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ENABLING VALUE CO-PRODUCTION IN THE PROVISION OF SUPPORT SERVICE ENGINEERING SOLUTIONS USING DIGITAL MANUFACTURING METHODS

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ABSTRACT

Traditional engineering business models in aerospace manufacture and deliver finished equipment to the customer. Service provision is typically limited to procedural documentation and providing spare parts to the end user. Commercial pressures have resulted in end users structuring their own core business activities resulting in the need for original equipment manufacturer (OEM) to integrate and manage support service activities *in partnership* with the customer to deliver the availability of the equipment. This improves the probability of commercial success for the OEM through shared operational risks while reducing the cost of ownership for the customer. This paper applies four of the seven *attributes of value co-creation* (AVCs) developed by Ng, Nudurupati, and Tasker (2009) required for an integrated and partnered approach to service provision between the OEM and the customer. It also shows how these are supported through applying digital manufacturing methods for the design and implementation of complex service processes.

1 INTRODUCTION

Business revenues in engineering are typically based on a value proposition that is within the control of the OEM acting almost exclusively as a product supplier. Although maintainability is an increasingly important consideration when a customer is contemplating the purchase of a complex engineering system, in the past there has been little incentive for the manufacturer to be pre-emptive in maintenance, to invest in reliability for spares or be innovative in service solutions. Challenging economic conditions and changing end user needs in service support have however meant that OEMs are increasingly being drawn into contracting for availability, where the contract is based on the outcome of value that is co-produced and co-created by the manufacturer and the customer. In addition, because the contract is largely agreed upon in advance of the product delivery, there is incentive to supply products complete with a service solution across their operational lifetime, while at the same time lowering post contractual costs and co-producing the value with the customer. Where previously suppliers simply manufactured and delivered a product which complied with customer specifications, OEMs are now being asked to design processes and exhibit people management skills beyond manufacturing into the broader product lifecycle. These processes and skills must ensure that the customer co-produces value, delivering the desired outcomes in service provision by which the company is now being assessed. These outcomes include mutually beneficial economic conditions which maximise both revenue flow to the OEM and the quality of service provision to the customer. A transparent, integrated framework using simulation for the development, management and delivery of process definitions and business metrics, is important to the delivery of these outcomes in a way that supports the attributes of value co-creation.

Given the current gaps between existing industrial practices and likely future needs in availability contracting, the challenges of this new business model need to be identified. For the OEM they include the management of the cultural change from traditional contracting to service provision, loss of perceived control by the customer, loss of perceived control by the OEM, lack of boundaries (rigidities & fluidities), co-ordination of suppliers, and the complexity and unpredictability of revenue levels (Ng and Yip 2009). As the OEM is confronted by these challenges, it is prone to several risks associated with the transition from manufacturer to product supplier and service provider. To minimise these risks, this work applies four generic value co-creation attributes which facilitate successful service delivery for availability-based contracts (Ng and Yip 2009). From Ng, Nudurupati and Tasker (2009), four attributes were identified as being relevant to digital process development. These are:

1. **Complementary Competencies** (AVC1)- Both the customer and the OEM have to provide the right competencies, in terms of expertise, judgment and access to resources.

2. **Behavioural Alignment** (AVC2) - Even where competencies and processes are aligned, both customer and OEM have to ensure that the right behaviours are in place to ensure effective and efficient value co-production and co-creation.

3. **Congruence of Expectations** (AVC3) - To be successful in co-producing and co-creation of value, expectations must be in congruence. This means that the customer expectations of the OEM must match the OEM's understanding of the customer's expectations of the OEM. Conversely, the OEM's expectations of the customer must match the customer's understanding of the OEM's expectations of the customer.

4. **Process Alignment** (AVC4) - In a multi-environment state, value-in-use changes and as such, value co-production and co-creation need to build in the alignment of processes whereby customer changes would flag up changes in the alignment.

The four attributes for value co-creation can be used to mitigate risks when designing and delivering the service system. One way of achieving this is to use the simulation techniques and data management structures which are available within the Delmia digital manufacturing platform. The need to minimise the risk of commercial failure by developing leaner products and processes, has led to the development of software systems like this one, which use simultaneous or concurrent engineering concepts for the design and engineering of new products and manufacturing processes. Manufacturability and maintainability are important considerations from the earliest concept, and traditionally these aspects of the development process have not been supported by predictive technologies to the same degree as other areas of product design, see Figure 1.

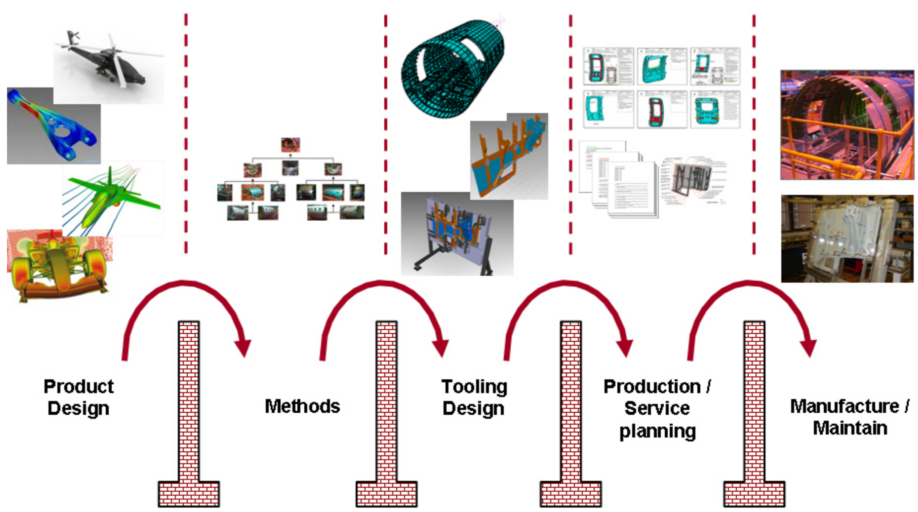

Figure 1: Traditional, Linear Process Development for Manufacture and Maintenance.

