

**Design/methodology/approach** – The "unitary structuring technique", originally developed within the context of manufacturing planning and control, is further enhanced for aircraft heavy maintenance applications, taking into account the uncertainty associated with condition-based maintenance. The proposed framework delivers the advanced functionalities required for simultaneous and dynamic forward planning of maintenance operations, as well as finite loading of resources, towards optimising the overall maintenance performance.

**Findings** – Execution of maintenance operations under uncertainty involves materials changes, rectification and re-assembly. It is shown that re-scheduling of materials (spare-parts), resources and operations can be taken care of by simultaneous and dynamic forward planning of materials and operations with finite loading of resources, using the integrated framework.

**Research limitations/implications** – As part of adopting the proposed framework in practice, it needs to be guided by an overall methodology appropriate for application-specific contexts.

**Practical implications** – The potential direct benefits of adopting the proposed framework include on-time project completion, reduced inventory levels of spare-parts and reduced overtime costs.

**Originality/value** – Existing approaches to aircraft maintenance planning and scheduling are limited in their capacity to deal with contingencies arising out of inspections carried out during the execution phase of large maintenance projects. The proposed integrated approach is, capable of handling uncertainty associated with condition-based maintenance, due to the added functionalities referred to above.

**Keywords** Aircraft heavy maintenance, Planning and scheduling, Re-assembly, Uncertainty, Business planning, Maintenance

**Paper type** Research paper

## Introduction

Maintenance of a large fleet of aircraft poses significant challenges for a business in terms of achieving the multiple, and in some ways conflicting, goals relating to maintenance and operation costs and desired service levels, including safety (Knotts, 1999; Wu *et al.*, 2004). Given the increasing technical sophistication of the asset and the intricacies introduced by different types of aircraft that make up a typical fleet, planning and scheduling of aircraft maintenance can be demanding. The impact of capital equipment downtime, regulatory compliance and the value of spare-parts inventory needed further accentuate maintenance costs. Historically, there have been considerable efforts directed towards developing approaches that help minimise the downtime by more effective planning and control of maintenance operations, as well as

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predicting spare-parts usage and other resources requirements using forward planning (Nowlan, 1972; Friend, 1992; Huiskonen, 2001). Many early software systems used in this area were standalone functional applications – developed based on the concepts of material requirements planning (MRP), project management and shop floor control – that were often interfaced for overall planning and scheduling purposes. These functional applications are currently available in enterprise resource planning (ERP) software systems as modules. However, ERP solutions with generic functional applications do not provide the full range of functionalities required for the planning and scheduling of more complex aircraft maintenance projects. For example, the current ERP systems lack the functionalities needed for simultaneous planning and dynamic forward planning of multiple maintenance operations, or finite capacity loading of resources, primarily because of their technical and design constraints, including lack of integrated data structures.

This paper examines how such limitations can be addressed using a single integrated framework, consisting of combined hierarchical bills of materials (BOM), closed-loop network activities and sequential operations routings, supported by unified data structures. The proposed framework builds on the "unitary structuring technique" (Woxvold, 1993) originally developed for providing the functionalities required for planning of materials and resources and scheduling of manufacturing operations. The unified data structures of the proposed framework incorporate both independent and dependent relationships of key data elements (that represent materials, activities, resources and suppliers), allowing alternative routes to emerge as a way of dealing with uncertainty. The paper first articulates the aircraft heavy maintenance problem and limitations of the current approaches to planning and scheduling, including the impact of uncertainty. It then discusses how some of these issues can be addressed using the unitary structuring technique before presenting the proposed framework that will adequately address the limitations of existing approaches. The key features of the proposed framework are presented and discussed using a numerical example drawn from the airline industry. The paper concludes with some implications of adopting the proposed framework for practice and future research directions in this area.

## The aircraft heavy maintenance problem

In industry terminology, heavy maintenance, line maintenance, engine maintenance, component maintenance and configuration management refer to the categories of aircraft maintenance that are typically based on aircraft structural or functional characteristics and associated maintenance requirements (Oelsner, 1979; Al-kaabi *et al.*, 2007; Lam, 2008). Heavy maintenance, which refers to a major overhaul of aircraft structures, includes scheduled maintenance, including inspections of various system components, as well as structural modifications and alternations. During heavy maintenance, an aircraft is temporarily taken out of revenue service, and the elapsed time is treated as downtime. Heavy maintenance is the most challenging undertaking of all categories, due to the magnitude and sophistication of the major overhaul of an aircraft. Activities undertaken as part of heavy maintenance can often have flow-on effects on activities in other categories such as configuration management and component maintenance. Furthermore, heavy maintenance can benefit from effective configuration and component maintenance. For example, Kilpi *et al.* (2009) asserted that cooperative strategies for the availability service of repairable aircraft components

play a significant role in aircraft maintenance involving a closed-loop maintenance process.

There are two major streams of literature that have studied the heavy maintenance problem: one focusing on the overall scheduling of a fleet of aircraft at a specific hanger(s), commonly known as "service scheduling" (Bird, 1976; Sherif, 1980; Smallwood, 1988; Elkodwa, 1996; Cheung *et al.*, 2005b) and the other dealing with various aspects of detailed planning and scheduling of activities, materials, resources and maintenance personnel (Dijkstra *et al.*, 1991; Ho and Chan, 1994; Alfares, 1999; Cheung *et al.*, 2005a; Li *et al.*, 2006; Kilpi *et al.*, 2009). The former and more extensive stream of literature has used such approaches as linear programming, heuristics, integer programming and algorithms aimed at solving the service scheduling problem involving multiple aircraft and limited hanger or resources availability, aimed at optimising the overall performance (e.g. labour costs, productivity, turnaround time, resources utilisation). The latter and relatively sparse stream of literature on detailed planning and scheduling has used mathematical models, expert systems, decision support systems and online systems while focusing, almost exclusively, on workforce allocation under varying circumstances, leaving the remaining aspects (such as planning of materials and resources requirements and operations scheduling) to be dealt with in a rather piece-meal manner.

In essence, the vast majority of research in the area of heavy maintenance has focused on the service-scheduling problem whereas the attention to detailed planning and scheduling of materials, resources and operations at the activity or task level has been limited. Furthermore, they not only lack integration at the process and data levels but also are not guided by any holistic framework that covers the full spectrum of maintenance operations from hanger scheduling to detailed lower-level tasks.

Moreover, one striking aspect of aircraft maintenance revealed through recent studies into industry practice (personal correspondence) is that only one half of the overall maintenance workload within heavy maintenance comes about as planned efforts. This means, the proportion of unplanned maintenance activities arising out of inspections carried out during an aircraft lay-up can be as high as 50 per cent of the total work involved in heavy maintenance. Anecdotal evidence further suggests the use of a number of *ad hoc* and ill-informed practices relating to spare parts inventory management, as well as information management, across the various functional departments within an organisation. For example, it is rather customary to resolve issues around resource allocation, spare parts supply and capacity utilisation through negotiation between functional teams in regular progress meetings, completely outside the ERP system environment.

