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Use of Digital Manufacturing to Improve Management Learning in Aerospace Assembly

J. Butterfield,* A. McClean,† Yan Jin,* and R. Curran‡
Queen's University Belfast, Belfast, Northern Ireland BT7 1NN, United Kingdom
and
R. Burke,§ Brian Welch,§ and C. Devenny¶
Bombardier Aerospace, Belfast, Northern Ireland BT3 9DZ, United Kingdom

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The primary goal of this work is to quantify any benefits that the use of digital manufacturing methods can offer when used upstream from production, for manufacturing process design, and tool development. Learning at this stage of product development is referred to as management learning. Animated build simulations have been used to develop build procedures and tooling for a panel assembly for the new Bombardier CRJ1000 (Canadair Regional Jet, 100 seat). When the jig format was developed, its simulated performance was compared to that of current CRJ700/900 panel builds to identify and quantify any improvements in terms of tooling cost and panel build time. When comparing like-for-like functions between existing CRJ700/900 (Canadair Regional Jet, 70/90 seat) and the CRJ1000 tooling, it was predicted that the digitally assisted improvements had brought about a 4.9% reduction in jig cost. An evaluation of the build process for the CRJ1000 uplock panel predicted a 5.2% reduction in the assembly time. In addition to the improvement of existing tooling functions, new jig functionality was added so that both the drilling and riveting functions could be carried out in a single jig for the new RJ1000 panel.

I. Introduction

THE motivation for the work lies in the cost savings that are possible through learning-curve improvements as digitally assisted knowledge acquisition drives a design for manufacture and assembly (DFMA) approach to product, process, and tooling design. The work was carried out to identify and quantify where possible the benefits that digital manufacturing methods can offer an engineering enterprise when developing concurrent design processes for the manufacture of complex assemblies. The benefits of simulation methods for specific engineering design disciplines such as design, structures, and aerodynamics is already well established; however, the application of integrated, predictive tools to manufacturing disciplines is less common or, at least, less widely published. This paper illustrates how predictive methods can be applied to the development and optimization of manufacturing processes across the range of disciplines involved in the production of a complex aerospace structure. Although the method has been applied to the operations required to prepare and assemble an aircraft panel, the tools and methods described here, are equally applicable to any complex engineering assembly.

The apron and uplock panel assembly for the new Bombardier CRJ1000 regional jet was used as an exemplar for this study. The apron and uplock assembly is located on the main fuselage in the wing area of the aircraft and it includes a flat external skin with internal structures designed to hold the undercarriage in place during flight. By applying a digitally driven DFMA analysis procedure supported by observational data from existing processes, it was possible to predict cost savings and introduce quality improvements through minimizing the number of interfaces during product and process development and maximizing ease of assembly through improved management learning. A key element that facilitates this analysis at all stages of development for the new panel build process is the use of animated build simulations. This approach was used to facilitate better quality, more timely decision making, and improved communication between the disciplines of product design, methods engineering, tooling design, and production. A combination of digital manufacturing simulation tools and DFMA principles were applied in an effort to improve the performance of the new CRJ1000 apron and uplock panel assembly processes when compared to the existing CRJ 700/900 panels. The benefit of this approach was to improve the degree of concurrency between process and tooling design activities, which traditionally take place in a linear sequence after product design has been completed. Product configurations,

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*Lecturer, School of Mechanical and Aerospace Engineering, Ashby Building, Stranmillis Road, BT9 5AH.
†Aerospace Engineering, School of Mechanical and Aerospace Engineering, Ashby Building, Stranmillis Road, BT9 5AH.
‡Currently Chair of Aerospace Management and Operations, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands.
§Methods Engineering, Airport Road.
¶Tooling Engineer, Airport Road.

which are sympathetic to efficient manufacture, efficient tooling functionality, lean assembly performance, and work cell layout, can all be rolled into this activity thereby facilitating better informed decision making from a manufacturing perspective.

II. Learning Process

The process of learning in any manufacturing enterprise can significantly influence product lead times, final cost, and, ultimately, competitiveness. It affects all contributors to the product development cycle from the design engineers working on the preliminary concepts to the individual operators and supervisors on the shop floor when production begins. In an aerospace context, total organizational learning includes the disciplines upstream from production, including design engineering, tooling design, methods engineering, and production control. For the purposes of this work, learning in these areas is referred to as management learning. 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 new product manufacture. Product design drives the manufacturing requirements and processes, which, in turn, control the performance of the assembly operators. All of these drivers as well as any parameters, which can have an affect on the total build time for an engineering assembly during manufacture, are rolled up into what is known as the learning curve, which represents two facts. Firstly, the time to do a job will decrease each time that job is repeated and, secondly, each time reduction will be less with each successive unit. Learning curves play an important role in bid preparation, estimation of resource requirements, performance measurement, and establishing cost trends. Any time the analysis and projection of costs is attempted, learning curves are used as one tool in the analysis. Figure 1 shows a generic learning curve with a conceptual learning improvement map.

The list of parameters shown in the key on Fig. 1, influencing the position of the individual curves, is not exhaustive. But the graph serves to illustrate the areas where learning curves representing total build times could be moved closer to the ideal horizontal plot of standard-hour content, which is used for aircraft manufacturing planning purposes. Improved methods for operator learning [1] will result in the learning curve dropping from curve 1 to curve 2 with the area between these two curves representing the total time saving. Both curves level out at the same build time because for two equally skilled individuals carrying out the same operation, the build time when the learning process is complete will be the same irrespective of instructional format.

