CASE STUDIES IN AIRCRAFT MANUFACTURING AUTOMATION

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Abstract

The development and implementation of automated equipment and systems at the Boeing Commercial Airplane Company are described in case by case scenarios. A variety of manufacturing operations are covered including fabrication of metal parts, assembly of aircraft structure, building of interior panels, and the automation of electrical wiring operations. The role of robotics in the development of these special equipment packages is outlined.

Introduction

Aerospace manufacturing has entered into a period of change that is unequaled since the days of World War II. The rate of change is becoming more revolutionary than the evolutionary nature of our post war progress. The need for improved productivity to meet global competitive challenges is fueling this revolution and deregulation of the U.S. airline industry has been a catalyst in focusing commercial aircraft manufacturers' attention on product cost reduction. With deregulation, surviving airlines have had to drastically change traditional business practices to reduce operating costs. Now they are asking manufacturers, "What are you doing to reduce the cost of your product?" Responding to this question has caused self-examination and evaluation of how we design and build our aircraft. It has stimulated the engineers as well as the manufacturing functions to elevate cost to a new, higher level of priority. This in turn is generating change throughout the organization. Changes on the factory floor are addressed in this paper.

Early on, building airplanes was a relatively simple proposition. All operations were performed in the same factory building. Design and manufacturing were located close together which made design-fabrication problem resolution and change introduction comparatively simple. The old cloth wing was constructed by a cadre of seamstresses (Figure 1). Master mechanics took products from design through completion. Little process information was required to be transferred to perform the work - the necessary expertise and knowledge were embedded in the minds of the craftsmen doing the job (Figure 2) working shoulder to shoulder with the designer.

As the industry grew, our product and the technology to build it became much more complex. The old ways of doing business could not meet the requirements of increased complexity and reliability. Many intermediate steps evolved between the design concept definition and the actual product production. Various engineering technologies were expanded along with system and structural testing functions to support increasing product sophistication for improved performance as well as flight safety and longer service life. Manufacturing functions also grew. Planning, tool design, tool fabrication and production control, to name a few, were created to cope with production complexities. This growth forced geographic and organizational separation making communication and coordination more difficult and costly.

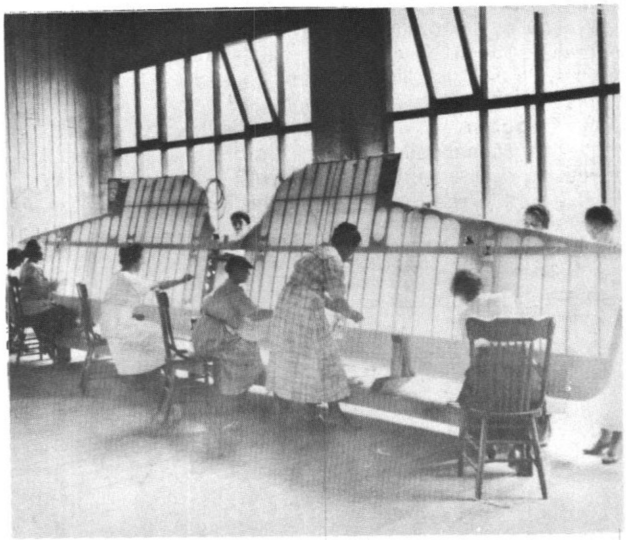

FIGURE 1. Wing Covering, Circa 1918, The Boeing Company

FIGURE 2. Small Part Shop, 1922, The Boeing Company

The continual drive to reduce costs using mechanization and automation is forcing the return of a closer working relationship between all functions. For example, automated manufacturing systems on the factory floor depend on the designers creating producible designs compatible with the capabilities of the specific system as much as on the development of the processes and equipment necessary to implement these systems.

Improved productivity has become a common goal for all functions. However, the ability to measure productivity gains is not always obvious. The most frequent measure of productivity has been the direct labor content of an operation. Improvements in productivity have been aimed at reducing this labor content. Analysis now confirms that the direct labor content is not always the significant cost factor that it once was (Figure 3). Nevertheless, the methodology of looking at productivity improvements has tended to concentrate on process technology with a justification based on direct labor reduction. The result is that technology has sometimes been applied indiscriminately. The phrase "A solution looking for a problem" thus has validity when it comes to some automation projects. Not enough knowledge or information system capability was available to integrate early automated systems. These "islands of automation", however, are a necessary learning experience and serve to identify potential benefits as well as the requirements needed for more optimized systems. Increased system optimization will occur as improved information integration becomes available along with material handling systems and faster computing systems.