The above empirical observations highlight the importance of dealing with uncertainty associated with heavy maintenance planning and scheduling. Component and system failure, in the context of engineering asset management, stems from inherent technical characteristics (reliability) of system components. Two generic strategies used in reducing the probability of failure are preventive maintenance (usage-based repair or replacement of items, at regular intervals, irrespective of their failure status) and predictive maintenance (condition-based repair or replacement of items-if failing). There is also a third category identified as detective maintenance – i.e. regular functional checks to see if items such as protective devices still work (Moubray, 1992). Unplanned maintenance activities, which typically arise out of inspections carried out as part of condition-based maintenance, have significant implications for spare parts inventory management, resources planning and execution of maintenance

tasks. For example, if there is a 50 per cent chance of an unplanned maintenance activity becoming necessary during an aircraft lay-up, there could also be an equal or greater chance of additional demands being placed on materials and resources, depending on the level of spare parts inventory and resources utilisation. Given the sophistication of the maintenance problem, these unplanned activities could also lead to further complications in scheduling, and hence cascading effects on achieving the overall objectives (cost, time, quality or safety) of a maintenance project. Thus, the basic functionalities required of heavy maintenance of aircraft include:

- planning of materials and resources, considering the interdependencies between activities at various points and unplanned activities arising out of inspections;
- scheduling of operations, considering the new activities arising out of inspections, routes of their progression and variations in activity durations; and
- capacity loading and levelling of resources in the context of unplanned activities.

Delivering these functionalities is predicated on developing a more holistic and integrated approach to planning and scheduling of heavy maintenance.

## Limitations of the current approaches to aircraft maintenance planning and scheduling

Traditionally, managing heavy maintenance within the airline industry was supported by functional applications such as critical path method (CPM) in project management, MRP in production planning and production activity control (PAC) in shop-floor operations scheduling, along with associated software tools. Limited interfacing of these applications was achieved within the later manufacturing resource planning (MRPII) systems. This meant, in a typical heavy maintenance project, activity planning for aircraft lay-up was supported by standard project management techniques whereas materials (including spare parts) requirements were planned at the commencement of an activity, using a standalone MRP system. The execution of maintenance orders, in particular scheduling of operations and allocation of resources, was undertaken with the help of operations scheduling techniques of PAC. As a result of lack of integration at the process level, planning of materials and resources requirements and scheduling of operations have been carried out by MRP, PAC and CPM in an uncoordinated fashion.

The main problem associated with the above approach, however, was that it often generated plans for materials, activities and resources that are "out of phase" with each other. The deployment of three separate techniques for planning and scheduling often required manual checks to see whether they were synchronised. On completion of each operation, it would also need to check whether all the task lists and additional work items have been completed. The main obstacle to integration at process level is lack of integration of individual data structures (i.e. hierarchical BOMs, sequential operations routings and closed loop activity networks) at the data-element level. Ideally, an integrated process for MRP, PAC and CPM requires an integrated framework, combining hierarchical BOMs, sequential operations routings and closed-loop activity networks at data-element level.

In general, interfaced systems lack the capacity for simultaneous planning of materials and resources involved, nor they have the capacity for forward planning of operations after the commencement of the maintenance project, leading to manual intervention throughout the remainder of the project. Furthermore, finite capacity

loading of resources is not possible since no capacity requirement planning (CRP) techniques are incorporated into such systems. As a result, even when the required materials are available, maintenance projects could still be delayed due to the unavailability of resources required for some operations.

Functional techniques and tools such as CPM, MRP and PAC are offered as modules, or parts of larger applications, within the current ERP systems. Integration of these modules (and others) at the business process level through cross-functional processes, supported by individual data structures within relational databases, has also been achieved by the current ERP systems. Integration of standalone modules at the business process level supports enterprise-wide business functions, including plant maintenance. For example, MRP explosion process is integrated with the production order creation of PAC through planned orders. In this case, MRP outputs are directly fed into production order cycle of PAC, making integration of MRP and PAC at the process level. However, MRP explosion and PAC production order creation use two sets of data elements guided by two different data structures – material masters and BOMs for MRP, and material masters, BOMs, operations routings and work centres for PAC. These data elements and structures are not fully integrated into a unified data structure as required for the simultaneous planning and scheduling under MRP, PAC and CPM. Furthermore, only a few systems offer the extended functionality required for aircraft maintenance planning and scheduling across the full spectrum of maintenance types. When generic ERP systems are used for aircraft maintenance planning and scheduling, they still require interfacing with other applications.

By comparison, ERP industry solution for aircraft maintenance commonly known as "maintenance, repair and overhaul (MRO)" has most of the required functionality. MRO is built on a number of building blocks from sales and marketing through spare parts management. These building blocks are supported by underpinning processes and take appropriate routes of business processes at the time of planning, control and execution of each maintenance project. Each building block incorporates a number of activities such as service contract handling, maintenance planning, project management, maintenance execution and billing (Mathaisel, 2005; Al-kaabi *et al.*, 2007).

The maintenance order cycle within MRO involves order creation with different task lists consisting of numerous operations whereas maintenance order scheduling involves scheduling of operations and work centres. Planning of operations requires scheduling of work centres with finite capacity loading. These activities are carried out at different levels of the maintenance hierarchy and at different times, using such techniques as MRP, PAC and CPM with individual data elements and structures. However, due to the inherent limitations of the individual techniques used, MRO may still require considerable manual intervention on finite capacity loading of resources and forward planning of maintenance operations. For example, planning and scheduling of maintenance orders at different times (creation, assignment into a network activity and scheduling) may lead to incompatible planned dates; and scheduled dates and times. This also can lead to infinite capacity loading of resources (work centres) with no prior warning. Furthermore, scheduling of a number of maintenance orders to the start-point of a network activity can lead to loosing information on the sequence of maintenance orders, thus resulting in infeasible plans. As such, MRO also suffers from a lack of capabilities for:

- simultaneous planning of materials and activities;
- forward planning of materials and resources once the maintenance order cycle has commenced (i.e. during the execution phase);
- sequencing of tasks within a heavy maintenance project activity; and
- finite loading of resources.

