Digital Twins in the Context of Digital Transformation

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ABSTRACT

Spirit AeroSystems' investments developing and deploying digital twin related technologies in aerostructures engineering and manufacturing have resulted in positive progress towards the principal objective of lowering overall production cost structures by accelerating the learning curve in program launch and recurring operations. A second but equally important goal, collapsing the program concept-to-industrialization span, has also been achieved as the scale of digital twinning proliferates to multiple segments of the lifecycle.

Through demonstrations of various scope across multiple programs, Spirit has validated proof of value for an assortment of tool sets and techniques as well as identified key technologies for further investment and maturation. These demonstrations, several of which are on-going, address a diverse set of digital capabilities in areas ranging from model-based systems engineering and general trade-space investigation to design for manufacture, human process modeling, resource modeling, discrete event simulation, and facility definition and design. Additionally, several specific data transformation and transmission topics that are critical to the success and long-term integrity of the concomitant digital thread have been addressed.

Spirit's progression of digital twinning efforts explains the evolving strategy, execution, and results that impacted direction of subsequent endeavors. From early efforts connecting assets and collecting data for monitoring process health, Spirit was able to move to larger scale initiatives; notably, advanced product development aircraft studies, multi-scale supply chain collaboration demonstrations, IIoT informing constraint-based factory scheduling, and a high-rate, low-mix serial production line (re-)design. This historical background sets the stage for lessons learned from a digital (and physical) transformation effort on a high-rate, high-mix legacy sub-assembly production line and Spirit's foundational enterprise digital transformation initiative called Spirit ONE™.

1.0 INTRODUCTION

A position paper released in cooperation between the American Institute of Aeronautics and Astronautics (AIAA) and Aerospace Industries Association (AIA) in 2020 titled *Digital Twin: Definition & Value*, defines a digital twin as "A set of virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value." [1]. It further distills this down to an abbreviated form stating that a digital twin is a "virtual representation of a connected physical asset." In either case, an essential characteristic of a digital twin is the existence of a physical thing. Without that thing, the virtual information is simply a digital model or representation.

Spirit AeroSystems has been developing and deploying digital twin related capability in aerostructures engineering and manufacturing for decades. In some instances, the focus is on creating sophisticated digital models that can be used to accurately simulate real-world conditions to help concept and pre-plan with greater fidelity. In some cases, the motivation has been to capture and learn from data produced during factory operations and through analysis gain insights to make smarter decisions faster. No matter the application, the focus points to the principal objective of lowering overall production *cost* structures either in program launch or recurring operations, or both. A second but equally important goal, collapsing the program concept-to-industrialization *span*, can also been achieved as digital twins proliferate to multiple segments of the lifecycle.

Through demonstrations of various scope across multiple programs, Spirit has validated proof of value for an assortment of digital modeling and twinning tool sets and techniques. The demonstrations address a diverse set of digital capabilities in areas ranging from model-based systems engineering and general trade-space investigation to design for manufacture, human process modeling, resource modeling, discrete event simulation (DES), and facility definition and design. Several specific data transformation and transmission topics that are critical to the success and long-term integrity of the concomitant digital thread have also been addressed.

From early efforts connecting assets and collecting data for monitoring process health, Spirit was able to move to larger scale initiatives; notably, advanced product development (APD) aircraft studies, multi-scale supply chain collaboration demonstrations, Industrial Internet of Things (IIoT) informing constraint-based factory scheduling, and a high-rate, low-mix serial production line (re-)design. This historical background sets the stage for lessons learned from a digital (and physical) transformation effort on a high-rate, high-mix legacy sub-assembly production line and Spirit's foundational enterprise digital transformation initiative: Spirit ONE™.

The sub-assembly line use case offers a unique example from which to explore the role that digital twinning is playing in transforming highly manual manufacturing into a modernized, more automated production line. A number of ground rules were established at the outset of that project to provide scope limits and guardrails. Chief among them were that no engineering design changes to the parts would be permitted and that the new process would be introduced as a new greenfield line to maximize flexibility for improvement. The need to employ digital modeling and twinning techniques on this program emerged quickly as complexities of the process and some of the challenges stemming from the ground rules became more apparent.