Previous work has shown that this amounts to a 14% reduction in the build time between curves 1 and 2 for the apron and uplock assembly shown in Fig. 2 [1]. A survey of existing aircraft builds showed that even a relatively small percentage improvement (less than 10%) in the time taken to build the first five fuselage assemblies for a regional jet would result in a financial saving that is of the order of $100,000. Figure 1 also shows how learning can be improved further with parallel curve movements made possible by process improvements resulting from management learning, use of higher skilled labour, implementing lean work practices, and use of virtual builds to descend the learning curve before actual production begins. Improved methods for organizational learning can lower learning curves (e.g., from curve 2 to curve 3) as more optimal processes are delivered to the shop floor. This, in turn, will lead to reduced production cycles, improved design agility [2], and, ultimately, lower cost and improved competitiveness.

Ultimately, the process of learning and the way in which the operator acquires skills contributes to the learning curve and its position relative to the axes shown in Fig. 1. The contribution of digital methods to operator learning has been examined [1], but there are human factors related to the learning process that are outside the potential influence of instructional media. For example, skill levels can vary between individuals or work forces at different locations, even if they have been exposed to the same instructional materials. These factors have become more influential as manufacturers consider the transfer of aerospace assembly activities to low-wage economies. In this case, tradeoffs have to take place comparing the financial benefits of this scenario with the likely shortcomings in the key skill sets required for aerospace assembly. This has the potential to have a negative affect on learning as the curve could move from position 4 to position 3 in Fig. 1. The manufacture of an aircraft is uniquely complex compared to consumer items and automobiles, and low-scrap rates and high-output are typically more important than low wages [3]. The impact of such a move on productivity and quality would also have to be considered. Based on this type of tradeoff, North American and European aerospace manufacturers are migrating only low-value operations to low-wage economies [4] at levels, which means that the threat of cheap aviation manufacturing to the established players has been exaggerated [3].

Lean manufacturing is a well-established production practice based on the principle that the use of resources for any purpose other than the creation of value for the end customer is wasteful and should be avoided. It is a generic process management philosophy derived mostly from the Toyota production system and identified as lean in the 1990s [5]. There are many texts dealing with the principles of lean [5,6] and the tools that can be used to implement them [7]. The full realization of the benefits of lean resulting in the reduction in the learning curve shown between curves 4 and 5 comes from a full implementation of lean practices in both product development and shop-floor practices. These benefits are also well documented as cycle times are lowered because the need for engineering change is reduced and labour usage becomes more efficient [8,9]. Although the application of the predictive methods available within digital manufacturing tools (and used during the course of this work) are lean in nature, the process improvements resulting from the approach presented here are mainly wrapped up in the learning improvements in the area between curves 2 and 3 in Fig. 1, but they also have an affect on the area between curves 4 and 5.

Use of virtual training methods in advance of production can result in the movement of the learning curve to the left of the build time axis in Fig. 1. The main advantage of virtual learning is the ability to descend the learning curve before physical manufacture begins, thus improving competitive advantage as cycle times are reduced during the early stages of production and operators are already familiar with new products and the processes required to build them. Virtual

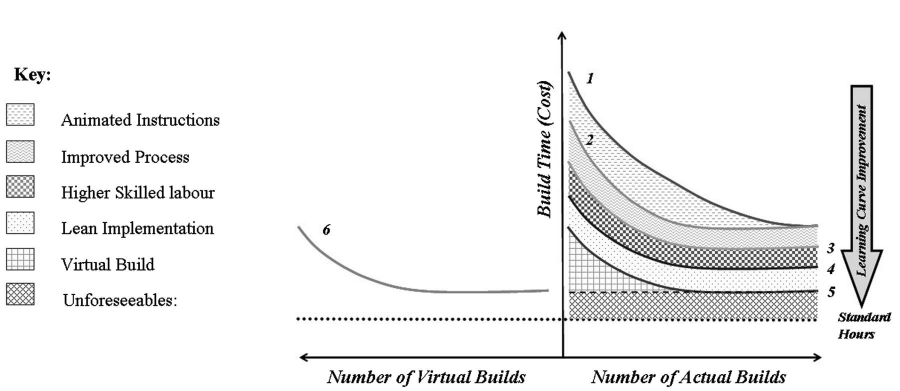
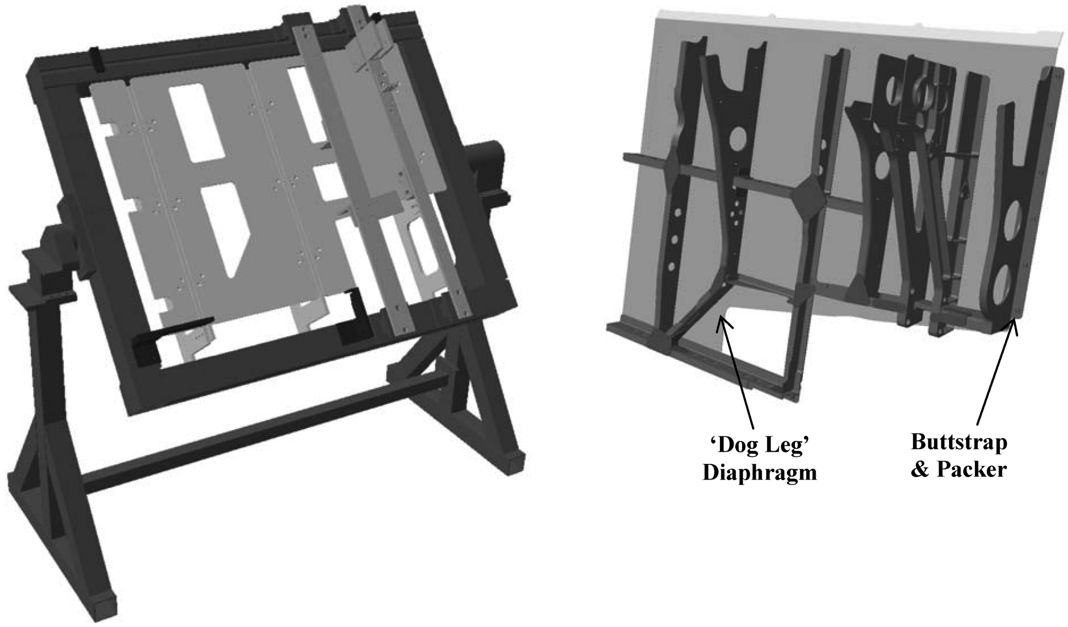


Fig. 1 Learning curve improvement map.



a) Drilling jig b) Apron & uplock assembly

Fig. 2 Existing jig and panel (one-piece skin) for apron and uplock assembly building.

learning also reduces the risk of commercial failure as potential problems are identified and corrected before metal is cut, thereby delivering leaner products and processes to the shop floor [10].