A key limitation of the current ERP systems is, therefore, that they lack the capabilities for simultaneous planning, dynamic forward planning and finite capacity loading. This is primarily because various data elements (relating to materials, operations, activities, resources and suppliers) are not fully integrated, at either the process or the data level, into a unified structure. In other words, existing data structures are designed for supporting individual techniques to operate in standalone mode with limited capacity for interfacing and integration. As such, a key problem associated with the use of these techniques, even when they are interfaced or partially integrated at a process level, is that they could still generate "out-of-phase" plans for materials, resources and operations. Furthermore, at this level of integration, the critical path of a maintenance project is determined by activity durations with no regard for the availability of materials or resources. However, in cases where the required materials are available in appropriate quantities, there is a chance that maintenance projects can still be delayed due to the lack of resources (labour or machine) required for executing activities. Lack of dynamic forward planning means, once the project is in progress, any changes to the original plan are only possible through manual intervention which undermines the efficacy of planning. Similarly, lack of capacity for finite loading means possible overloading of resources, and therefore, subsequent manual adjustments to the schedule are inevitable within the current ERP system environment.

In summary, there are two fundamental issues relating to the limited capacity of simultaneous planning and forward planning and finite loading of resources. They are partial integration of data structures – hierarchical BOMs, sequential operations routings and closed-loop project networks; and multiple levels of planning and scheduling of materials, resources and operations. Multiple levels of planning and scheduling with various data elements involved in a given plant maintenance scenario is a result of the limitations of current data structures (i.e. materials are planned using explosion of hierarchical BOMs in MRP; operations and resources are planned using operations scheduling of PAC; and activities and resources of projects are planned using CPM). Thus, in this paper, data integration is sought as the key approach for resolving the issues of planning and scheduling limitations that exist within the current ERP context. Integration of hierarchical BOMs, sequential operations routings and closed-loop project activity networks, at the process level, incorporating both independent and dependent relationships of data elements and alternative routes for planning with uncertainty is achieved through extending the unitary structuring technique.

## Overview of the unitary structuring technique

The vast majority of the limitations referred to above can be addressed at a more fundamental level by applying the unitary structuring technique (Woxvold, 1992; Samaranayake *et al.*, 2002). It is based on a conceptual framework developed by merging the functionalities of the three individual techniques; CPM, MRP and PAC into a unitary structure (i.e. conceptual integration at the process level, supported by data integration of individual data structures at the data-element level).

The framework, as illustrated in Figure 1, integrates MRP hierarchical BOM, PAC sequential operations routings and CPM project networks. The formalism adopted in the unitary structure uses the icons "M", "A", "R" and "S" (outer line) to denote four data elements as represented by the first letter of the words material, activity, resource and supplier, respectively. The formalism also allows three forms of relationships between these data elements to be represented as follows:

- vertical MRP BOM (parent-child relationships);
- horizontal PAC operations routing (standard sequences); and
- arbitrary CPM activity network (precedence relationships).

Because the three techniques are merged into a single integrated structure, some of the functionalities of the individual techniques are not retained in their original form. For example, unlike the case with conventional MRP, materials had no intrinsic lead time because timing data are incorporated into the corresponding activity data element within the unitary structure. Resources are associated with individual activities and represent human (labour) and machine categories required to execute the activity. The integration of these three techniques (process integration, supported by data integration at data element level) can be represented by a schematic view, as shown in Figure 2.

The unitary structure integrates all three functions of materials planning, resources allocation and operations scheduling, effectively at both business process and data structure levels, thus introducing the capabilities to simultaneously plan for materials and resources, as well as the scheduling of operations. For example, while MRP applies a single lead time to all components of a parent item irrespective of the quantity required (and lot size), PAC allows the use of both quantity dependent and independent activity durations (i.e. setup and operation times). However, in practice, lead times are often dependent on lot size, and activity durations are often subject to the availability of materials. Thus, when the two techniques are merged, PAC benefits from the association (with MRP) through the planning of material requirements by the MRP function and the explosion process of MRP benefits through PAC provision of a more realistic measure of lead time. This phenomenon can be illustrated using the three

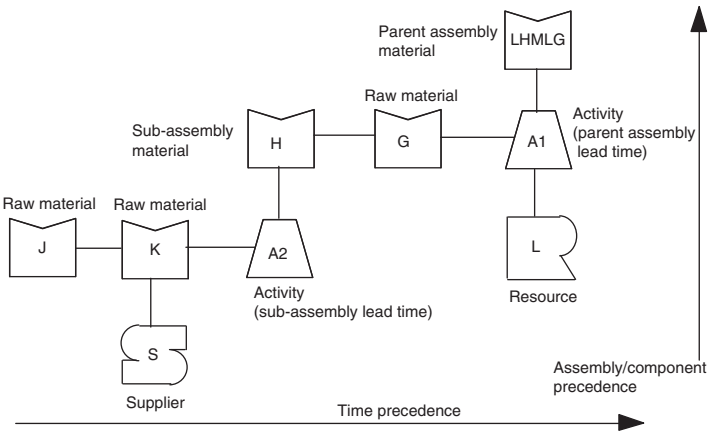



**Figure 1.**
An example of the unitary structure

different combinations of activities and materials (i.e. BOM and operations routings) shown in Figure 3.

The standard PAC functionality of the unitary structure enabled a dependent PAC routing to be defined in the entire branch (Figure 3a). Consequently, the fixed lead times of MRP (independent of parent quantity) were used to define the schedule of the maintenance project (Figure 3b). The functionality required for maintenance planning and scheduling is given in Figure 3c. Thus, any component of a parent item could act as the start-point of an operations routing. This means that an arbitrary number of operations routings (multiple operations routings for a single parent component) can be defined within a single-level structure and it is then possible to describe maintenance procedures with sufficient detail.

However, to take account of the effects of the above hierarchical, sequential (i.e. operations in an operations routing) and precedence (i.e. activities in a project network) relationships, planning and scheduling within the unitary structure require additional information relating to the quantities of materials needed and durations of activities allocated with resources. This information is incorporated by means of a "relator". The relator field indicates whether the quantity of one data element (one unit of material, activity duration or resource) affects other data elements associated with the assembly. Relator field values are assigned as shown in Table I.