Three primary forms of digital modeling and simulation were essential to comprehensive development of the new line: discrete event, physical process, and data process. DES was needed to adequately analyze product flow through the processes of the line and characterize constraints. Physical process modeling would enable workcell design concepting matched to the work breakdown and help identify ergonomic issues and sequence efficiency. Data process modeling would be a crucial tool in architecting innovations to successfully leverage the legacy data sources to derive digital work instructions and to utilize them throughout the dynamic orchestration of the line.

Additional beam configurations introduced to the new line acted as a stress test of the various elements and functions of each workcell and the overall production system. Manifestation of system shortcomings, even with the use of digital modeling during development, resulted several supplemental efforts review the existing digital models and identify opportunities for improvement including establishing true digital twins. It became evident that siloed digital models not linked to an authoritative source of truth (ASoT) and not connected via a robust digital thread are ultimately of limited use. This was acknowledged as an additional demonstrated need for the enterprise digital transformation initiative Spirit had already launched called Spirit ONE™.

2.0 SPIRIT AEROSYSTEMS' DIGITAL TWIN PROGRESSION

The aerospace industry has been using product design digital twinning concepts at least since the Boeing 777, the first aircraft to have been designed completely with computer aided design (CAD) tools [2]. While there are many different definitions for and interpretations of “digital twin” that span products, processes, and production systems (including the previous AIAA/AIA citation), the one commonality across all of them is data.

Beyond engineering design efforts, one of Spirit’s first attempts at digital twinning related to connecting automation assets in the factory and collecting data for monitoring process health. Through incorporation of custom scripts running on machine controllers, operations management was able to aggregate data from connected assets to report information about processes like automated riveting, composite lay-up, and autoclave runs. This effort to “connect & collect” was an initial attempt at digitally representing real factory operations and was a first rudimentary step in the data transformation process (Figure 1), related to the widely known concept of the Data-Information-Knowledge-Wisdom (DIKW) Hierarchy [3].

ACTION		EFFECT
Connect Systems	=▶	Data Collection
Analyze Data	=▶	Information
Synthesize Information	=▶	Knowledge
Act on Knowledge	=▶	Closed-loop Control

Figure 1: Data transformation is the process by which data is converted through layers of context and subsequently leveraged to improve decision making and control.

Considering data within a contextual framework (i.e., analysis) converts it into information suitable for decision making. Synthesizing such information over time through observation of cause and effect (as well as synthetic formulation and testing of various scenarios) is a means of generating knowledge. And acting on that knowledge results in a form of closed-loop control providing better and faster decision-making capability, the purpose of smart manufacturing and a primary goal of digital twinning.

A more extensive example of this principle of factory digital twinning is IIoT solution called Smart Factory Fabric (SFF) [4] first deployed as a pilot effort at Spirit in 2019. It is designed specifically to support improved decision making through situational awareness of resources – including parts, automation, and workers. The first of SFF’s three modules, Floorsight tracks the flow of fuselage panel assemblies and kits into a specific automated fastening line as well as machine cell utilization metrics which are accessible in real-time through a variety of interface options (Figure 2). Floorsight further recommends adjustments to shop scheduling based on algorithms considering a combination of Work-In-Process (WIP) and automation status along with enterprise resource planning (ERP) and supplier inventory data. Another capability within the system, OptiCrew, assigns manual jobs dynamically to shop personnel by priority, resource availability, required certifications, and skills. It uses continuously updated work progress data to synchronize manpower and material flows. And a third component, Constraint Command Center, helps to resolve a variety of schedule constraints by centralizing visibility and impact and identifying resources needed to optimally resolve the constraints. Benefits of this digital twin deployment have been estimated as:

- Up to 20% reduction in hours/unit and up to 10% increased throughput.
- Up to 25% reduction in production efficiency as a function of variation.
- Up to 20% inventory reduction and 40% improved inventory accuracy.
- Up to 10% reduction in machine downtime and improved machine utilization.