The aim of this work is to identify and quantify the benefits, if any, that digital manufacturing methods [11] can offer to manufacturing planners and tooling designers when developing efficient processes and tools for the manufacture of complex aerospace assemblies. The work seeks to quantify any improvement in the learning curve shown in Fig. 1, resulting from a change in the area between curves 2 and 3 as processes improve, as well as curves 4 and 5 as leaner build practices are built into the new process. The apron and uplock panel assembly for the new CRJ1000 regional jet will be used as an exemplar for this study. By following a rigorous DFMA analysis procedure, it is possible to produce cost savings and quality improvements through minimizing the number of interfaces and maximizing ease of assembly [12]. According to Boothroyd and Dewhurst [13], one of the main purposes of DFMA principles is to provide a basis for concurrent engineering studies, which provide guidance to design teams in simplifying the product structure, reducing manufacturing and assembly costs, and quantifying the improvements. The method used for this work facilitates a more concurrent approach to engineering process design, resulting in a more efficient production solution. Concurrent engineering tools have traditionally been divided into two categories: those that promote consideration of manufacturing quality and assembly criteria and those that aid and improve the communication between members [14]. These categories can now be integrated under the umbrella of digital manufacturing, which aligns the practice associated with DFMA driven assemblies with the predictive methods and concurrent activities required to deliver them.

III. Method

The development of the apron and uplock assembly for the new CRJ1000 regional jet has benefitted significantly from the experience gained from the equivalent panel on earlier aircraft. Current build documentation and practices were thoroughly reviewed before the development work for the new panel. The intention was to capture as a starting point or base line current build practices, including any process inefficiencies based on experience. Figure 2 shows the apron and uplock assembly for the CRJ700/900 aircraft as well as the jig required to carry out the drilling operations on the panel. Process design concepts for the apron and uplock drilling jig were then simulated and the performance of the final version was compared to existing methods so that any improvements achieved through the use of advanced digital methods could be measured against the important performance metric of assembly time and cost. The direct comparison of apron and uplock manufacturing performance data for the new CRJ1000 and the existing CRJ700/900, was considered valid as the core design and required assembly processes were the same at the outset. Improvements to the new CRJ1000 version could then be benchmarked against current data for the existing aircraft. The following sections discuss in more detail how digital methods were applied to the CRJ1000 apron and uplock assembly development.

A. DFMA: Product

When the panel is complete, it is attached to the main fuselage structure. At the point in the assembly process where the uplock is attached, access to the mounting points is restricted due to the proximity of surrounding structures. Significant and time consuming effort is required on the part of the operator to make the panel secure enough to meet specified design tolerances. This was a known production issue with this panel. In developing the new version for the CRJ1000, the panel configuration was changed to include a two-piece skin format, which improves access during final assembly. The new build procedure was validated using mannequins within DELMIA digital process for manufacturing (DPM) to examine access issues in detail. Having changed the configuration of the uplock the next stage was to allow for this change in the design of the tooling required to assemble it.

B. DFMA: Tooling

The apron and uplock panel is a well-established component in manufacturing terms as it is already in service in CRJ700/900 aircraft. The current assembly process requires that the skin and backing structure are drilled and riveted in separate stations. The first stage of the process examining the uplock manufacturing process looked at the performance of the drilling jig (see Fig. 2). The skin is mounted in a rigid backing plate to maintain the flatness tolerance on the panel. When the skin is clamped in place, the structure (diaphragms, frames, brackets, etc.) required to control post-assembly skin flatness and the features required to hold the undercarriage in place when they are withdrawn in flight (i.e., the uplocks) are added. This takes place in accordance with the assembly sequence specified in the engineering process record (EPR) and requires the use of removable support features on the jig to control part positions during assembly. The EPR is a hardcopy document, which verbally defines the assembly sequence using 2-D drawing references to clarify the relative position of parts. This work involved a detailed review of assembly documentation as well as periods of observation on the shop floor to gain familiarity with the build and to identify possible areas for improvement. When the assessment of actual current build practice was completed, the process record was recreated in a digital format using DELMIA DPM. This included a fully animated build sequence showing each of the parts moving into place on the jig as well as the interaction of the panel parts with the jig. When the digital process record was complete, a series of reviews were completed, which included inputs from methods engineering and tooling design, resulting in a final, optimized version of the panel build. This included textual supplements in addition to the graphical information, which were required to provide details for activities not directly related to the CAD data used for the animation (e.g., quality procedures). To quantify any improvements that the new process offered, the assembly simulation was used to drive a digital time estimation exercise combining methods time measurement (MTM) functions with the activities created in the digital process record to complete the drilling jig operations. Having changed the jig design to suit the new process, the cost of the new jig was also estimated using digital means so that a comparison could be made with the CRJ700/900 tool cost.