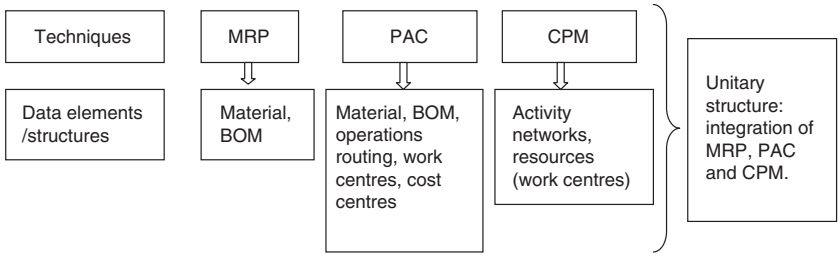
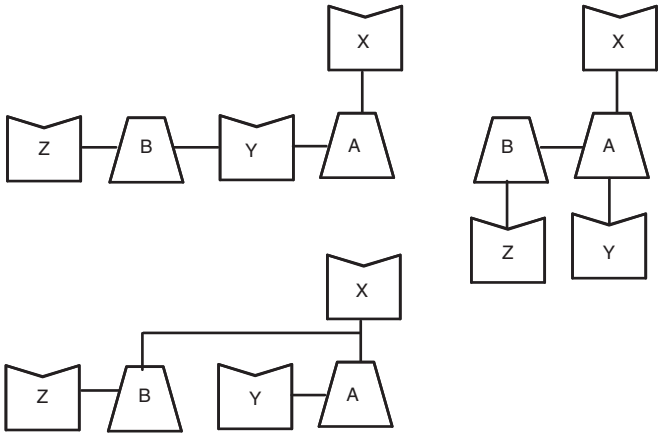



**Figure 2.** Schematic view of process integration, with integrated data




**Notes:** (a) Dependent components – PAC; (b) independent components – PAC; (c) independent components – MRP

**Figure 3.** Dependent and independent time components in PAC and MRP

The traditional BOM logic represents only the "m" relator for its lower-level component materials (BOM items) to indicate the material quantity that is required for each unit of the assembly (parent material). The CPM logic uses only the "a" relator for its activities as all activity durations are expressed in absolute terms (i.e. are unaffected by an assembly quantity of parent material). As such, the "m" relator does not affect the calculated assembly quantity, or the exploded quantity of preceding adjacent component materials on the horizontal axis. Similarly, the "a" relator provides an absolute (batch) value that does not affect the calculated assembly quantity or the exploded quantity of preceding adjacent component materials on the same level. Conversely, the "M" relator does affect the calculated assembly quantity and the exploded quantity of preceding adjacent component materials on the horizontal axis. Likewise, the "A" relator does affect the calculated assembly quantity and the exploded quantity of preceding adjacent materials on the horizontal axis.

As shown in Figure 4, unitary structure could combine both operations routing sequence of PAC and hierarchical BOM of MRP, using relators m, a, M and A. While the relators "m" and "a" provide a basis for explosion of BOMs and scheduling of operations, respectively, the relators "M" and "A" are required for representing relationships between additional data elements and dependencies, to provide for planning of all data elements involved. Furthermore, those relators distinguish between the set-up and operation time elements associated with each activity. Relationships between data elements are directly linked with the relators of each data element, at the time of planning of all activities, materials and resources. While the relators "m" and "a" are similar to BOM quantity and activity duration, respectively, the relators "M" and "A" are specific and have different meanings. In Figure 4, for example, 20 units of final product requires four hours of activity N (independent of assembly quantity) and 40 hours of activity P (two hours per unit × 20 units).

**Table I.**
Relator field values and effects

| | Affects only the lower level data elements (components) | Affects both the same level and lower level data elements (components) |
|---|---|---|
| Multiple | M | M |
| Absolute | A | A |

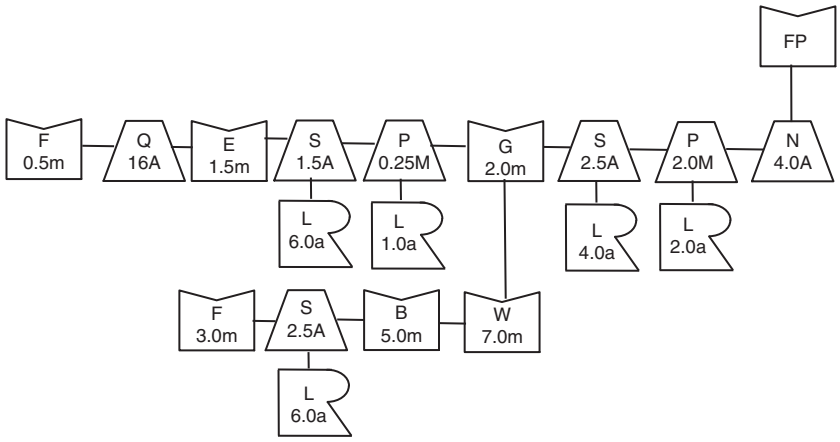



**Figure 4.**
The unitary structure with relators

In addition to the relators and additional relationships between data elements, unitary structure can allow for activity precedence of project networks. In project-based manufacturing situations such as aircraft manufacturing and ship building (special type of discrete manufacturing), unitary structures are based on a combination of BOMs and the project network. In such situations, activities can be identified with respective events and are linked with activity precedence relationships. A simple case of a project with relevant materials and events is illustrated using Figure 5.

It is assumed that each event shown in Figure 5 (EV1-EV6) corresponds to one material (either available in stock or completion in production/procurement). However, as an event marks the transition from one activity to the next, there may be multiple materials required and/or available at a particular transition point. The materials required at an event, in turn, may affect the timely completion of the project.

Within the unitary structure, there are two sources of timing data: the CPM activities and the stock material availability dates. The availability of material in stock is dependent on the completion of purchase orders or lower level assembly or maintenance orders. Thus event times are dependent not only on the times of its incident activities but also on the availability times of any material that co-exist at the event.

An event exhibits slack if there is a positive discrepancy between the earliest time the event may occur (according to the forward schedule) and the latest time the event may occur (according to the backward schedule). Since the unitary structure incorporates events with both availability and requirements of materials, as well as completion of preceding activities, realisation of those events are best described by numerical formulation of event times, taking all the components and time durations into consideration.

Therefore, for an event $i$ which is directly preceded by $J$ events and shared by $M$ materials, the earliest event time ($EET$) at event $i$ is given by:

$$EET_i = \max\{\max_j\{EET_j + \max_\alpha(D_{j,\alpha})\}, \max_m\{MT_{m,i}\}\}, j \in J \tag{1}$$

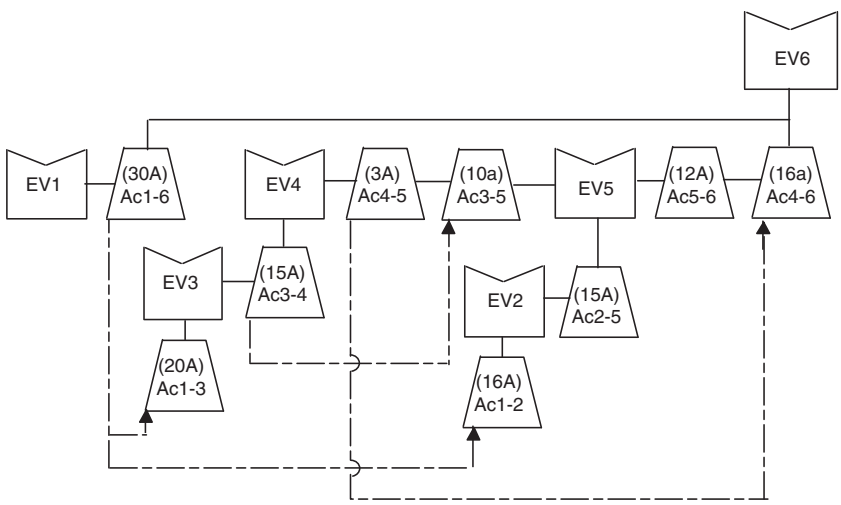



**Figure 5.**
The unitary structure of project network with materials

The duration of activity $\alpha$ from event $j$ is given by $D_{j,\alpha}$. $MT_{m,i}$ is the material availability time for material $m \in M$ at event $i$. The *EET* is calculated from the forward schedule. For the initial event, where there are no incoming activities, the *EET* is taken from the later of the material availability times or the planned project start date.