Figure 2: IIoT feeds a digital twin of factory operations enabling constraint-based scheduling.

Digital modeling and twinning were viewed as an essential tool to enable higher fidelity trade studies as Spirit began in earnest to establish advanced product development capability. This required not simply product design in a CAD environment but also the ability to take CAD product concepts and begin digitally defining options for manufacturing processes as well as overall build plans and possible factory layouts. In an integrated digital environment, these steps could be done concurrently to a greater extent than previously possible with conventional best-practice procedures. This concurrence provided two benefits: it facilitated more iterations and options to be explored in a given timeframe and thereby also reduced overall time span to arrive at high-fidelity trade study recommendations. The basis for this was dramatically improved responsiveness between engineering functions enabled by speed and quality of communication.

This capability was put into practice on a major new-generation commercial airplane study conducted internally by Spirit. The process began with establishing overall product and associated design requirements as well as project goals including structural performance thresholds and cost targets. A “digitally-enabled” integrated product team (IPT) comprised of Design, Stress, Manufacturing Planning, Research & Technology, and Operations Fabrication & Assembly initiated development of potential solutions for manufacturing a complex forward fuselage. This development process (Figure 3), which would typically consume on the order of 18 to 36 months from commencement to completion, was able to be completed in approximately nine (9) months while also resulting in an array of technical options.

This enabled optimization in the context of production rate and cost considerations over the anticipated lifecycle of the notional program inclusive factors such as non-recurring capital and tooling as well as inventory and recurring production costs as indicated in Figure 4. The end result was the front end of a digital twin for the fuselage section product, processes, and production system.

This capability was applied to a production scenario for a high-rate, low-mix re-design effort. Spirit was an incumbent supplier of spoiler products on a high-rate program, with manufacturing in a low-cost country. The customer informed Spirit the work package was to be competitively rebid with requirements for a significant cost reduction facilitated by product redesign but while also maintaining weight neutrality and interchangeability with the existing fleet for integration simplicity. The Spirit IPT utilized a set of digital tools and multiple digital twinning techniques to generate multiple hypothetical product configurations, taking them through various levels of concept maturity using quick-iteration digital design and analysis tools. Meanwhile, industrial and manufacturing engineers simultaneously assessed manufacturing processes and modeled production system concepts correlated to each of the proposed design configurations.

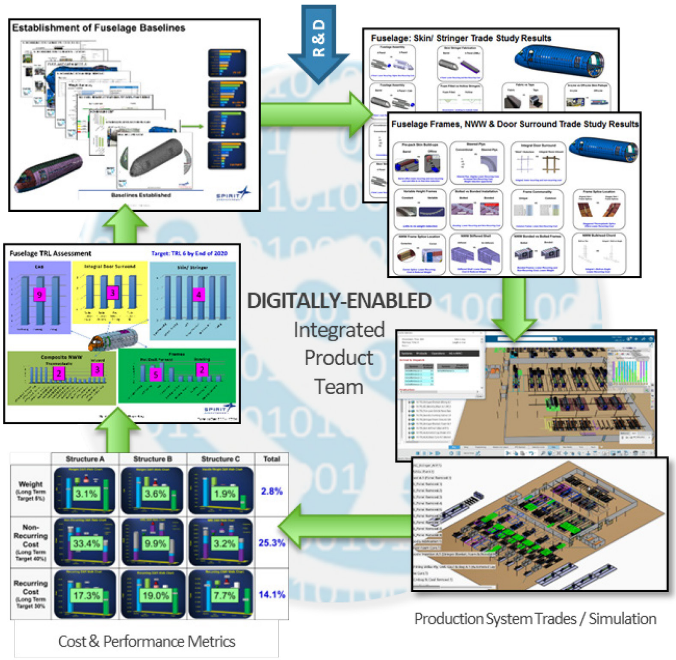


Figure 3: A digitally-enabled IPT helped create a successful comprehensive product development trade study process.