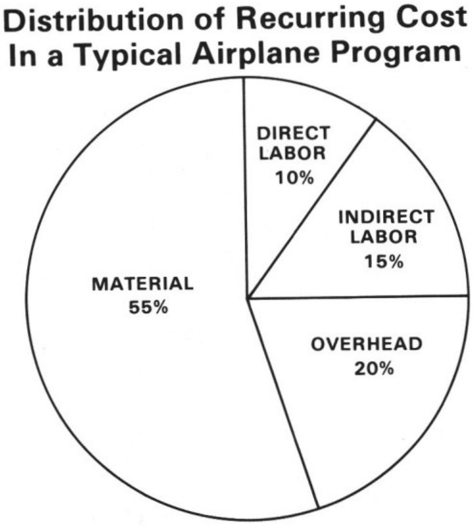

FIGURE 3. Typical Recurring Cost Distribution

Successful individual projects, however, have been completed or are in various stages of development and implementation at the Boeing Commercial Airplane Company, and several examples will be described.

Case By Case Scenarios

An example of an early approach to automation/mechanization is wing skin fabrication. Wing components are considered "lifeline" items. In addition, the size of large aircraft wing parts for the 747 aircraft led to the decision to establish a dedicated facility to handle wing skins and spar chords ranging in length to 105 feet. Although a large portion of wing panel fabrication was, and still is, accomplished by numerically controlled (N/C) machines such as skin mills, hand sanding was used to meet the finish requirement (Figure 4). Fatigue considerations require that all machining marks and mismatch be sanded out. Through the development of a flexible abrasive media and in conjunction with a machine tool manufacturer, a unique, highly successful machine now completes the sanding operation, both sides at once (Figure 5). This has improved quality and consistency of the sanding process in addition to producing a cost saving.

FIGURE 4. Blending Cutter Mismatch Marks On Wing Skins

Forming wing panels to the required aerodynamic contours was a labor intensive, difficult process using manual incremental "bump" forming or high cost tooling for "creep forming" at elevated temperatures. Most skin panels for the commercial models require both spanwise and chordwise contouring. Each panel is different but must match the adjacent panel exactly upon assembly.

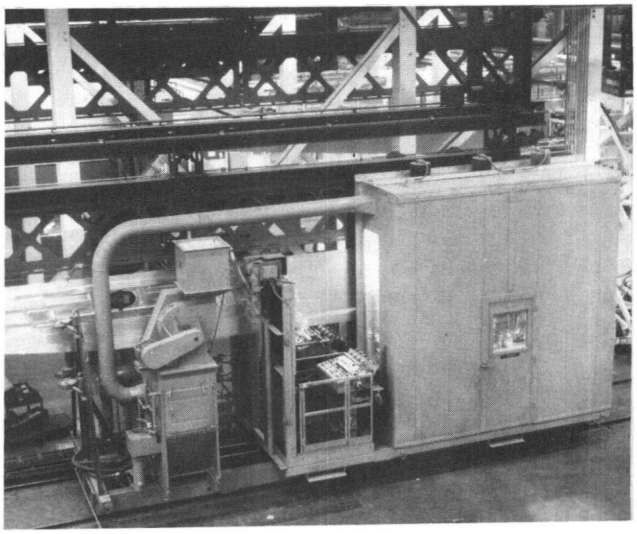

FIGURE 5. Wing Skin Sanding Machine

Presented with this productivity and producibility challenge, automated N/C shot peening equipment was developed to form wing skins (Figure 6). Both sides of the skin are peened at once which forms the spanwise contour in a single pass through the machine. A similar but separate N/C system is used for the chordwise contour. The skins are hanging vertically when processed through these machines. The overhead handling system used is the same one used to move skins through the sanding machine. These two peening machines and the associated handling system have given us an 8 to 1 improvement in productivity over previous methods. Automated control of the shot flows and intensities has improved the consistency of the forming.