C. Integrated Time and Cost Measurement

One of the significant functional benefits of digital manufacturing software is the degree of integration between the traditional CAD environment and the relatively new tools which bring manufacturability into the design arena [15]. DELMIA digital manufacturing solutions are centered on a product, process, and resource (PPR) hub, which contains structured design and process data that can be linked directly to the specialized functions required to simulate manufacturing activities, including line balancing, manufacturing clash detection, human analysis, work instruction authoring, process design validation, etc. DELMIA process engineer (DPE) is used in the product development process from the conceptual design phase through the preplanning and detailed planning stages right up to the production phase [15]. The data contained in the hub can be accessed by anyone involved in the product development process, from design engineers to manufacturing process planners and tooling engineers. It provides a complete, up-to-date view of the links and dependencies between products, processes, and resources at any point in time. For the purposes of this work, the optimized assembly sequence and process activities that resulted from the digitally assisted DFMA activities, as detailed in Secs. III.A and III.B, were built into a DPE database, which included the graphical CAD data for the product (panel) and manufacturing resource (jig/tool). With the PPR hub populated with part data and process structure, the database was completed by adding assembly times to the build activities. Tooling cost was also determined using part characteristics extracted from the CAD data. The following sections describe how this was achieved.

D. Time Measurement

Time analysis was carried out to compare the simulated assembly of the new CRJ1000 uplock with the equivalent, actual time for the existing CRJ700/900 uplock. The assembly time for the new CRJ1000 uplock was based on the simulated build sequences established in Secs. III.A and III.B, which resulted in the addition of new operations and the removal of redundant activities. MTM technology was used to derive the assembly timings for the activities specified within DPE. DPE functionality was enhanced to include an expert system, which enabled the breakdown of activities to the individual task level required for the use of MTM timings. The activity breakdown was passed automatically to a spreadsheet that added the task timings and returned the data to DPE where the activity times in the process tree were automatically populated. Figure 3 shows a flow diagram for the exchange of data between DELMIA DPE and the time/cost tools.

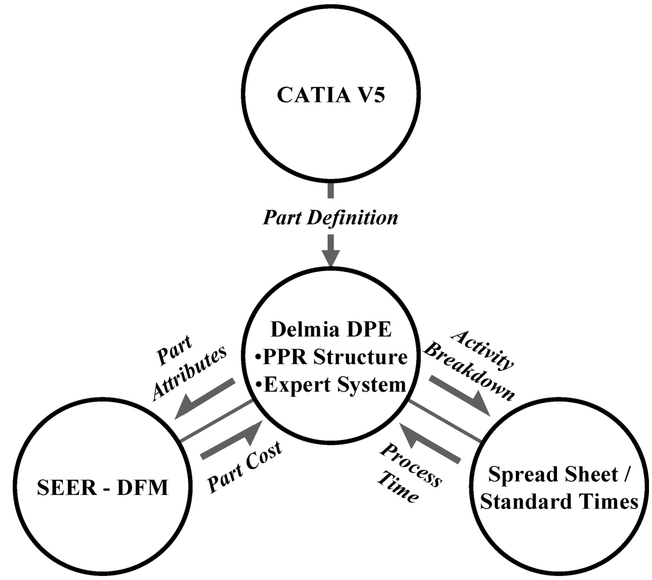


Fig. 3 Integration of automatic time and cost generation functions with DPE–PPR hub.

E. Cost Measurement

A cost analysis was also carried out for the new CRJ1000 uplock assembly process to compare cost of the new CRJ1000 uplock jig with the equivalent cost for the existing CRJ700/900 tool. The CATIA part attributes required for costing were automatically extracted from DPE software and used by SEER-DFM to calculate and return a part costing to the PPR hub (see Fig. 3).

IV. Results

A. DFMA: Product

The current apron and uplock assembly design is a well established product in the Bombardier production line. The current configuration is tailored to existing tooling and processes and includes the use of separate drilling and riveting stations. The build strategy is efficient for the currently specified drilling and riveting processes. Having examined the part assembly sequence using an animation in DPM and by observing the actual shop-floor build, two opportunities for process improvement based on the panel design were identified. The first and most important assembly issue related to the apron and uplock assembly is meeting design tolerances when the panel is mounted on to the fuselage. This is not helped by the difficulties surrounding final fit when the operator can experience problems in fitting the panel into the restricted spaces which are available at the point in the fuselage assembly process when the apron and uplock is required. The new version of the CRJ1000 panel uses a two-part skin where the upper piece is fixed in place when the apron and uplock assembly is secured on the fuselage structure (see Fig. 4). This improves access to the panel mounting point, which reduces build time and improves build accuracy. The need for this change was identified through shop-floor experience. Simulation using mannequins was used to validate the new configuration (see Fig. 4).

The second issue was flagged during a digital DFMA assessment of the constituent parts of the panel. A diaphragm (see Fig. 2) is installed with a butt strap and a packer. Adhesive is used to bond the three items before placement on the jig. Part proportions mean that the manufacture of the diaphragm with the butt strap and packer geometry included and using a single billet of material is not possible, but by making the butt strap and packer in one piece, the part count could be reduced from three to two and the adhesive application time reduced.

Another issue was related to the application of the paint before part assembly. As paint was applied to the apron and uplock parts, there were several cases where the paint in fluid form accumulated on part edges as it cured. On the majority of parts, this was of no consequence.

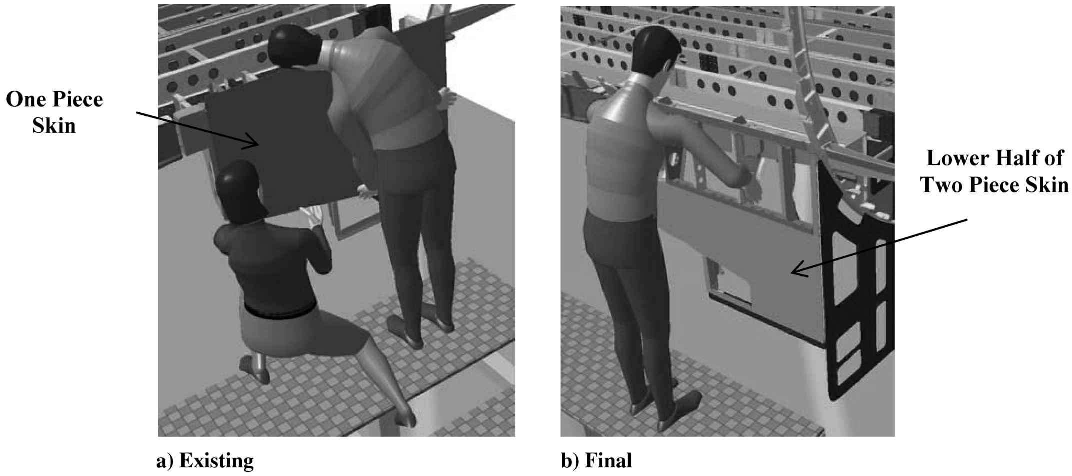


Fig. 4 Product DFMA: design concepts for new apron and uplock assembly building.