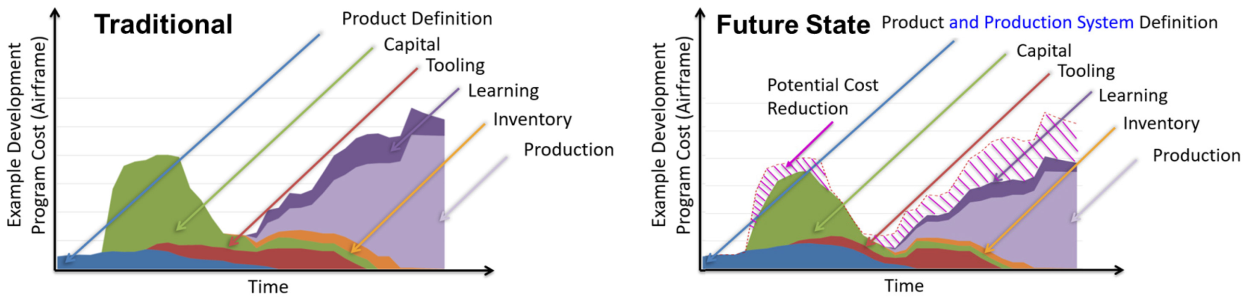


Figure 4: Substantially reduced lifecycle cost and industrialization estimates result from digital trade study and concurrent design of product & production system for a notional fuselage section.

The team also collaborated with factory and equipment suppliers early in the process to help with facility design to help keep practical factory requirements in check. The suppliers' ability to work digitally alongside the team as they were investigating manufacturing and production system options further leaned out the overall time span to determine and incorporate changes based on product redesign updates. Using digital layout design and DES tools, the team optimized the blend of automated and manual work considering ergonomics, speed and efficiency, and the overall recurring and non-recurring cost trade-offs (Figure 5). The analyses afforded by digital twins translated to details including physical sizing, quantity of cutting tables, automated cell configurations, queue sizing, and more.

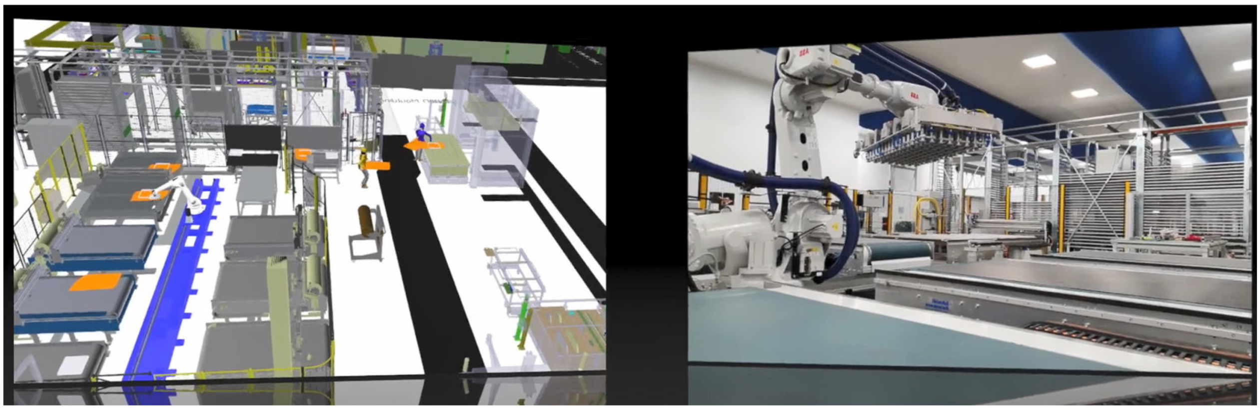


Figure 5: Digital layout and process modeling like DES enabled holistic optimization of variables in the context of ergonomics, speed and efficiency, and the overall non-recurring / recurring costs.