To deal with this problem, concurrent engineering concepts are now available in computer aided design (CAD) and computer aided engineering (CAE) tools and they can used to determine electronically, how a product needs to be built (Guerra and Ramirez 2006) and serviced, see Figure 2. The development and validation of maintenance procedures using simulation ensures that processes are optimised, and potential problems are eliminated before the transition from *virtual assets* and *committed cost* to *tangible assets* and *actual costs*. This in turn, will lead to reduced production cycles, improved design agility (Garbaya, Coiffet, and Blazevic 2003) and ultimately lower cost and improved competitiveness.

The mechanisms used to develop optimal maintenance processes will produce digital instructional materials which ensure the effective communication of methods and work breakdown structures between the technical author- the OEM - and service personnel - OEM or customer (Butterfield et. al. 2009) . In addition to the practical aspects of process definition and validation, the digital manufacturing environment provides an effective framework for data management and sharing. The enhanced connectivity which is possible through a virtually defined manufacturing hub, provides a live, collaborative environment where engineers and process designers can create, share and store engineering and manufacturing data related to products, processes and resources. This approach allows the complete range of engineering disciplines across the enterprise to interact with the latest contract information thereby increasing productivity and ensuring a higher-quality end product. At a time when manufacturers are increasingly evolving from suppliers to service providers, the attenuation of risk is doubly important. The application of simulation methods for process design needs to be extended beyond manufacture into the complete product lifecycle because manufacturers now have responsibilities beyond the production environment - into product service and disposal. In the context of this work, the need for value co-creation in availability contracting means that digital manufacturing principles must also be extended beyond a single enterprise. This can be achieved by giving the customer access to the product process resource (PPR) hub so that they can contribute to process design and delivery for service provision. It is through this approach that simulation methods become directly relevant to the attributes of value co-creation. In addition to the more tangible requirements of process definition such as work breakdown structure, bill of material, costs (material, labour), instructional materials etc., the approach supports the need for managing the less tangible implications of the transition of an OEM to availability contracting. These are mainly associated with the integration of cultures between the supplier and the customer, and they are captured in the main section, within the attributes of value co-creation presented in this paper.

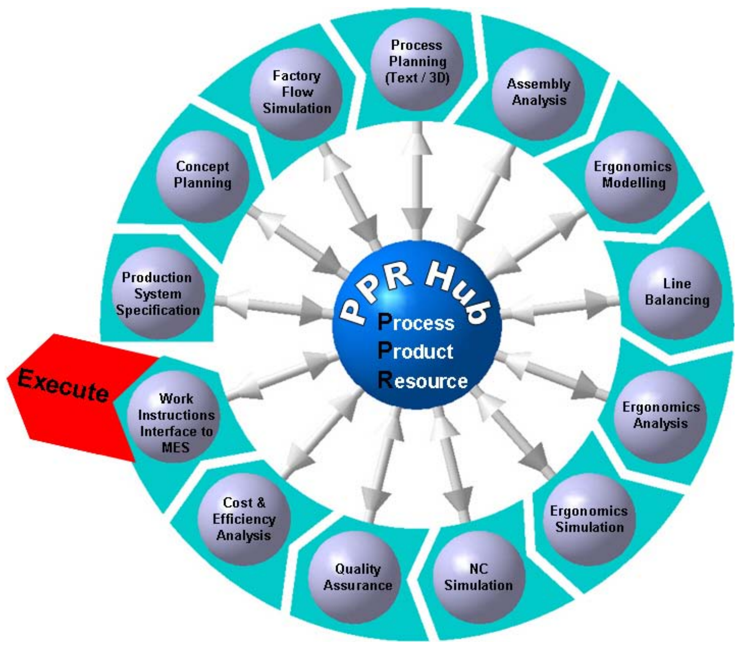

Figure 2: Digital Approach to Concurrent Process Design for Manufacture or Maintenance.

In generating cost drivers directly from a simulated process environment, the work also addresses the question of the uncertainty which is intrinsic in formulaic cost estimation methods. This method can be disconnected from the system for which the costs have been generated, and although the approach is unavoidable for systems where data or processes are not available, the PPR hub offers the maintenance planner an opportunity to build processes around even the most basic product definitions, for example, those available at a bid stage. This in turn, enables the generation of cost estimates based on representative processes which consume realistic resources. The chronology of current availability contract planning means that nearly all systems are in existence and in some cases, are of considerable vintage in engineering terms. The availability of established processes and system data does not negate the need for simulation, as planning for availability contacting may not be carried out by the original designer or manufacturing planner. This results in the need for knowledge re-capture which again is a process well suited to a simulation approach - using the PPR hub to create and manage process knowledge for the purpose of identifying cost drivers and generating costs.