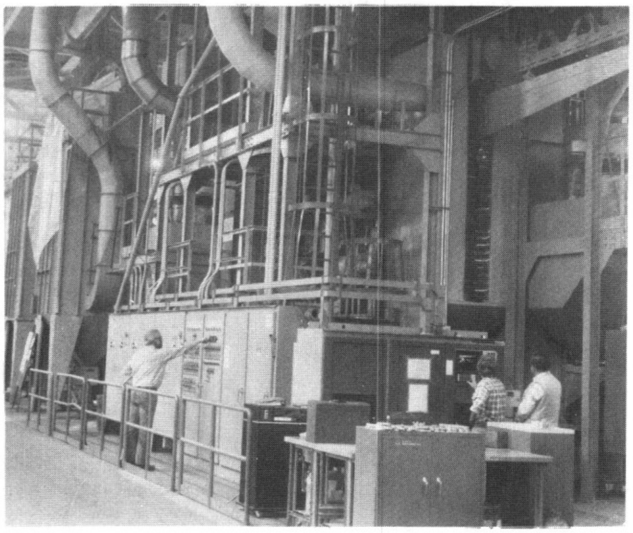

FIGURE 6. N/C Shot Peening Machine

The next example looks at an approach to automation which is currently being implemented into production. The task has been to devise methods to automate the assembly of aircraft structure. In this example we are using a robot system to drill the strut/skin assembly of the 737-300 engine strut. The operation is labor intensive and requires the drilling of 1100 holes through both aluminum and aluminum/steel combinations. Hole diameter tolerance is .0015 inch.

A gantry robot has been equipped with special multiple end effectors which will drill, countersink, inspect for hole dimensions, and install fasteners as required (Figure 7). The drill motor control system is unique in that it has the ability to monitor the cutting tool performance and provide corrective action. For example, a sensor for detecting dull or broken drills is integrated into the system. Hole inspection is by a ball gauge system attached to the drill motor to assure that the precision holes meet dimensional requirements before the fasteners are installed. Hole dimensions are recorded. A significant reduction in floor to floor cycle time is forecast for the system.

The third example concerns the automation of electrical wiring operations. The typical aircraft contains hundreds of wire bundles and the trend is toward increasing numbers in the newer models. Automation of the wire harness assembly process is a difficult and complex task because of all the handling, sorting, and coding operations which must be performed on a large number of wire segments (Figure 8). The 747, for example, contains 720,000 feet (136 miles) of wire per airplane. This wire must be cut into 42,968 segments, formed into 1,015 bundles, and terminated in 5,024 connectors.

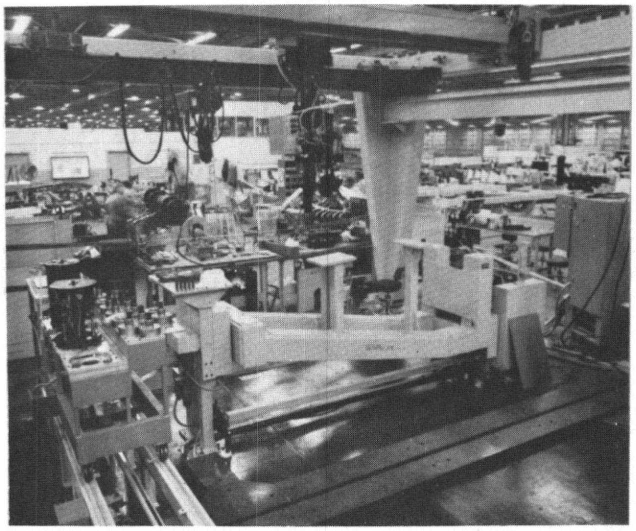

FIGURE 7. Engine Strut Assembly Robot

FIGURE 8. Conventional Wire Bundle Routing

The goal was to automate all of the wire processes where a reasonable payback could be shown. Due to the complexity of the processes we chose an incremental approach. The first successful attempt to automate a part of this process was a computer controlled harness maker (CCHM) which has been in production for 10 years building wire bundles for the 747. The CCHM is programmed to route the harness wire in one continuous strand by running it from one connector location peg to another. Using this equipment, wire is routed twice as fast as the manual forming it replaced.