The latest event time (*LET*) is dependent of the material availability times and is calculated during the backward schedule. As such, for an event $i$ which is a direct predecessor of $K$ events, the *LET* of event $i$ is given by:

$$LET_i = \min_k \{LET_k - \max_\alpha (D_{k,\alpha})\} \; k \in K \tag{2}$$

For the terminal event, the *LET* is the later of the *EET* for the event and the project due date. The *LET* provides an indication of the event slack. If the earliest time of an event is dependent on the availability of material at the event, then all activities incoming to the event will have different floats depending on float definitions. So the latest a preceding event can occur is the *LET* of the current event minus the duration of the longest activity between the current event and the preceding event. If the preceding event occurs any later than the current event occurs (i.e. after its *LET*), this may upset the event times of succeeding events and hence prolong the entire project if the current event lies on the critical path. The total slack (*TS*) of event $i$ is, therefore, given by:

$$TS_i = LET_i - EET_i \tag{3}$$

In addition to the total slack of the event, the materials that share the same event have their own slack. The safety slack of a material is the time by which the material's availability can be delayed without affecting the schedules of neighbouring activities. Thus, the safety slack (*SS*) of Material $m$ at Event $i$ is given by:

$$SS_{m,i} = EET_i - MT_{m,i} \tag{4}$$

The activity start and finish times can be calculated from the event times and the activity durations. Similarly, the various floats (total float (*TF*), free float (*FF*), independent float (*IF*) and safety float (*SF*)) for an activity spanning events $i$ and $j$ can be evaluated from the *EET* and *LET* and using standard equations.

In conventional CPM networks, event times depend only on activities, and there will be a sequence of activities having zero total floats. Any such sequence spanning over a complete project is called "critical path". Delaying or prolonging any activity on the critical path will prolong the entire project. By comparison, in the unitary structure, event times may depend on material availability as well as activity durations. As a consequence, the initial node is not necessarily critical (unlike the case with conventional CPM), and the critical path does not necessarily span the entire network (from initial to terminal nodes).

An event in a unitary structure is critical if it has zero total slack (i.e. the same case as for conventional CPM). The critical nature of activities and materials in a unitary structure is determined according to the following rules: first, an event is critical due to material availability if the *EET* of the event is defined by a resident material (i.e. the safety slack of the material is zero) and the total slack of the event is zero – therefore, any material with zero safety slack on an event with zero total slack is treated as critical; and second, an event is critical due to an activity if the *EET* time of the event is defined by the earliest finish time of an incoming activity (i.e. the activity has zero free float) and the total slack of the event is zero. Therefore, any activity with zero total float incoming to an event with zero total slack is treated as critical.

Overall, unitary structure can seamlessly integrate the functionalities and supporting data elements of the three techniques, i.e. hierarchical BOMs of MRP; sequential operations routings of PAC; and closed-loop project networks of CPM. By merging three different functionalities and associated data elements, the unitary structure eliminates limitations inherent in the use of idiosyncratic data types thus allowing simultaneous and forward planning of multiple types of data elements and finite loading of resources. As such, the unitary structure eliminates limitations of planning, control and execution in a vast majority of situations within plant maintenance contexts. Further improvements to the unitary structure are sought before it can be applied in planning and execution of large and more sophisticated projects such as aircraft heavy maintenance that have a high level of interdependency and unpredictability.

## Proposed framework: further enhancements to the unitary structuring technique

The unitary structure, as illustrated above, may still not be robust enough to deliver the full range of functionalities and data structures required for the planning and scheduling of materials and resources requirements, as well as operations, involved in the aircraft disassembly and assembly. This is mainly due to the additional dependencies between the various data elements and network links not discussed in the previous section. For example, dependencies could be in the form of data element to data element and activity precedence relationships. Such dependencies could result in a number of alternative schedules subject to outcomes of various activities and tasks involved, particularly for large systems such as those used in the airline industry. As such, there is the need for further enhancing the unitary structure to represent these dependencies, so that it is capable of delivering the additional functionalities of:

(1) handling multiple operations routing branches (i.e. operations scheduling with multiple branches and materials availability at the right time);

(2) the ability to branch out, based on the outcome of an event (i.e. CPM activity planning with both planned and unplanned maintenance); and

(3) incorporating finite capacity loading of CRP.

Thus, the enhanced unitary structure should not only provide basic functionalities of MRP, CPM and PAC but also the added functionalities of dynamic forward planning and finite capacity loading of the all resources involved in aircraft maintenance. In effect, it should provide the basis for comprehensively addressing those problems discussed previously by incorporating the functionalities of simultaneous planning and scheduling of materials, resources and operations; dynamic forward planning; and finite loading of resources.

The means by which these functionalities are delivered within the proposed framework are illustrated in the remainder of this section using a simplified example (industry scenario) drawn from a commercial airline in the region – the left-hand main landing gear of a Boeing 737-300 aircraft. The maintenance process, on the assembly side of the structure, as identified by the airline, involves three processes: materials changes; rectification; and re-assembly.

The process of materials changes involves planned removal and replacement of material components of the assembly with materials from stock (inventory). The rectification process involves performing planned and additional maintenance work

(unplanned work identified during inspection). The overall maintenance operation concludes with the re-assembly which returns the entire system to a functional state (normal operating condition).

The materials change and rectification processes are independent and can be performed in parallel. Hence, they should occupy separate PAC branches. The re-assembly process is dependent on the completion of the first two processes. This precedence can be represented through a common branch where the re-assembly process can share a branch with one of the other processes and the dependence of the other process is then identified via a network link. Alternatively, both dependent processes can indicate their precedence via appropriate network links. This allows the re-assembly process to follow a distinct operations routing (task list) and, therefore, provides a more meaningful representation of the assembly-side maintenance work. The resultant structure of the maintenance process is shown in Figure 6.