It should be noted that cost drivers are not a new concept nor are they wholly predictable using simulation methods. A series of generic drivers (Erkoyuncu and Datta, 2009) have identified to reduce uncertainty and improve the efficiency of the cost estimating process for availability contracting for BAE Systems. These cover a range of cost categories including the supply chain, engineering, training, maintenance, performance and business management. The components of cost have been identified in each category, and each component has been given a ranked score in terms of its level of uncertainty (the higher the score the lower is the uncertainty). Although simulation methods have an indirect influence on almost all of these categories, this work will compare simulation outputs to the least uncertain components within the categories of maintenance and training. This will identify the relationships between the sub-system level simulation, lower level cost drivers with the system level cost drivers.

This paper establishes the relationship between the four attributes of value co-creation and the modelling capabilities within the PPR hub when it is used for process design in availability contracting. A methodology is developed showing how a digital manufacturing framework could be used to ensure that the attributes are supported using simulation. A sub system within a modern jet fighter aircraft has been chosen as an exemplar to show how simulation methods can be used to deliver work breakdown structures and cost drivers for maintenance processes, using the four attributes as guiding principles for successful maintenance process development. The work also shows how a digital manufacturing environment can be tailored to suit maintenance process design, and how the simulated environment can support the less tangible implications of merging the requirements and expectations of both the OEM and the customer in value co-creation in availability contracting.

2 METHOD

2.1 Supporting Attributes of Value Co-creation Using the PPR Hub.

In defining an integrated approach to maintenance process design which supports the AVCs, the following is considered within the PPR structure.

Product:

- The Engineering Bill of Materials (EBOM), including links to relevant CAD data for aircraft components, *with a specification of material and equipment ownership and acquisition.* Thus, the EBOM is not merely defined in terms of materials required, under whose ownership (the OEM or the customer - AVC1), and the expected responsibility of acquisition (AVC3). This directly applies the *complementary competencies,* where key competency is for both the OEM and the customer to be able to "access the resources necessary to get the work done" (Ng, Nudurupati and Tasker, 2009; Yusuf et. al. 2004) as well as ensuring that expectations of responsibilities are designed into the operation.
- The Manufacturing Bill of Materials (MBOM) linked to the component CAD data in the EBOM, again *with a specification of material and equipment ownership (AVC1) and the expected responsibility of acquisition and manufacture (AVC3).*

Process:

- MBOM merged with detailed process data including:
    - o Operator levels (Minimum, Normal, Maximum) *at customer or OEM employee skill levels (AVC1) and cooperation between the team if it's a mix of customer and OEM's teams (AVC2) and designing for the alignment of OEM and customer processes (AVC4)*
    - o Standard hour content for each operation *at customer or OEM employee skill levels (AVC1)*
    - o Precedents which control the order in which the operations are carried out *with a proportionate consideration of where the operations are carried out (the sites of the OEM or the customer), and designing for OEM-customer existing processes in the implementation (AVC4)*
    - o Instructions for each operation *to both the OEM and the customer (AVC2, AVC3)*

Resources:

- Production site locations and layouts - *designed to include the system level choice of the customer or OEM location (AVC1)*
- Tooling types and availability (Cranes, hand tools etc.) - *designed to include its accessibility to the OEM and the customer (AVC1)*

- CAD data for any specialised tooling (jigs) used during the maintenance process - *designed to include their accessibility to the OEM and the customer (AVC1)*

The planning and execution of the simulation using an AVC centric approach within the PPR hub above sets out expectations on both parties, thus integrating AVC3 - congruence of expectations, as well.

2.2 Use of Digital Manufacturing for Maintenance Process Design.

2.2.1 Exemplar - 'The Sub System'.

The replacement process for a significant structural panel section within a modern jet fighter aircraft was chosen as the sub-system exemplar for this work, see Figures 3 and 4. The purpose of the simulation in this case, was to establish an optimal solution for the work breakdown structure and to identify the key cost drivers when considering a process for the removal and replacement of the panel. It was intended that the capture of simulation techniques for one sub-system application would result in a transferrable methodology that could be applied to other sub-systems. This methodology, in turn, could be used to examine the system as a whole, as quantifiable outcomes are rolled up to give an indication of maintenance requirements for a complete aircraft.

2.2.2 Simulation of Maintenance Processes.

The application of digital methods to maintenance processes represents a departure from the manufacturing applications for which the software was originally developed. The PPR structure within Delmia Process Engineer (DPE) is normally based on the manufacturing bill of materials (MBOM), where the hierarchy of the engineering bill of materials (EBOM) is changed to suit the build sequence. Typically, this is constructed using a '*Part to Sub-assembly to Assembly'* build order where aircraft parts are freely accessible as they are assembled, and operator access within the product only becomes restricted during the latter stages of assembly. In the context of this work, digital manufacturing is a misnomer but the tools and methods within the Delmia simulation environment are equally applicable to maintenance process design. This differs from a manufacturing setting as the service process order will be driven primarily by the chronology of maintenance requirements e.g. flight hours for an aircraft or mileage for a vehicle. Maintenance procedures can often mean gaining access to the restricted spaces within a complete aircraft, and carrying out procedures which require significant disassembly activities prior to any part replacement. The higher level nodes within the maintenance process tree will be dictated by the service needs and beneath these milestones, the process will be structured to take account of part removal as well as part replacement or assembly. Given that the operator is not dealing with a new product, activities such as 'cleaning down' also take on a new significance. Although tolerance build ups can be simulated for a manufacturing scenario, maintenance planning can mean dealing with dimensional issues that may arise due to the stresses and strains of operational use during the time that has elapsed between delivery and the first replacement of significant aircraft structures. This is a primary concern for this application where interference with significant pre-stressed, structural items around the frame could result in positional changes which add significantly to the challenges of panel replacement.