The next improvement depended upon the ability to mark the wire for identification. Boeing engineers saw an ink-jet system marking beer cans at a trade show and decided that the technology could be adapted to wire. Boeing thus became the first company to use a non-contact ink jet printing system to mark aircraft wire which had previously required hot stamping, tape or sleeves. The ink jet can print wire part numbers on the wire at 3-inch intervals up to 350 feet per minute and can change from one number to the next on the fly.

A combination of the technology and software developed for the computer controlled harness maker and for high speed continuous filament ink jet marking was used to develop the computer aided hand forming system (CAHF). The CAHF system uses a TV monitor to instruct the operator on the gage and type of wire to route and the location of the pegs to which the wire is to be routed. The screen is then advanced to the next formboard coordinates with a switch. The operator routes continuous strand wire and twisted constructions directly from wire supply spools. The CAHF system represents an optimum blend of man and machine with the computer handling the tedious data hookup and sorting task. CAHF can handle more wire types and sizes than the CCHM and is just as fast but requires only a fraction of the capital investment and maintenance required by the CCHM.

Another improvement in wiring operations is the automated cut, coil and tie (CCT) system (Figure 9) which is designed to automate the handling and sorting of either precoded continuous filament single conductor wire or uncodeable wire into wire groups. (Uncodeable wire is defined as irregular-surfaced, multi-conductor wire.) The CCT system will automatically apply labels to the uncodeable wire as it is processed. Direct cost savings for the system are achieved from several sources. These include reduced labor; automated wire selection, coil processing, and wire bundle collating; and increased usage of high speed reel to reel ink jet coding. A significant part of the savings will come from automating the labeling of the multi-conductor uncodeable wire.

The final scenario to be covered is an excellent example of our current systems methodology in automation. It not only integrates an entire system but also can be accomplished in discrete identifiable steps. The technology area, the manufacture of airplane interiors, is one which is labor intensive and highly customized by the desires of the airline customer.

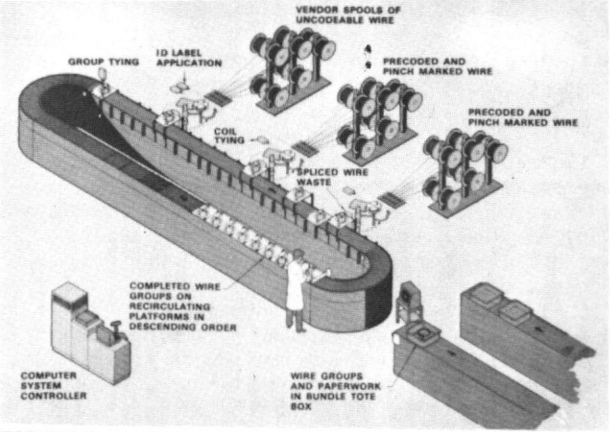

FIGURE 9. Sketch of Automated Cut, Coil and Tie System

In any given year, Boeing will manufacture over 20,000 sidewall and ceiling panels, 15,000 stowage bins and 10,000 passenger service units for four basic airplane models. The more than 350 operators of these airplanes each require unique configurations and decorative patterns for their interiors. Over 550 skilled manufacturing personnel are needed to produce these components each year. To meet the demand for customer flexibility in interiors and to reduce airplane costs, an automated interiors manufacturing facility is being implemented. This facility will consist of three centers dedicated to fabrication, panel decor and assembly.