Activities are generally coarse descriptions that apply to high-level sub-assemblies such as a main landing gear assembly and may have large durations which vary according to inspection outcomes. Each activity in the above maintenance process can have a series of tasks, identified by an individual task list. Tasks can be activated according to inspection outcomes and the overall activity duration can be determined by the sum of active task durations. Thus, while a task may have a fixed duration, the time for completion of an activity that involves such task may vary from one instance to another. This is different to the condition that each task would have its own distinct instance with a known duration. This situation of varying activity durations during maintenance process requires existing scheduling methods to be changed. The proposed framework allows for this variability of activity duration. For example, activation and deactivation of tasks would result in them being added to or removed from the maintenance plan for the current project. However, the use of variable activity duration may require fundamental changes to the current data definitions or adopting existing data definitions with appropriate selection of data fields and associated values.

The ability to specify multiple operations routing branches of PAC in the enhanced unitary structuring technique is essential for the construction of equivalent BOM from a project network, since standard operations routing alone cannot handle all the links (in particular routes resulting from uncertainty). As a result of merged functionalities of the three techniques (MRP, PAC and CPM), the critical path can be established not

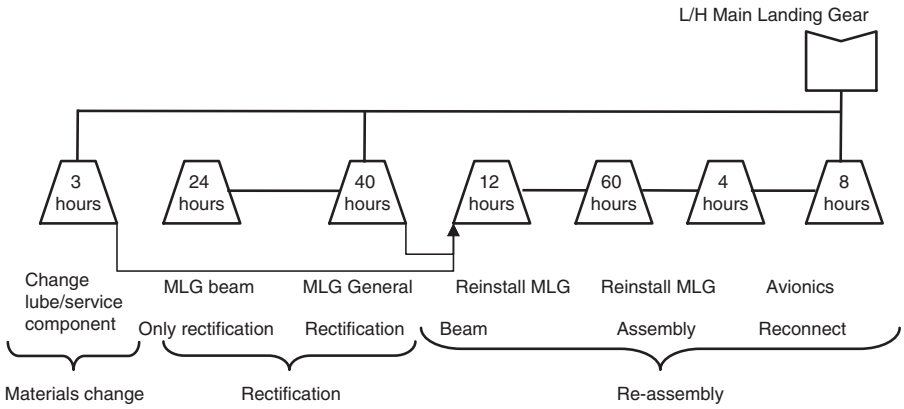



**Figure 6.**
737-300 left-hand landing gear assembly-side maintenance process

only based on critical activities, but also on the availability of materials and resources. Furthermore, finite capacity planning of all resources involved can be achieved through the process of balancing the available capacity with the required capacity at the time of planning of materials and activities.

*Uncertainty associated with condition-based maintenance*

As previously discussed, unplanned activities often arise out of the inspections carried out as part of predictive or detective maintenance procedures. For example, if the inspection reveals a fault or failure, then an unplanned maintenance activity is initiated. If the inspection reveals no fault then the project proceeds to the next activity (inspection or planned maintenance). This implies, depending on the nature and extent of unplanned maintenance activities, that the expected completion time of a project may vary substantially from one case to another. This unpredictability can also have wider implications for budgeting, inventory management and capacity planning.

Classical project management techniques do not have the ability to branch out network activities contingent upon the outcome of an event. As such, all upcoming events had to be known and the duration estimates of the activities that join them should be given, for a confirmed schedule of activities. If there is any uncertainty about the events themselves then it is not possible to form an accurate schedule from the outset. Although, theoretically, a project can be scheduled for all possible outcomes, the schedule would quickly become infeasible as the number of uncertain events and their possible states increase. The project evaluation and review technique addresses uncertainty in activity duration by specifying the best, worst and most likely activity durations, and applying a statistical distribution to arrive at an acceptable estimate for the duration to be used in the network. By comparison, the graphical evaluation review technique allows for conditional and probabilistic treatment of logical relationships between events and activities (i.e. some activities may not be performed, depending on the outcomes of the event). Although both techniques significantly contribute to addressing uncertainty at the activity scheduling level, they do not have the capacity to simultaneously plan for material requirements and resource availability. Consequently, the effectiveness of such planning in terms of achieving the overall project objectives becomes limited.

For example, if inspection reveals that a part needs to be replaced and that part has a manufacturing or procurement lead time of five days then it would be five days before it would be replaced. As such, the effect on the project of introducing the task would be immediately visible. However, if the inspection activity had sufficient float in it to consume the maintenance task then the schedule remains unaffected. Otherwise, compensatory action (re-scheduling) could be initiated or the new schedule could be accepted. Likewise, the capacity requirements would also need to be re-examined to ensure no resource becomes overloaded following the introduction of the new maintenance task. Again, the problem can be dealt with at a more fundamental level within the proposed framework as illustrated below.

The contingency discussed above can be accommodated into the unitary structure as shown in Figure 7. Once the contingency is factored in to the unitary structure, the problem can be handled using the forward planning capabilities of the unitary structure (Samaranayake and Toncich, 2007) with additional functionalities for handling multiple operations routing branches resulting from possible unplanned maintenance tasks. The forward planning of the unitary structure is a combination of operations scheduling of PAC, explosion of MRP and activity and resources scheduling

of CPM, using scheduling paths (Samaranayake, 1998; Samaranayake and Toncich, 2007) for identifying the sequence of data elements from independent data elements to the completion of the maintenance project (final assembly). Details of additional functionalities of forward planning capabilities of the unitary structure are illustrated through the use of a numerical example.

When dealing with uncertainty, a more realistic alternative to applying judgemental probability would be to assign activity durations that include the actual inspection time plus the duration of the longest resulting maintenance task that might be initiated by the inspection. This would produce the longest possible schedule which, if all activities go as anticipated, would remain valid throughout execution. However, this approach would result in substantial floats if anticipated maintenance tasks, upon inspection, are found to be not required. Therefore, as the project progresses, the expected completion date would become earlier than originally estimated. The negative impact of this situation can be mitigated by enhancing the capacity to reschedule the project on a real time basis (dynamic forward planning). In conventional project management, the CPM network is a static description of the project. Uncertainty means that there is insufficient information available at the outset to produce an accurate project network. In such situations, a static network is of little value. A more dynamic network could be produced in two ways: fixing the activity durations but allowing for the addition or deletion of nodes (activities or events) as they unfold during the project; or fixing the structure of the network (number of activities, events and their connectivity) but allowing for the duration of activities to vary (increase or decrease) as the project progresses.

The first option allows materials to be included in the structure as inspections determine them due for maintenance, or removed from the structure if no maintenance is required. Applicable maintenance tasks can also be added or removed from the structure as required. The second option assumes materials, operations and resources involved are known at the outset but their exact contribution to the project can change as the project progresses. This means that the maintenance project structure contains, at all times, a complete record of all data elements subject to inspection outcomes, irrespective of whether the related tasks are actually performed or not, during the project. As such, once the project is underway, the maintenance structure remains autonomous where there is no need to refer to the generic or configuration structure to retrieve information.