But on faces, which were in contact with the panel skin, the raised bump of hardened paint meant that it was not possible to achieve the surface to surface contact required to satisfy structural requirements. This condition can be addressed during assembly but it requires time on the part of the operator. This is a practical aspect of the build that cannot be predicted using digital manufacturing. Recognition of this problem at this stage means that part orientations can be considered during the painting process to avoid paint buildups on critical edges and the problem resolved by attention to detail and good housekeeping.

The final issue was the positional problems causing part clashes and low-clearance issues. In the time that the apron and uplock has been in production, none of these issues have been related to the main structural items in the apron and uplock assembly. Historically, there have been no positional problems with parts as long as they are modeled in CAD as part of the design process. All of the clash and clearance problems on the current uplock have been related to the relative position of parts and fasteners. Panel assemblies are not generally modeled in CAD down to fastener level. If all parts and fasteners are modeled, then using digital manufacturing methods means that clash and low-clearance issues are detectable using both design and manufacturing clash detection.

B. DFMA: Tooling

The process of shop-floor observation and digital evaluation of the current assembly process for the apron and uplock drilling jig revealed several aspects of the build that could be improved when the new RJ1000 apron and uplock panel goes into production. More important, the improvements were all predictable using digital means had this technology been available when the jig was originally designed.

Following the DFMA assessment of the panel assembly and mounting processes, the most significant change was the use of a two-part skin for the new CRJ1000 apron and uplock (see Fig. 4). Validatory simulations showed that this change significantly improved access issues during final assembly. The drilling jig was modified in accordance with the new skin format. This required raised areas on the backplate which allowed the diaphragms and beams to be mounted in the correct position, allowing for the skin thickness that would be added after the main structure had been attached to the fuselage. Clamping arrangements were also modified to suit the new skin layout. This required repositioning clamps lower down on the jig to hold the smaller skin and adding clamps to hold diaphragms, which had been positioned and held using part-to-part holes through the larger skin on the CRJ700/900 uplock.

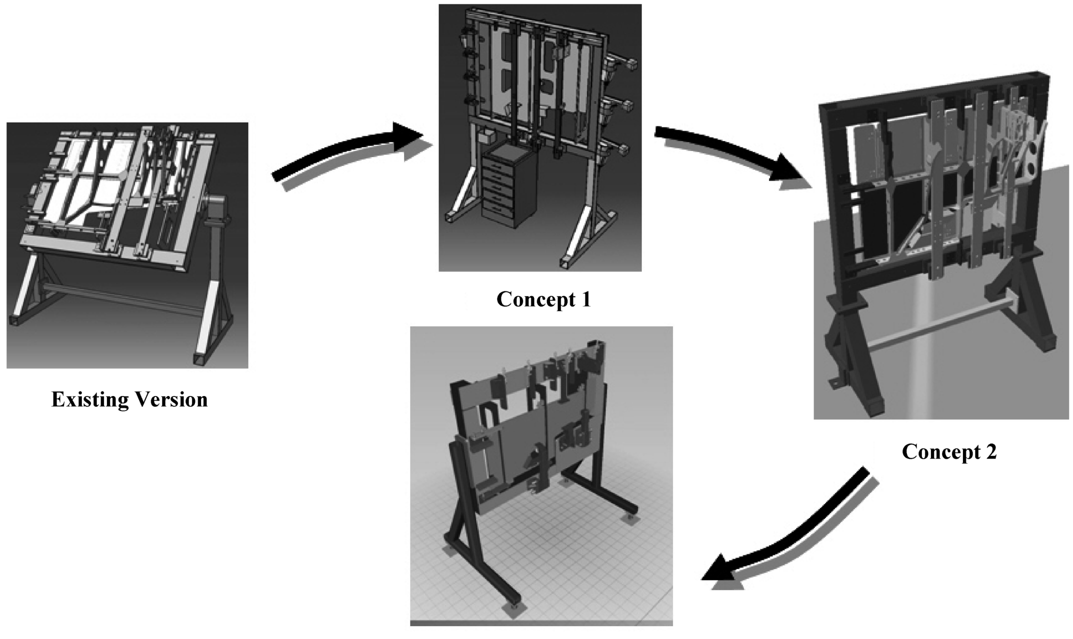


Fig. 5 Tool DFMA: development process concept for new apron and uplock assembly jig.

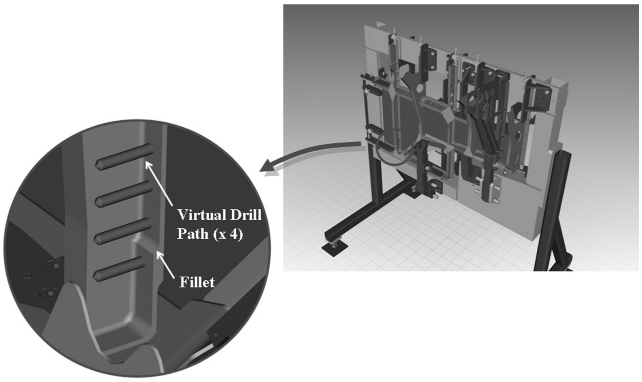


Fig. 6 Virtual drill path/hole positional check.