The airframe components, associated fixtures and spatial constraints around the exemplar panel, were modelled utilising the Product Process and Resource (PPR) structure within Dassault Systemes' Delmia digital manufacturing suite. The work breakdown structure was configured through the BOM (Bill of Material) within DPE which is where the manufacturing hub is located, see Figure 2. This 'hub' can be used to service all of the key functionalities used in engineering process design such as DPM (Digital Process for Manufacture) which was also used for this work. Simulations within DPM were used to develop and validate specific proposals by using animated process concepts with clash detection, as well as ergonomic analysis, to establish the optimal work breakdown structure.

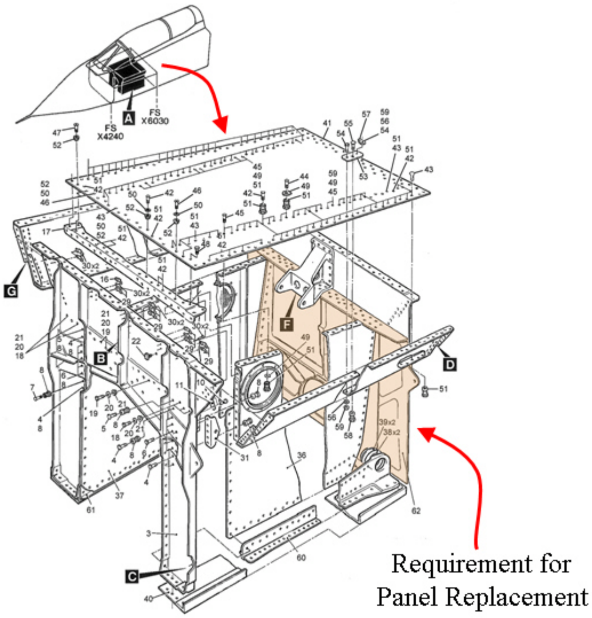

Figure 3: Panel Location Within Aircraft Structure.

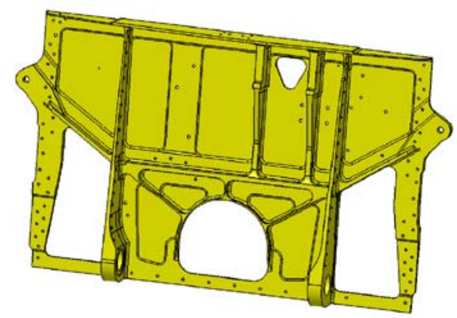

Figure 4: 3D CAD Model Representing Pre-Modified Panel.

2.2.2.1 Process Definition for Panel Removal

For the panel replacement activity, it was first necessary to detach the undercarriage assembly in front of the panel and remove the associated hardware. These activities are well established under the normal operating routines for the maintenance of the undercarriage itself. Panel replacement was not a maintenance requirement when the aircraft was originally designed, and therefore there was no provision for this activity in the aircraft's design or existing maintenance procedures. Once access to the cavity in front of the panel was established, the assorted items fastened to the interior surfaces of the cavity were removed or loosened, and moved from position to provide the operator with adequate access to the panel and the cavity. An initial evaluation of this process showed that significant time and effort was required to remove and replace the panel in its entirety. This also impacted significantly on the important structural members surrounding the panel, extending the maintenance period required for the work. It was decided that a partial replacement of the panel involving the removal of worn features only would be a more efficient way of achieving the desired outcome, see Figure 5. From this point onwards, all activities were modelled within the digital environment. All movements, associated tooling and fixtures were considered as time dependant variables.

Although the use of simulation adds significant value to process design for manufacture or in this case maintenance, the method is not automatic and it requires planning and input from the user. Based on an assessment of the existing product layout, the following process order was used to plan the simulation of the panel section replacement process:

- Clear area surrounding section to be removed (fastener and part).
- Disassembly and removal of sub-components directly connected to panel (hinge & dish - fasteners & part)
- Fastener strip around perimeter of panel section.
- Clean down of exposed panel.
- Introduction of equipment / fixture(s) for the removal of panel section. Options include:
    - Automation (robot)
    - Semi Automate (mobile mill)
    - Manual
- Cut & dress panel section in a single operation.
- Remove panel section (Note: Use multiple cuts if required)
- Clean down
- Location of new panel section

- Attach new panel section c/w fasteners
- Replace sub-components directly connected to panel (hinge & dish - fasteners & part)
- Re-populate panel section area with secondary parts
- Inspection

Each of the above processes was broken down into sub-activities with different requirements in tooling, labour and hence time and cost. Clearly, many of the sub-activities which are focused directly on the panel will be derived directly from the simulation as optimised solutions are generated.