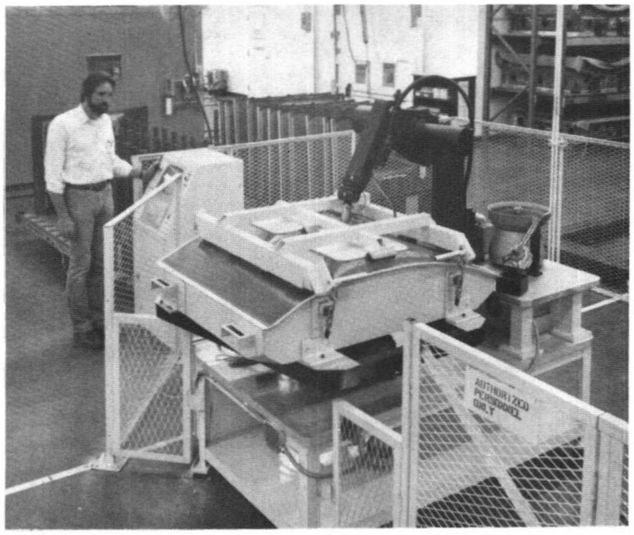

FIGURE 10. Robotic Application of Hardware Attach Stud Screws

The first phases of development for this facility were in the hardware assembly and panel fabrication areas. Prior to 1982, threaded fasteners used for attaching hardware to sidewall and ceiling panels were applied using a hand-held induction heating unit. At peak airplane rates this simple, repetitive task required more than eight workers to complete. A robotic system was developed to automate the application of these fasteners (Figure 10). Each threaded stud is retrieved from a feed bowl by vacuum pick-up and is electronically checked for the presence of adhesive. Robotic application of the thirty-one fasteners on the back of each panel requires a total of ten minutes. The robot has its own in-process quality checks and automatically signals an operator in the area if process requirements are not met. This system reduced the manual labor required to apply fasteners by 80%.

The technology developed for the stud bonding work station served as the foundation for automating the manual attachment of all hardware to sidewall and ceiling panels (Figure 11). This automated assembly effort required the development of 13 unique end effectors to properly manipulate flexible interior parts into the required position. The interchangeable end effectors are operated by a large two-arm gantry-type robot. The entire assembly process took one hour manually. The robotic workcell can produce four complete panels in that same time period.

The technology developed for the sidewall and ceiling hardware assembly workcell was then applied to the assembly of the Passenger Service Unit (PSU), a complex and laborious operation. A 757 airplane will require over sixty of these units. Similar to sidewall and ceiling hardware assembly, assembly of Passenger Service Unit hardware is to be performed by a robot using flexible geometry end-of-arm tooling. This tool is designed to change overall shape for pick-and-place operations on parts ranging in size from a single nut to a fully assembled PSU. The assembly process is now accomplished robotically in twelve minutes with only two tool changes. For a human, it normally took over an hour to assemble the sixty-three parts which make up a PSU.

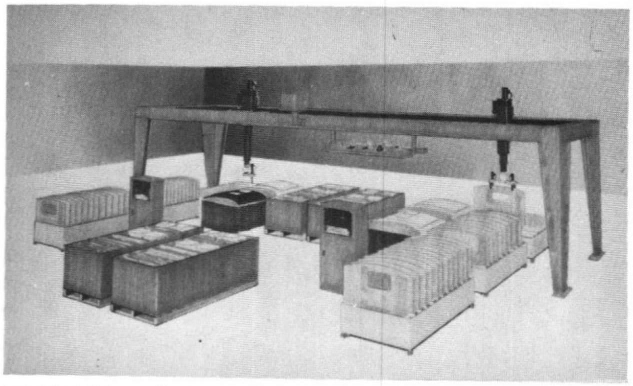

FIGURE 11. Sketch of Interior Hardware Attachment Cell

The Passenger Service Unit automated hardware assembly cell will ultimately be integrated with a Passenger Service Unit frame assembly and bonding cell and a wiring and testing cell. These cells are the next incremental follow-on steps and are currently in the development process (Figure 12).

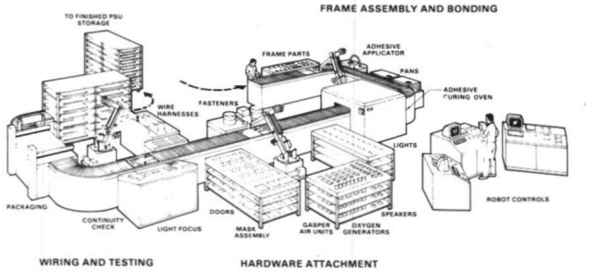

FIGURE 12. Sketch of Passenger Service Unit Assembly Cell

The three hardware assembly developments completed to date have resulted in labor savings of many thousands of manhours per year with improved and consistent quality. They also provide flexibility in our manufacturing process which allows us more responsiveness to changes in configuration due to customer airline specific needs.

Significant progress has also been made in the automation of interior panel fabrication.