In enhancing flexibility to reschedule a project, there remains, however, a key challenge regarding the availability of materials and resources to cope with the uncertainty of the maintenance project. Conventional MRP requires intuitive judgement to rectify discrepancies arising from changes to the requirements, within planning time fences. Of equal significance is the capacity for finite loading of resources as new tasks are activated.

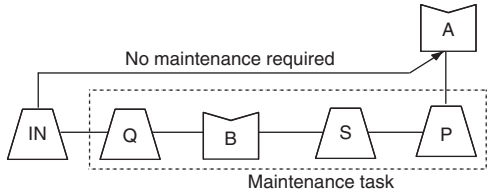



**Figure 7.**
Planned and unplanned maintenance tasks within the unitary structure

The aspect of re-scheduling of materials, resources and operations can be taken care of within the unitary structure, by simultaneous planning of all those components, dynamic forward planning of operations with materials and finite loading of resources. It is expected that the maintenance project is required to be re-scheduled at any given time, based on both the planned and unplanned activities involved, using a forward scheduling functionality. As the dynamic project network is a more accurate reflection of the required work due to uncertainty, comparing the resulting schedule with the actual progress of work provides a more meaningful indication of the project status than if a static project structure is used. The issue of "out of phase" plans can be resolved by using the forward scheduling capability of the enhanced unitary structuring technique when the maintenance project is forward scheduled not only at the beginning but also at various stages during a project, in particular, on completion of inspection activities. Re-scheduling with finite loading of resources is also possible with forward planning within the proposed framework. These perspectives are sufficiently covered within the proposed framework and associated functionalities as illustrated in the following numerical example.

## Numerical example on maintenance planning and scheduling with uncertainty

The numerical example is based on a test case of aircraft assembly sourced from the industry (Lewis, 2000), in which a selected set of aircraft components of C-130 propeller assembly (PA) is grouped into a test configuration as shown in Figure 8. The PA of C-130 contains approximately 2,000 components, which is a fraction of the total aircraft components but sufficient in resolution for their maintenance requirements.

The configuration structure, presented with the unitary structuring technique, contains parent-child, as well as data element-data element relationships. The numbers shown next to each data element represent the planning sequence of data elements, based on a scheduling path algorithm (Samaranayake and Toncich, 2007) of the overall planning and scheduling approach. However, the application-specific implementation methodology is not discussed in this paper. It should be noted that in the configuration structure shown in Figure 8, each component has a corresponding quantity; hence each of the four propeller blade components of the assembly has a unique instance.

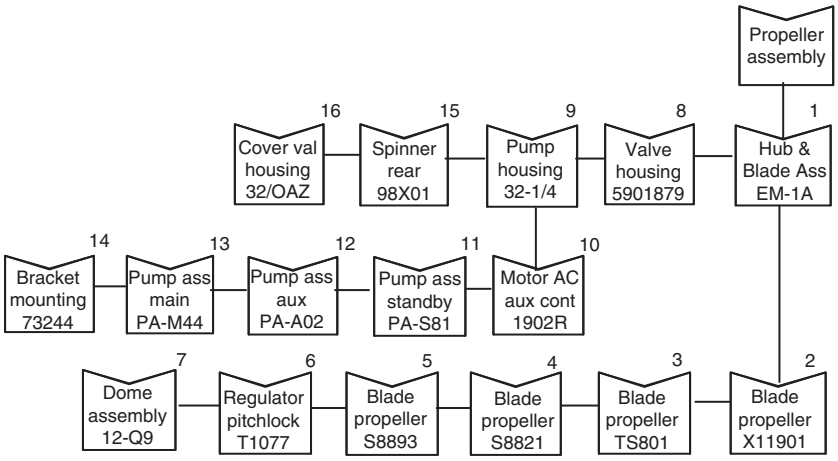



**Figure 8.**
A configuration structure for the C-130 Hercules propeller assembly

Expanding the structure to reflect respective unit component quantities means that each component should be allocated a unique serial number, as shown in Figure 8 (e.g. blade propeller shown as components three to six have serial numbers X11901, TS801, S8821 and S8893, respectively).

The maintenance project for this case is a simple activity network and can be represented by a combination of both standard and parallel sequences of activities, which are equivalent to operations routing in production planning. The resulting maintenance project network is shown in Figure 9. The details of activities, including their respective durations, are shown in Table II. When operations scheduling of PAC is applied to the above maintenance project, comprising of combined operations routings, it can provide only the scheduling of operations times. That means, operations scheduling does not guarantee feasibility of the schedule since it does not include either possible unplanned activities or availability of materials and resources, at the time of operations scheduling. This situation can be avoided when the activity network is expanded by incorporating any possible unplanned maintenance activities based on the unitary structuring technique.

The activity network shown in Figure 9 does not show the relationships between activities and their associated materials and resources. Additionally, the maintenance project network does not allow for any activities required for replacement of the propeller blade arising out of blade inspection (Op50). This means that the network shown in Figure 9 is inadequate to represent the full range of relationships between activities, including precedence. If any forward planning is to be incorporated into the maintenance project, there has to be additional activities between activities 50 and 90. These aspects are accommodated within the unitary structure-based project network shown in Figure 10.

The generic structure comprising of both assembly and disassembly activities and relevant resources, as well as materials for the PA is shown in Figure 10 (PA is the top level material component of the structure). The generic structure is characterised by:

- maintenance tasks as activity data elements;
- multiple data elements for a given position in the structure;

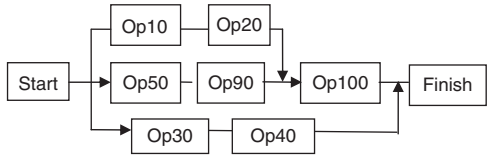



**Figure 9.**
Maintenance project for the C-130 propeller assembly

**Table II.**
Maintenance project activities for the C-130 propeller assembly

| Activity no. | Description | Duration (days) | Activity type | Material component |
|---|---|---|---|---|
| Op10 | Inspection and access | 2.5 | Disassembly | Propeller assembly |
| Op20 | Pump overhaul | 6 | Re-assembly | Pump housing |
| Op30 | Disassembly | 2 | Disassembly | Dome assembly |
| Op40 | RP service | 0.5 | Re-assembly | Regulator pitchlock |
| Op50 | Blade inspection | 1 | Disassembly | Blade propeller |
| Op90 | Blade refit | 2 | Re-assembly | Blade propeller |
| Op100 | Blade remount/reconnect | 1.5 | Re-assembly | Hub & Blade Assembly |