As well as the change required to accommodate the new skin configuration after the DFMA exercise, several issues were identified in the build method, which left room for improvement in the new process. The first was related to mounting the dogleg diaphragm (see Fig. 2). Although detachable, rigid jig guides are used during the build for mounting important pieces such as the uplocks. No jig guides have been designed into the tool to guide the dogleg. This item is locally stiff at the extreme ends but it is flexible at its center as the flanges on the edges do not continue through the bend. Although there are currently no quality or dimensional issues with the dogleg or the parts placed relative to it, mounting this part on the jig takes time and requires considerable skill on the part of the operator. Figure 5 traces the development of the new CRJ1000 jig from the existing version through two concepts to the final version. A third removable jig arm has been added to facilitate fast, accurate fitting of the dogleg. From concept 2 to the final jig design, the configuration of the jig guides was improved further by changing the guides themselves from rigid, heavy structures that have to be lifted on and off the jig to hinged arms that remain attached to the tool.

The second issue was the placement of the drill guides on the backplate of the jig. These are intended to make the drilling process as accurate as possible, as they control the position of the finished holes through the components, as well as the angle of the drill as it passes through the material. The current build has a number of locations where the hole guides have been positioned in such a way that the hole if it were drilled, it would pass through features on the structural members behind the skin, which would make it impossible to rivet and has implications for structural integrity (e.g., fillet radii on beams; see Fig. 6). At the points where this has occurred, the guides are redundant on the current jig but the build requires that the holes are hand drilled in more appropriate positions when the structure is removed from the jig. The number of holes that this affects is less than 2% of the total number in the panel, but again, this takes up more of the operator's time and it is an issue that could have been flagged if the original process had been validated using digital means. Figure 6 shows how a virtual drill run can be carried out before tool manufacture to ensure that the placement of holes can be sympathetic to riveting and structural needs. This is achieved by using virtual drill paths to ensure that proposed hole positions avoid features such as fillet radii. The tooling designer can tailor the hole spacings to suit feature variations, as well as structural and build requirements.

A significant amount of the operators time is spent moving around his work area retrieving parts and fasteners as well as interacting with the jig and hand tools. Parts are currently delivered to the workstation in containers that require sorting before and during assembly. Fasteners are retrieved from bins and carried to the jig when required. Pneumatic tools for securing wedge locks and drilling holes are on station but have no fixed location for storage when not in use. Drilling operations also require several bit changes for various hole sizes as the apron and uplock assembly comes together. Concept 1 in Fig. 5 shows how storage for small parts and fasteners could be moved to the jig and how attachments for pneumatic tools could be added to the jig structure. Fig. 7 shows a conceptual work cell layout with improved part visibility and access. From a lean practice point of view, this eliminates the nonvalue added activities arising from unnecessary movement around the work area.

C. Process Improvement: Integrated Jig For Drilling and Riveting

A full lean assessment of the drilling and riveting jig functions for the current apron and uplock assembly revealed that the addition of hinges to the rigid backplates on the new tooling for the CRJ1000 means that the structure could be riveted without being removed from the drilling jig. Figure 8 shows two snapshots from the digital assessment of this functionality. The integration of drilling and riveting functions in one jig has several advantages. The time required to remove and remount structures between drilling and riveting stations has been eliminated thereby reducing recurring assembly costs. With real estate in the production environment at a premium, space has been saved as the riveting station is no longer required. More important, minimizing the amount of movement and work required as the panel comes together increases the likelihood of achieving design tolerances as the parts spend more time under the control of the jig and less time in transit between jigs and work stations.

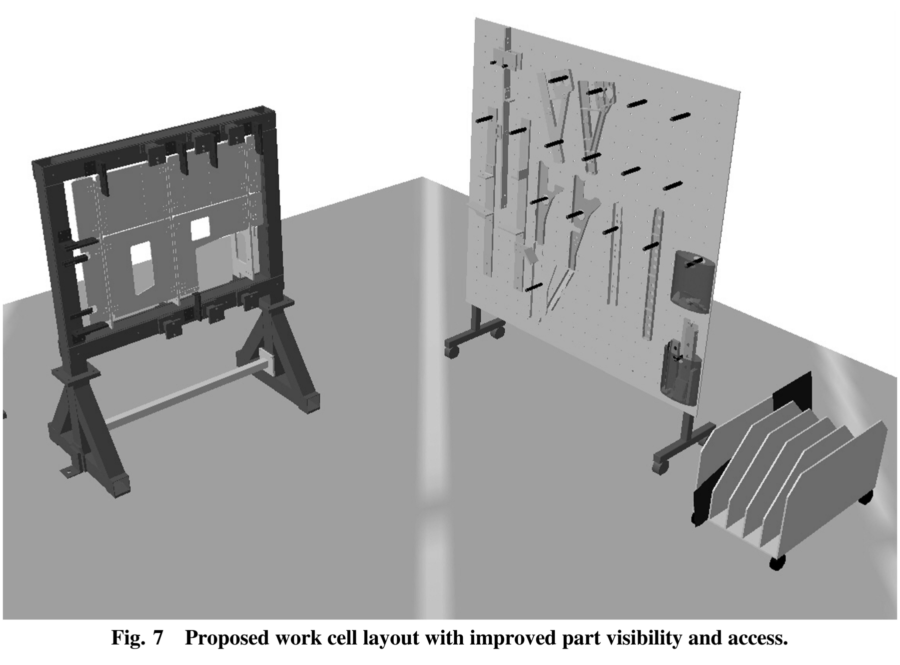


Fig. 7 Proposed work cell layout with improved part visibility and access.