Digital twins representing the part, process, and production (P^3) environment, even when not fully connected to one another with a true digital thread, allowed conducting more comprehensive trade studies in fractions of the time typically required and delivered higher fidelity results that provided confidence both for Spirit and the customer. The end result was a product that met all performance requirements and came within a very small margin of the stated cost target. In this application, the customer's confidence in the product and production concept, chiefly due to the level of digital detail to which Spirit was able to demonstrate maturity, was sufficient to outweigh the minor cost offset.

This line continues to operate on the digital twin principle based on the manufacturing execution system (MES) and supervisory, control, and data acquisition (SCADA) backbone that connects all segments of the factory and manages operations at the shop floor level.

3.0 AUTOMATED BEAM LINE

The Automated Beam Line (ABL) is one of Spirit's most ambitious digital engineering and manufacturing efforts to-date. It sought to transform a commercial aircraft fuselage floor beam sub-assembly production from a mostly-manual, batch process to a mostly automated, takt-based hybrid single-piece flow approach.

It is important to understand some of the non-obvious complexities of this application. As is typical, the subject aircraft program is actually a family of aircraft that encompass a number of "minor models" that relate to vehicle sizing and configuration that affect quantity and detailed design of fuselage floor beams. In addition to minor models, any individual aircraft can contain a wide array of customer variations and options that also directly affect quantity and detailed design of fuselage floor beams. One common example of such a customer variation would be quantity and arrangement of galley and lavatory provisions throughout the cabin. Spirit builds every floor beam for every fuselage of this family of aircraft. Each fuselage will have approximately 100 total floor beams, and the configuration of each can vary from one unit to the next. So, each beam configuration comes with an associated manufacturing "recipe" requiring a dynamic and flexible factory build process.

The legacy production line (Figure 6) was a combination of multiple discrete bench positions incorporating six final build stations that could each produce a completed beam sub-assembly. While redundant in some respects and theoretically less efficient compared with a single-piece flow approach, this line configuration offered the needed flexibility to deal with the complexity of part configurations with a high degree of (engineered) variation.

Additionally, the internal customer shop for these floor beam products consumes them on a unitized (i.e., per line unit) basis from a demand perspective. While the single-piece flow line design concept was motivated partially by reductions in assembly flow time and resulting work-in-process (WIP), because the consuming shop does not operate on single-piece takt basis and is located in another building, beams completed on the ABL still must be aggregated at the end of the line for transport to the customer when tooling becomes available for the next fuselage unit (i.e. batch) of specific beams in the downstream assembly system.

Regarding detailed assembly process procedures and tools, the existing line employed substantially the same build practices as used on the original legacy aircraft program. A digital upgrade was introduced in the early 2000s involving scrolling electronic displays to provide engineering drawing information to assembly mechanics illustrating the build content for each beam. Another upgrade came when a digital projector configuration verification system was implemented after the assembly stations. Most other processes, from drilling to fastening and grommet installation, remained as they had been since the start of production in the 1970s.

Figure 6: Original floor beam production line using batch processing and parallel build positions.

3.1 Floor Beam Assembly 2.0

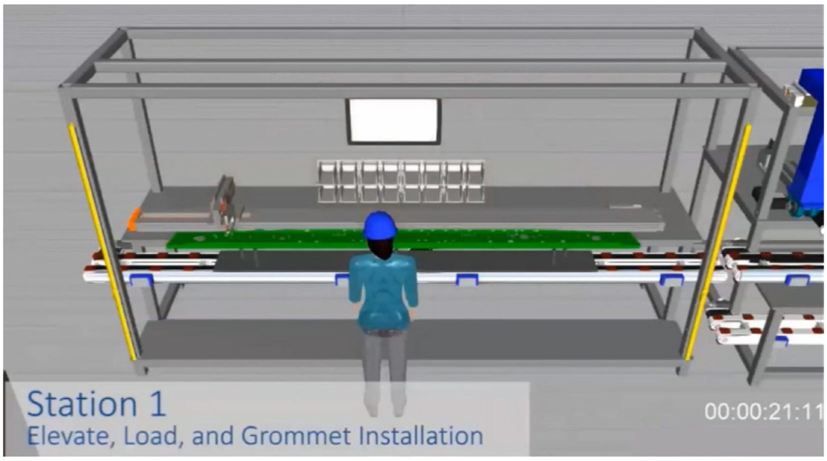
From the beginning, the stated intent was to use the ABL as a pathfinder to investigate and demonstrate Industry 4.0 capabilities that could be replicated across additional applications. A number of ground rule constraints were established at the outset of the project to provide scope limits and goalposts. Chief among them were that (unlike the spoiler example cited previously) no engineering design changes to the parts would be permitted and that the new process would be introduced not as upgrades into the existing line but as a fresh greenfield line to maximize flexibility for improvement. The need to employ digital modeling techniques on this program emerged quickly as complexities of the process and some of the challenges stemming from the ground rules became more apparent.