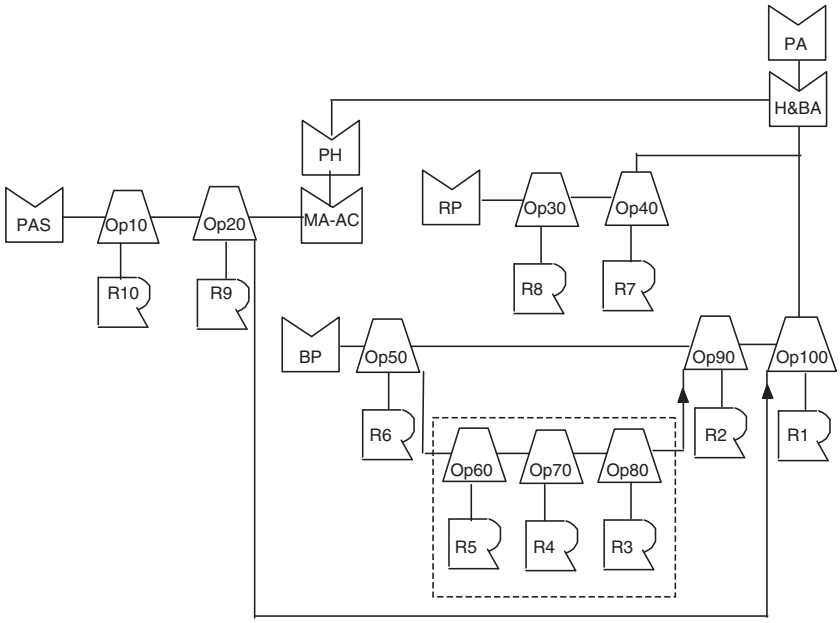



**Figure 10.**
The generic structure for the C-130 Hercules propeller assembly

- data elements with non-unit quantities (e.g. variable length of a material component);
- activity precedence relationships using network links;
- provision for specifying the sub-structure to which a data element applies; and
- generic data elements rather than instance-specific data element details such as serial numbers.

It can be noted from Figure 8 that spinner rear and regulator pitch-lock at their respective generic positions do have multiple material data elements whereas the configuration structure contains only a single material data element for each of those positions. Additionally, the configuration structure does have both disassembly and re-assembly tasks recognised as maintenance tasks. The positioning of maintenance tasks in the generic structure is not described here in detail. However, for the purpose of this illustration, basic rules are considered and demonstrated using test cases. For example, disassembly tasks should be considered as prior instances of their corresponding component instance, and re-assembly tasks should be treated as succeeding instances to their corresponding component instance. However, the generic structure in Figure 10 is in non-disassembled format. Hence, the disassembly tasks, along with their re-assembly counterparts, appear on the right of their associated component. In this unexpanded representation, the data element-data element relationships have different significance, depending on the type of maintenance tasks (disassembly and re-assembly tasks). However, when the maintenance structure with tasks is expanded, the conventional data element-data element (mainly parent-child relationship of BOM and sequential relationship of operations routing) is restored.

It can also be noted from the generic structure of C-130 Hercules PA that the Hub & Blade Assembly comprises of two operations routings (task lists) – one for the blade

propellers and one for the Regulator & Dome Assembly. This indicates that, although the readiness of the parent assembly (Hub & Blade Assembly) depends on all three components, there is a degree of independence between the components of the assembly. The two routings are independent and, therefore, can be scheduled to be performed in parallel, provided that there is no contention for resources. The same resource has been allocated for both re-assembly tasks in the Hub & Blade Assembly but different quantities are required for the two tasks. Possible contention will be identified and rectified during the planning phase, guided by an application-specific implementation methodology, on finite loading of resources. In comparing the total activity durations based on the project networks shown in Figures 9 and 10, under different conditions, the following can be illustrated:

$$\begin{aligned}&\text{Project duration under ideal situation}\\&= \text{Max}\left\{\begin{array}{l}\sum(Op10, Op20, Op100);\\ \sum(Op50, Op90, Op100);\\ \sum(Op30, Op40);\end{array}\right\}\\&= 10\,\text{days}\end{aligned} \tag{5}$$

Project duration with uncertainty planned :

$$= \text{Max}\left\{\sum(Op10, Op20, Op100); \sum(Op50, Op60, Op70, Op80, Op90, Op100); \sum(Op30, Op40)\right\}$$

$$= 13.5\,\text{days}$$

Project duration with material shortage :

$$= \text{Max}\left\{\sum(Op10, Op20, Op100); \sum(Op50, Op60, Op70, Op80, Op90, Op100; \sum(Op30, Op40); \sum(Op50, Procurement\ LT, Op90, Op100)\right.$$

$$= 24.5\,\text{days}$$

It is assumed that procurement of materials for unplanned maintenance takes 20 days while it takes only nine days to complete the three project activities (Op60, Op70 and Op80) and no material shortage as a result of proper planning. Thus, planning with uncertainty using the unitary structure (Figure 10) can reduce overall project completion times. This could, in turn, improve customer service level by allowing more accurate promise dates, based on finite loading of resources and allowing for uncertainty during maintenance.

Furthermore, inclusion of unplanned maintenance operations can allow forward planning of the entire structure, taking not only planned operations but also unplanned operations and the availability of associated materials and resources. This additional feature provides flexibility in planning under changing situations and estimates the critical path based not only on activity durations (both planned and unplanned) but also on the availability of resources and materials, during a lay-up. Thus, in order to handle the unplanned maintenance, the following steps need to be carried out:

- incorporate maintenance tasks associated with possible replacement of part, upon inspection of major assembly;

- plan all tasks, including unplanned branches of tasks, materials and resources; and
- at the time of execution, depending on the outcome of the inspection, forward planning of remaining tasks and resources, using simultaneous planning and finite loading capabilities of the enhanced unitary structure.

This numerical example illustrates that the critical path can be different, depending on the outcome of blade inspection (Op50) activity. Overall, this provides accurate completion times, which can lead to cost savings and improved customer service levels.

## Conclusion

This paper demonstrated that maintenance of complex systems such as aircraft benefit vastly from an integrated approach to planning and scheduling of multiple activities, materials and resources, as well as using unified data structures that integrate multiple types of data elements over a large spectrum of maintenance types. It was evidenced through investigations into current practices that around 50 per cent of the total heavy maintenance workload is identified typically as part of inspections carried out during lay-up. The proposed framework facilitates a proactive response that mitigates the adverse impact of such unpredictable maintenance activities. By way of accounting for a wider range of situations at the planning stage, any unplanned maintenance activities can be effectively deal with at the execution phase using the forward planning capabilities built into the unitary structure with merged functionalities of the three techniques of CPM, MRP and PAC. The utility of the proposed approach was demonstrated using a test case where a maintenance project with possible unplanned maintenance tasks and associated activities and resources was briefly discussed. Potential benefits of adopting the proposed framework include on-time project completion, reduced inventory of spare-parts and reduced overtime costs. However, implementation of such complex maintenance projects should be guided by an overall methodology within application-specific contexts.

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