2.2.2.2 Representation of Parts and Fasteners

This aircraft was designed before the widespread application of three dimensional (3D) CAD models for aircraft development, hence complete 3D CAD representation for the aircraft structures was not available. Primary product geometry was based on CATIA V5, CAD models of the panel and the items immediately surrounding it. These were created specifically for the development of the panel replacement methodology.

3D CAD definition of major structural parts is the minimal requirement for the application of a digital approach to process design. The format required for CAD models intended for use in Dassault Systemes simulation platforms, is CATIA V5. In this case the models representing the panel and its surrounding components were created in CATIA V4. Although model transfer through universal file formats is possible when using non native models for V5 applications such as Delmia, there are inherent risks associated with the transfer process. CATIA V4 to V5 transfer can lead to difficulties due to loss of model properties during translation. In practice this can mean loss of positional accuracy or omission of part forms altogether for more complex shapes if the base geometry used to create the non-native part is not compatible with CATIA V5. Although there have been no issues arising from the conversion of the panel data to the V5 format, it should be noted that non-native files cannot be edited within V5 after import. This has a negative impact on one of the key advantages of digital manufacturing methods which automatically updates all simulations consuming a part, if its base geometry has been edited. Where geometry relevant to the panel replacement simulation was not available, idealised surfaces were modelled in order to accurately represent the working volume constraints within the cavity. These models included the side wall shear webs and the rear wall of the cavity, see Figure 6. With the interior working volume established sectioned, exterior surfaces were added to accurately place the work area in the context of the aircraft's front end. Although the outer skin does not play a direct role in the simulation of the panel replacement, it was important to add this feature to the simulation model. Optimal use of simulated environments requires that the end user should have at least an impression of scale, otherwise the size of geometry represented as an isolated image of a localised area is left open for interpretation. A simple idealised surface model of the exterior of the forward fuselage skin was used to place the panel cavity in context and to allow the ergonomic assessment of technicians, tooling and any fixtures, see Figure 7. The workshop floor was also added as this directly influences access to the panel cavity and the extent of the operator's reach within it, see Figure 8.

Fasteners, which number in their thousands for an aircraft of this type, are typically not modelled even with today's high-powered CAD systems. They are typically positioned by a hole centre represented by a pair of crossed lines. For the purposes of this work, data for secondary items such as fasteners, brackets etc. was extracted from two dimensional (2D) drawings of the type shown in Figure 3. Each fastener type and count was recorded manually and when merged with the associated time for removal or replacement, yielded the total time required to process all fasteners in the work area. The times associated with the fastening processes were extracted from a digital library containing standard times for common aerospace assembly tasks. Where no such data existed, experimental removal of representative fasteners was carried out in a laboratory environment in order to generate typical timing information. It should be stressed that this manual approach was necessary because there was no CAD definition available to drive the fastener time calculations. Even in the absence of full 3D representation of fasteners or the holes required to accommodate them, it is possible to use a parametric approach to convert hole positions and diameters from a 3D CAD model, into a part type count. This in turn, can be merged directly with standard time definitions to yield fastener addition or removal times.

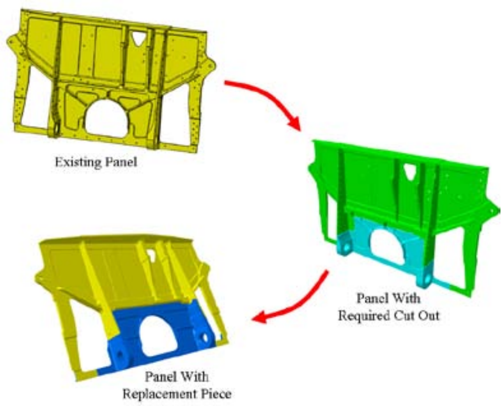

Figure 5: Three Main Stages of Panel Section Replacement.

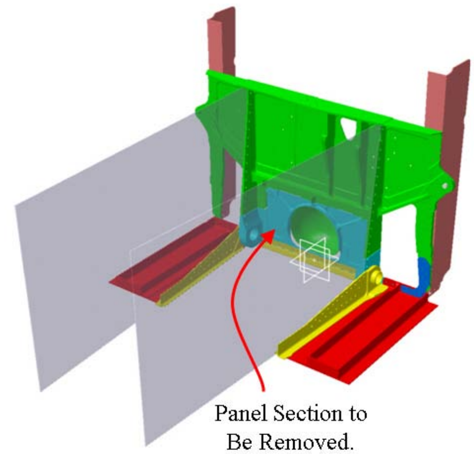

Figure 6: Constrained Work Volume Around Panel.

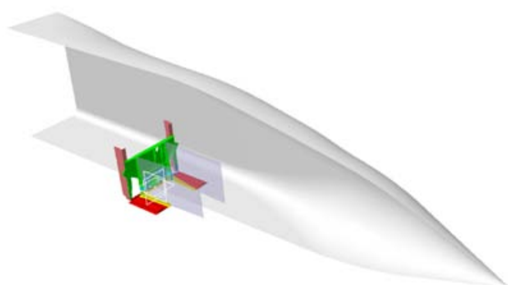

Figure 7: Cavity Relative to front End of Aircraft.