3.1.1 Digital Twin Methods

For this application, the aforementioned P³ view of digital twinning led to focus on three primary forms of modeling deemed to be essential to comprehensive development of the new line: discrete event, physical process, and data process. While a digital twin of the parts being produced (i.e., as-built digital record) was considered a desirable outcome, it was treated as secondary to the other three forms in terms of priority to get the line established and running successfully. Moreover, the data process modeling topic incorporates creation of a digital twin representation of the part according to the engineering definition and related process requirements.

3.1.1.1 Discrete Event Modeling

Following preliminary calculations (via spreadsheet) to define basic manufacturing process decomposition to accommodate the takt-based hybrid single-piece flow production concept, a rudimentary discrete event model of the new line concept was constructed to provide the ability to run simulations analyzing product flow and identifying constraints. Employing DES in preliminary planning stages can provide great benefit by allowing many different ideas to be virtually constructed and tested iteratively to both get initial indications of capability as well as to aid in optimizing by identifying individual constraints and eliminating or compensating for them. Figure 7 shows early iterations of DES visualization for different stations of the line.



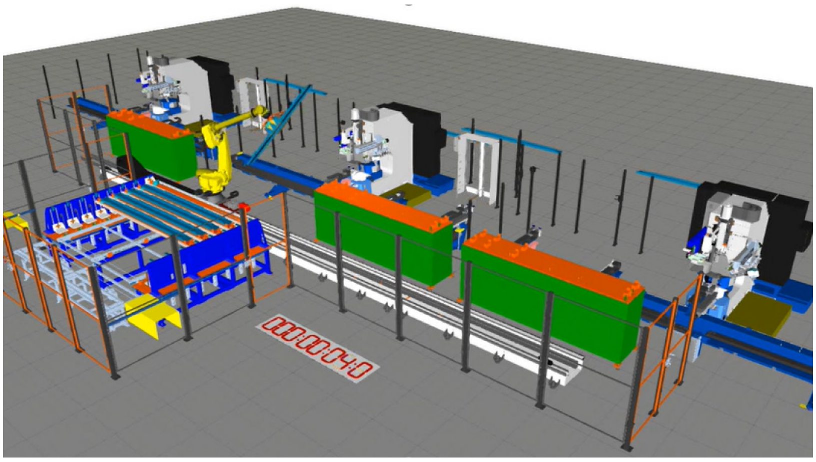


Figure 7: Use of DES in concept and design phases can help identify potential system bottlenecks.

These initial DES iterations were conducted at a relatively low level of fidelity to accommodate speed of analysis to reach quick conclusions about potential quantity of workstations and required floor space as well as to gain an elementary understanding of the scope of non-recurring and recurring costs. This included building a basis from which to facilitate early discussions with equipment and integration suppliers.

The rapid pace of the project required establishing multiple upfront assumptions about many aspects of the line, and while the discreet event model was intended to be updated and maintained throughout the life of the project (i.e., treated as a digital twin), it eventually succumbed to resource pressures and became a neglected asset. As the line design and implementation plan matured over time, the discrete event model was not updated accordingly and therefore was not being utilized as a core verification tool. It became a digital orphan instead of a digital twin.