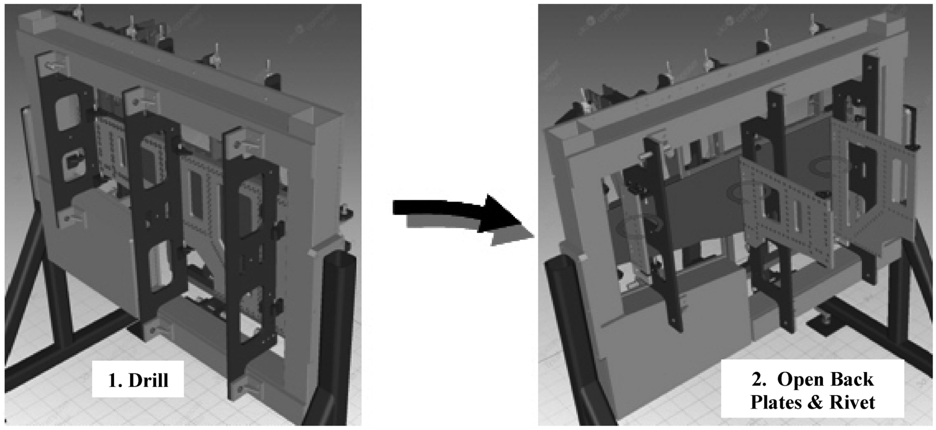


Fig. 8 Backplate design to facilitate drilling and riveting on one tool.

D. Integrated Time and Cost Measurement

1. Time Measurement

The uplock build was divided into three operations dealing with the three main stages of the drilling operation for the panel. Each of the stages was subdivided into a series of repeated standard tasks, which are required to complete the assembly. The first stage was fitting the skin and uplock brackets to the jig. The second stage was fitting the main structural items to the inner face of the skin and the final stage was the attachment of the minor brackets and gussets required to hold the structure together. The standard activities included in the setup time, completion of the work, and signing off were: clock on job, prepare tools, review paperwork, locate, fix, drill, remove, deburr, refix, install fastener, and call inspector/stamp paperwork. The location activities were further subdivided into activities related to small, medium, and large parts for timing purposes. The change in the assembly times between the existing CRJ700/900 uplock and the conceptual CRJ1000 uplock were determined by simulating the performance of the redesign and repopulating the procedural times for each activity. Table 1 shows the final outcome in terms of assembly time differences between the CRJ700/900 uplock and the CRJ1000 uplock assembly times.

2. Cost Measurement

A breakdown of the current cost for the manufacture of the CRJ700 jig revealed that 56% of the final cost for the jig is accumulated in the manufacture of the tool. This shows that any improvements in new CRJ1000 jig that facilitates more cost effective manufacture will have the greatest impact on final cost. The use of digital manufacturing methods, including animated simulations, could also have a significant affect on the design process, which accounted for 35% of the total jig cost, giving another potential cost saving in this area. The remaining 9% of total jig cost was for materials. Table 2 shows the net change in cost having taken into account the change in these main cost areas for the new CRJ1000 apron and uplock assembly. This reduction cost corresponds to a net 4.9% reduction in the overall cost of the CRJ1000 jig.

The majority of this saving is due to a reduction in the number of design iterations, which was achieved by using knowledge acquired through the use of simulations generated using digital manufacturing methods. This shows the extent to which management learning has been improved through the use of the simulations during process design. The manufacturing and material costs have increased marginally because of the necessary design changes required after the DFMA exercise, resulting in a new assembly procedure for the skin (i.e., the addition of the dogleg support feature and hard stops on the upper half of the jig). These were offset by cost reductions due to the removal of redundant features (e.g., the skin retaining clamps and jig frame spindles).

Table 1 Time differences between CRJ700 (actual) and CRJ1000 (simulated) uplock build times

Assembly stage	Build time differences
Skin and uplocks	−16.00%
Diaphragms and structure	−3.22%
Brackets and gussets	−1.86%
Total	−5.20%

Table 2 Cost changes for CRJ1000 uplock jig relative to CRJ700/900 jig

Increase in cost	——
Material	+1.1%
Manufacture	+1.1%
Decrease in cost	——
Design	−5.8%
Material	−0.8%
Manufacture	−0.5%
Net change in cost	−4.9%

V. Discussion

The application of DFMA principles to the existing panel design identified three areas for potential improvement. Mounting the finished panel to the fuselage of the CRJ700 and 900 fuselages is a time consuming process where the limited access around the panel makes it difficult for the operator to attach it accurately. Configuring the skin in two pieces improves access allowing faster and more accurate fitting. A digital assessment of the part count for the apron and uplock showed that it would be possible to reduce the part count by machining a butt strap and packer for one of the main diaphragms from a single billet of material. Time losses because of part-fitting issues arising from paint buildup on edges is a problem in practice, but this cannot realistically be simulated as the CAD data will not include paint. This demonstrates why the area between curve 5 and standard hours is required in Fig. 1. There will always be differences between the simulated and actual processes and although software packages such as 3DCS can take account of possible dimensional differences, parameters related to manual processes, such as the application of paint, use of sealants, etc., are difficult to predict accurately in the digital world.

The use of a digitally driven DFMA approach to the tool format resulted in several improvements. The change in skin format from a one- to a two-piece configuration required several changes to the jig. Although this required a net increase in materials (e.g., clamps), the new assembly format will significantly improve the final assembly process by reducing assembly time and improving build accuracy. Other practicalities, such as faster mounting of the dogleg diaphragm, drill-path checks, integrated drilling, and riveting on one jig and work cell layout, have all been addressed and validated using simulation. At this stage, the more tangible benefits of the approach taken are in the improvement of the quality of process design information and interdisciplinary communication. These parameters are difficult to quantify but the real benefit and validation of the approach will come when the CRJ1000 apron and uplock goes into production.