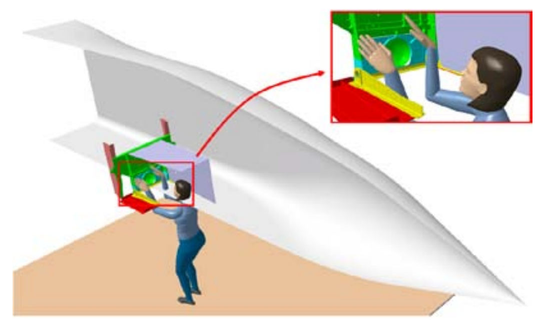

Figure 8: Ergonomic Assessment of Work Area.

2.2.2.3 Simulation Techniques

Having established the high level plan and assembled the available 3D CAD data for the system, the process illustrated in section 2.2.2.1 was defined and animated using Delmia DPM. This included the removal and re-fitting of the main structures and the completion of clash detection studies to establish optimum pathways for each discrete component. An ergonomic study was carried out to establish how many personnel could operate in the restricted space, and to examine the postures that an operator must adopt when working within the cavity surrounding the panel. Part type counts yielded the times required to remove and replace fasteners as well as the data required to control part inventories. The definition of the cutting path(s) required to remove the panel section allowed the removal time to be determined by using a standard cutting rate, which accounted for the tool used and the material type / thickness along the cut line. This now represented a full digital simulation of the environment as it would be experienced by the technical personnel on commencement of task.

2.2.2.4 Cost Drivers

Based on an assessment of the process required to replace the pintle frame section, expected cost drivers included replacement parts, fasteners, operator time (for disassembly and assembly), fixturing, tools and inspection/quality control. These were checked against the most relevant cost components identified by BAE systems within their generic system level cost drivers, see Table 1. A mapping between the sub-system level cost drivers with the system level cost drivers will identify opportunities to reduce uncertainties in the cost estimating process.

Table 1: A Selection of System Level Cost Drivers in Availability Contracting.

Cost Category:	Cost Drivers:	Cost Category:	Cost Drivers:
Maintenance	Maintenance policy	***Engineering***	Query response time
	Labour effectiveness		Quality of response
	Labour cost		Cost of Labour
Training	Facilities	***Performance***	Customer actual usage
	No. of trainers / students		Maintenance event per hour
	Length of course		Revenue rate
Supply Chain	Stock Levels	***Business Management***	Risk management
	Repair cost		Labour
	Turn Around Time		Information Technology

3 RESULTS

3.1 Simulation of Sub System Maintenance Processes for Availability Contracting

Four main outputs were derived directly from the digital simulations which now include the structure and parameters necessary to support the attributes of value co-creation. The outputs include:

- Definition of work breakdown structure.
- Delivery of representative times for ‘Hands On’ activities.
- Identification of cost drivers.
- Generation of instructional materials.

3.1.1 Work Breakdown Structure.

With reference to Figure 9, the methodology for task definition and the associated data extraction can be followed hierarchically in the following way:

- **Major task** - From the overall contract requirement, in this case the removal and replacement of an embedded panel section within the aircraft.
- **Standard maintenance protocol** – Removal of the surrounding hardware normally occupying the enclosed volume, as seen in Figure 6, is already well documented by the supplier as part of their normal maintenance activities and as such, is not investigated here.
- **Work Breakdown Structure (WBS)** – An overarching tabulation of the process order of each major activity in its general sense. Here, the activity shown in red (see Figure 9), “Disassembly and removal of sub-components directly connected to panel” is taken as an example of a primary activity - the next level down in the hierarchy.
- **Primary activity** – A process order for the removal of minor components attached to the panel. Here, the example of, “Remove bracket assembly” has been selected.
- **Secondary activity** – A detailed process order based on components and fasteners. Part and fastener definitions are detailed at this stage, including location, type and number of. Here the example of, “Strip fasteners from lower bracket” has been selected.
- **Tertiary activity –** The final detailed process order based on the physical actions to be carried out by the operator, including all requisite tooling and methodology. At this level, the times associated with each task are assigned and can be totaled and rolled up back through the model as functions of component type, location, number of and labour utility.

3.1.2 Activity Times.

Temporal data relating to overall activity is expressed as a roll-up of the total time required to perform each task, multiplied by the number of times each task is performed. The simulation provides the 'hands on' time for a given task based on standard times for that task (Butterfield , Crosby et. al. 2007). In order to determine a total time for costing purposes, the OEM will have to use a utilisation figure to take account of the fact that an operator will not spend his entire shift period adding value to a contract, even though he is paid for a full working day. A typical utilisation figure would be in the 75 – 80% range. This may differ depending on OEM and customer working practices. A system level costing model which uses sub-system costs will also have to take account of the learning curve. Any parameters which can have an affect on the total time taken for an engineering task, are rolled up into the learning curve. A learning curve represents two facts; first, the time to do a job will decrease each time that job is repeated and second, successive time reductions will be less with each consecutive unit. Learning curves play an important role in bid preparation, estimation of resource requirements, performance measurement and establishing cost trends. Anytime the analysis and projection of costs is attempted, learning curves are used as one tool in the analysis. Any improvement in knowledge acquisition can significantly reduce the number of hours tied up in the learning curve thereby reducing cost, especially in the preliminary stages of any new process implementation. Although primarily used for manufacturing planning, learning curves are equally applicable to maintenance activities. Previous work (Butterfield, M^c^Clean et. al. 2009; Butterfield, Curran et. al. 2007) has quantified the benefits of simulation when it is used to generate and deliver animated instructional materials for assembly processes. These benefits include a 14% reduction in the assembly time for an aircraft panel and a 5% reduction in tooling cost for a new version of the same panel, brought about by the digital application of design for manufacture and assembly (DFMA) principles to fixture design.