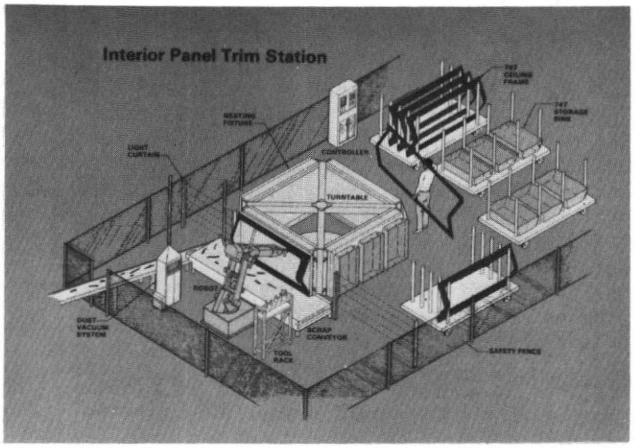

FIGURE 13. Sketch of Interior Panel Trim Station

Currently, production of interior composite panels requires manual preparation of materials prior to molding and forming operations. An automated material charge preparation station is being developed to reduce material handling operations and improve productivity. A prototype machine has demonstrated that automation of this process is possible. Once the interior composite panels are formed, they require trimming to net dimensions (Figure 13). Trimming of flat and simple contoured components has long been performed using numerically controlled routers, but compound contoured panels still requires manual trimming methods to be utilized. Manual trimming is being replaced by robotic trimming methods. In the production workcell, three-dimensional compound contoured phenolic panels are routed to net dimensions by a six-axis pedestal robot in conjunction with a four station turntable. With a feed rate of 20 inches per second, a full-size 767 ceiling frame will be trimmed in just under five minutes. The process requires no guide tooling and automatically rotates its program coordinate axes to match reference points on the part holding fixture. Total labor savings for these developments in the panel fabrication area alone will be nearly 20,000 manhours per year. Material waste will be significantly reduced.

Summary

Our automation activities have taught us some important lessons about manufacturing productivity improvement projects. Probably the most important is the need to follow a structured development methodology which is often termed a "systems approach". Solutions must be appropriate to the needs of the system and not just patterned so that a selected technology can be included. Conversely, the capabilities of the equipment used must meet the requirements of the job to avoid costly second operations. For a part to be successfully manufactured, designs must be compatible not only with the major equipment but also with the software capabilities and limitations. When purchasing or designing the equipment, consideration of the total process requirements must be included. For example, inspection may be more effectively and economically accomplished if it is properly incorporated into the process.

A systems view must also be taken in performing the cost/benefit analysis of a particular solution. That means that we must specifically address the indirect costs, support labor, overhead charges, and materials handling functions in addition to direct labor, because these other costs are very often the cost drivers rather than direct labor. Both physical integration and data integration are also essential considerations for detailed scrutiny during project planning. The unexpected aftercosts required to provide a system with an interface to the data it needs to work can be substantial.

Clearly, a great deal of front end planning and teamwork is required to successfully use the systems approach. However, if proper emphasis is placed on the requirements definition and planning phases of the program, the cost of this planning is more than compensated by the reduced overall project costs, the reduced schedule problems, and the increased rate of successful implementations.

We have also identified a number of general rules governing successful projects. We must have well-defined objectives. These are essential to long-range planning and, without them, development efforts are often disjointed. A top-down commitment is important to ensure that the long range plan is not subordinated by near-term concerns. We must be prepared to invest in the enabling technologies required for successful automation and we must avoid applying technology just for the sake of technology or the appearance of doing something. Bottom-up implementation permits small subsets of the final systems to be constructed independently, allowing benefits to be achieved incrementally and making each project a manageable size. Using this approach, errors are small, quickly fixed, and overall disruption is minimal. Participation by people at all levels is essential. The people working in an area have the best understanding of the problems and how to fix them.

Concerning the utilization of robots, we are using them where their features are appropriate to the task but we have learned not to implement "robots by rote". That is because robots do not fit all applications. They are not panaceas nor are they the only means of automating a process. Robots should be considered as part of an integrated system rather than looked upon as stand-alone devices. Additionally, robotic technology must be matched to the needs of the application and not the reverse. To increase the range of applicability of robots we forsee the need for additional developments in robotics technology, particularly in the areas of offline programming and vision systems.

The automation scenarios are typical of what is being done at Boeing to continue to meet cost and quality challenges. Extensions of these developments plus others in progress will be included on our new airplane models. Improved productivity to reduce product cost is being worked in conjunction with attaining even higher quality performance in every facet of our organization.

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