By building time and cost measurement functions into DPE, it was possible to quantify time and cost savings for the panel build based on drilling-jig assembly time as well as the cost of the jig itself. This method allows the process designer to compare the relative merits of different conceptual processes and tooling formats, which is important during the early stages of process design where changes can be made relatively quickly with little or no impact on design costs. The outcome showed that the nonrecurring cost of jig design and manufacture could be reduced by 4.9%. This was due mainly to a 25% reduction in design hours as the number of design iterations was reduced by 60%, which is included in the 5.8% reduction in the design cost listed in Table 2. At each stage of the process, methods engineers and tooling designers were able to make faster, better-informed decisions as the process and jig design evolved through the use of animated build simulations. Having estimated the non-recurring development cost of the CRJ1000 jig relative to its predecessor, the change in the recurring cost of the assembly time for the new CRJ1000 apron and uplock was determined. The 16% time reduction in the time taken to mount the skin and drill the uplocks is due to the omission of the top half of the uplock skin. The saving comes mainly from the improved handling characteristics of the smaller skin. The additional dogleg bridge was the most important aspect of the jig design in terms of the 3.22% timesaving for the operations required to mount the diaphragms and structural items. This is the most time consuming of the three main operations. This process relies on the skill of the operator for positional accuracy. The addition of the third bridge insured that the time taken to complete this operation was reduced as the dogleg was jig located. There is a relatively small improvement of 1.86% in the time required to complete the final stage of the drilling process. This where the smaller items such as brackets and gussets are fitted. Although minor changes were implemented in the assembly sequence for these parts, it had little impact on the overall time reduction.

VI. Conclusions

The use of the jig and build process for the new CRJ1000 uplock has been improved by reducing the number of design iterations and improving the levels of concurrency in the process design activities. Jig usage and work cell function have been improved ergonomically and jig design and panel build have been made leaner. This was achieved through the integration of drill and rivet functions in one fixture and improved access during final assembly through the use of a two-piece skin format. The use of digital manufacturing methods in the support of these activities has achieved a predicted reduction in panel assembly time of 5.2% and a reduction in tooling cost of 4.9%.

The use of digital manufacturing methods in the development of the new process and hardware formats for the CRJ1000 apron and uplock assembly is not an automatic process. It still requires inputs from the various disciplines involved in producing aerospace structures. In addition to the more tangible time and cost benefits detailed in the preceding sections, digitally assisted knowledge acquisition using an integrated digital manufacturing framework improved the quality and timeliness of the decision-making process and improved communication and understanding between disciplines.

References

[1] Butterfield, J., Curran, R., Watson, G., Craig, C., Raghunathan, S., Collins, R., Edgar, T., Higgins, C., Burke, R., Kelly, P., and Gibson, C., "Use of Digital Manufacturing to Improve Operator Learning in Aerospace Assembly," *7th AIAA Aviation Technology, Integration and Operations Conference*, Belfast, Northern Ireland, U.K.,AIAA Paper 2007-7865, 18–20 Sept. 2007.

[2] Garbaya, S., Coiffet, Ph., and Blazevic, P., "Experiments of Assembly Planning in a Virtual Environment," *Proceedings of the 5th IEEE International Symposium on Assembly and Task Planning*, Besançon, France, Inst. of Electrical and Electronics Engineers, Piscataway, NJ, 10–11 July 2003, pp. 85–89.

[3] Aboulafia R., "Industry Insights: The High Cost of Building Jets," *Aerospace America*, Vol. 44, No. 4, April 2006, pp. 13–15.

[4] Butterworth-Hayes, P., "Moving South: Trends in Outsourcing Aircraft Manufacturing—China," PMi Media, Ltd., Fort Wayne, IN, Sept. 2008http://www.pmi-media.com/downloads/low-wage-global-aerospace-study.pdf [retrieved 25 March 2009].

[5] Womack, J. P., Jones, D. T., and Roos, D., *The Machine That Changed the World*, HarperCollins, New York, 1991.

[6] Womack, J. P., and Jones, D. T., *Lean Thinking*, Simon and Schuster, Upper Saddle River, NJ, 2003.

[7] Bicheno, J., *The New Lean Toolbox: Towards Fast, Flexible Flow*, PICSIE Books, Buckingham, England, U.K.,2004.

[8] Walton, M., *Strategies for Lean Product Development*, The Lean Aerospace Initiative Working Paper Series, WP99-01-91, MIT Press, Cambridge, MA, Aug. 1999.

[9] Murman, E. M., "Lean Aerospace Engineering," 46th AIAA Aerospace Sciences Meeting and Exhibit, AIAA Paper 2008-4, Reno, NV, 7–10 Jan. 2008.

[10] Binder, J., "Systems and Software: Manufacturing Systems For All Seasons," *Aerospace America*, Vol. 42, No. 7, July 2004, pp. 20–22.

[11] Butterfield, J., Crosby, S., Curran, R., Raghunathan, S., McAleenan, D., and Gibson, C., "Optimization of Aircraft Fuselage Assembly Process Using Digital Manufacturing," *Journal of Computing and Information Science in Engineering*, Vol. 7, No. 3, 2007, pp. 269–275.

[12] Gauthier, B., Dewhurst, P., and Japikse, D., "Application of Design For Manufacture and Assembly Methodologies to Complex Aerospace Products," 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL,AIAA Paper 2000-3404, 2000.

[13] Boothroyd, G., Dewhurst, P., and Knight, W., *Product Design for Manufacture and Assembly*, 2nd ed. CRC Press, Boca Raton, FL, 2002.

[14] Delchambre, A., *CAD Method for Industrial Assembly: Concurrent Design of Products, Equipment and Control Systems*, 1st ed., Wiley, New York, 1997.

[15] Butterfield, J., Crosby, S., Curran, R., Raghunathan, S., and McAleenan, D., "Optimization of Aircraft Fuselage Assembly Process Using Digital Manufacturing," *Journal of Computing and Information Science in Engineering*, Vol. 7, No. 3, Sept. 2007, pp. 269–275. doi:10.1115/1.2753879