3.1.3 Cost Drivers.

One of the key outputs from this simulation is the identification of sub-system cost drivers. Based on the simulation outlined in section 2.2, the main cost drivers include:

- Labour hours (see section 3.2.2)
- Inventory: Part count based on replacement of the fasteners removed during the strip down and the replacement panel section. It should be noted that this represents a considerable risk in terms of the availability of replacement items in the case of products that have been in the field for a significant length of time.
- Fixtures: Required to guide cutting tools during panel section removal.
- Tooling: Specialised equipment required to perform panel section removal e.g. mobile mini mill.

In terms of the cost categories listed in Table 1, the cost drivers identified here align with the components associated with both maintenance and the supply chain. Maintenance policy has a high pedigree score, which means less uncertainty with this cost driver. Exposure to risk through this component can also be minimised by using simulation to define and deliver processes which control or dictate policy through the full range of simulation outputs. Labour costs can be defined and optimised through effective labour utilisation within process structures. Definition of 'hands on' labour hours contributes both to labour cost and turn around time for maintenance operations. Again, simulation can be used to facilitate this and to reduce uncertainty. Part count definitions define inventory requirements.

3.1.4 Instructional Materials.

The use of animated simulations for process design, including the definition of work breakdown structure, creates an opportunity for improved concurrency. Process simulations are used to design optimal processes. When these have been optimised, work instructions become a bi-product of process design, thus negating the need for separate instructional authoring. Figures 5 – 8 represent typical graphics from process design which are re-used for the delivery of work instructions. Previous research has shown that animated instructional materials can significantly reduce the labour hours required to complete a technical task, through the use of animated instructions. This has a direct impact on cost as it reduces the area beneath the learning curves used to project time and cost in manufacturing. A learning curve reflects the fact that the time taken to complete a given task costs to manufacturing processes, and it is expected that a similar result can be achieved with regards to maintenance and repair activities. The use of animated process definitions facilitates the delivery of accurate instructional materials for training purposes. This can help to improve the quality and duration of the learning process which then reduces the uncertainty levels associated with training, see Table 1.

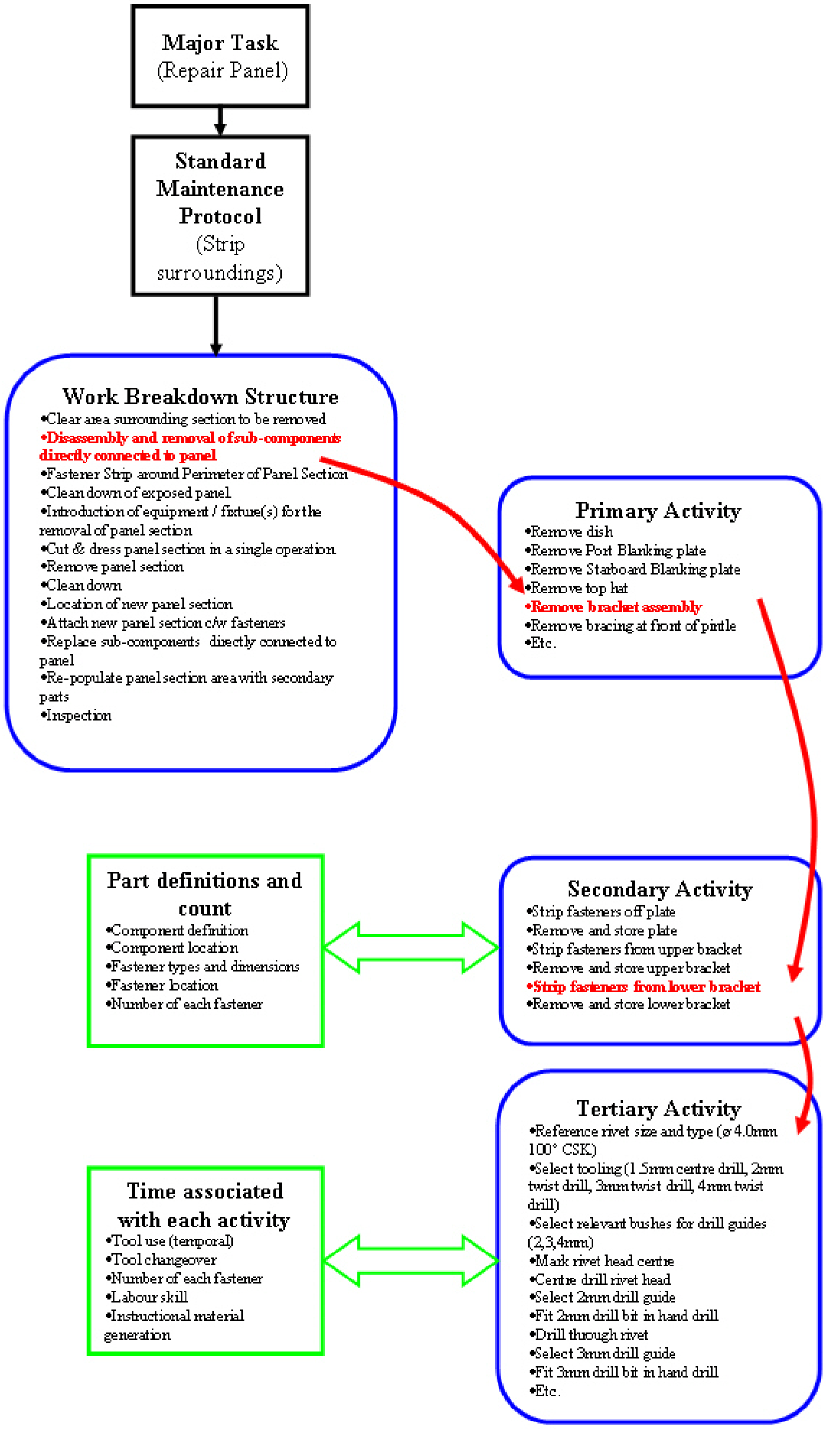

Figure 9: Work Breakdown Flow Schematic for panel Section Replacement.

4 DISCUSSION

A move to availability contracting changes the nature of the OEM/supplier relationship fundamentally as business practices merge and self interests are replaced by the need for optimal ‘co-performance’. Finances and engineering can be measured and controlled in a scientific way, but optimally designed systems do not always deliver optimal outcomes unless the human aspects of system delivery and performance are addressed. Data related to the impact of change on people within an enterprise cannot be extracted easily from organisational statistics nor can it be measured comfortably using a formulaic approach. This difficulty is magnified when considering the type of organisational amalgamation between two entities that is required for availability contracting.

The four attributes of value co-creation described in this work define the less tangible aspects of co-performance. They have been derived from the outcomes of face-to-face meetings and interviews with those responsible for both product and service delivery (Ng, Nudurupati and Tasker, 2009). This approach has ensured that the attributes result from almost wholly human inputs, thereby bridging the current gap between attempting to use a sanitised, numerical approach to measure the effects of a business transition strategy and the need to engage with the people who are expected to deliver the desired outcome.

The aerospace sub-system exemplar presented here shows how simulation and the principles of digital manufacturing is integrated with four attributes of value co-creation, thus increasing its viability in designing service solutions in a partnered environment. This increases the likelihood of a positive outcome for both the OEM and the customer by providing a framework by which the attributes can be facilitated using a controlled, measureable methodology. The simulations deliver tangible outcomes from an engineering perspective which include defined work breakdown structures for maintenance operations, delivery of representative times for 'hands on' activities (which can be used for resource optimisation and cost analysis), identification of cost drivers such as labour, tooling, fixturing, inventory etc., and the generation of instructional materials. More importantly, digital manufacturing provides an integrated framework for the generation, management and delivery of engineering process definitions. Within a single enterprise, this facilitates concurrent activities between the engineering disciplines. The transparent, collaborative environment can be enhanced to include maintenance activities, as the process node in the manufacturing hub is extended to include the broader product lifecycle. The definition and optimisation of maintenance processes in a virtual environment using virtual assets reduces the uncertainty associated with availability contracting. Simulated process scenarios allow the process designer and implementer to reduce or eliminate exposure to risk and uncertainty by generating realistic data for important cost components (see Table 1).

The use of this approach at the OEM/customer interface, where all parties have access to the manufacturing hub, facilitates the use of combined resources in the simulated environment thereby conforming with attribute *1. Complementary Competencies*. Previously separate resources and technologies are then effectively shared as processes are jointly developed. Collaboration within the digital manufacturing framework and joint responsibility for the development of processes also conforms with attribute *2. Behaviour Alignment* as all parties become more willing to share resources and are more open to new ideas which are developed jointly. The use of a single collaborative environment to generate and store process definitions for availability contracting jointly promotes attributes *3. Congruence of Expectations* and *4. Process Alignment* as the co-contributors to the contract, gain a better understanding of their respective roles, responsibilities and expectations and information and material flows are aligned and integrated. It allows employees throughout the combined enterprise to make situational decisions and implement new ideas in a controlled way, thus innovating the service offerings and allowing process evolution to lead to optimal maintenance practices. Finally, the generic attributes used in this study supported by a digital approach to process design and delivery, not only benefit the contract by improving the design and configuration of service delivery system in value co-production and co-creation, but also alleviate some of the risks and tensions that can arise from the contracts.

CONCLUSIONS

The main aim of this work was to show how value co-production in the provision of support service engineering solutions could be enabled using digital manufacturing methods when integrating four attributes of value co-production. A sub-system level exemplar based on the partial replacement of an aerospace structural panel has shown how simulation can deliver tangible outcomes in terms of work breakdown structure, process times, cost drivers and instructional materials. The evolution of manufacturing simulation techniques for use in maintenance process design has been demonstrated. Links were identified between the management and utilisation of the collaborative simulation environment and the enablers of value co-creation, clearly demonstrating that they can be supported using a digital approach. Relationships have been established between simulation outputs and system level availability contracting cost drivers identified by BAE Systems. These links demonstrate that exposure to uncertainty can be reduced by using simulation to control maintenance labour costs. This can be achieved by delivering fully optimised service solutions complete with sub-system performance parameters that facilitate accurate cost estimation. From our understanding of extant literature, this paper presents for the first time, an integration of behavioral aspects of service with value co-creation in a partnered environment into engineering solutions. The solution presented is sufficiently generic for the design of future solutions, an original contribution to the science and engineering of complex service systems.

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