3.1.1.2 Physical Process Modeling

Physical process modeling allowed creation of workcell design concepts that matched with initial work breakdown estimates. While it is not uncommon to plan individual workstations or even an entire production line (Figure 8) using a static computer-aided design (CAD) approach, this provides limited information beyond layouts for the purposes of defining utility requirements, transportation aisle dimensions, or safety fencing, or sometimes a volumetric verification of ceiling or crane clearances. All are important aspects of designing industrial spaces, but much more can be gained by studying the physical activity that occurs within an industrial environment.

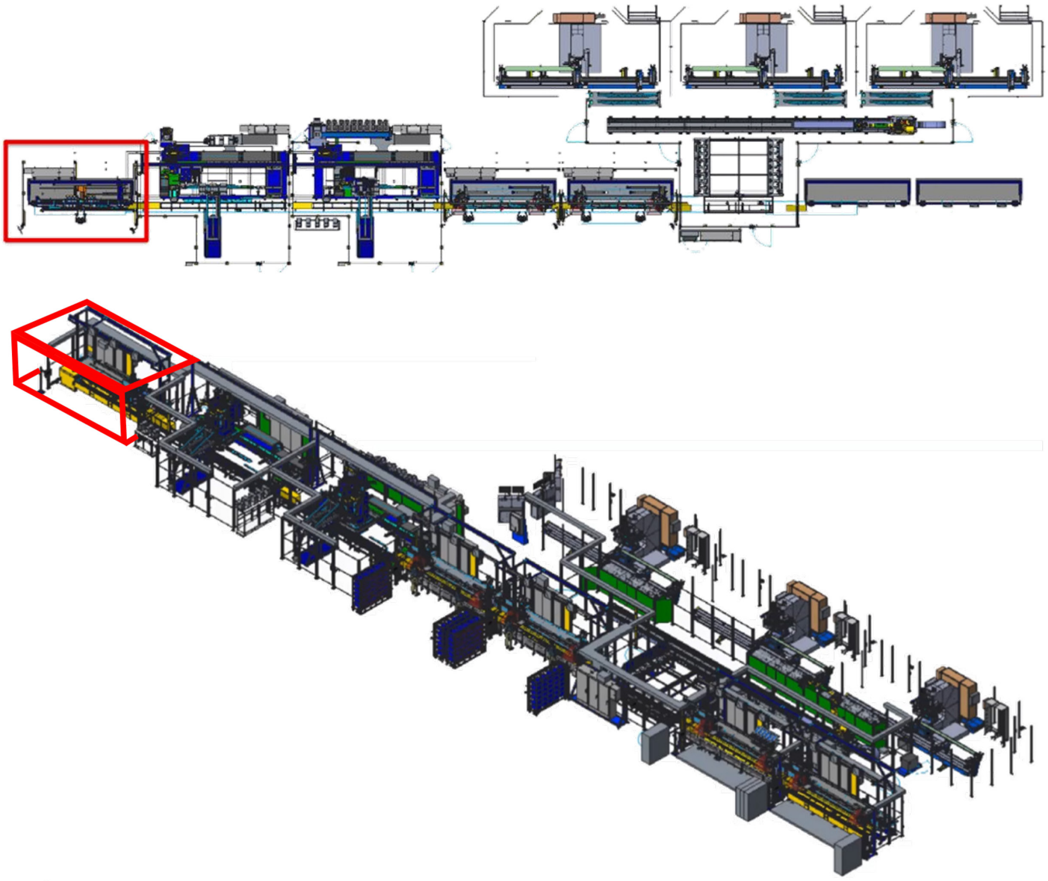


Figure 8: CAD representations of the physical systems in both 2D and 3D space help to define footprint and related static characteristics.

Spirit's industrial and manufacturing engineers worked in conjunction with system integrators to develop more comprehensive 3D process models (Figure 9) of each of the resulting five manual / semi-automated and three automated workcells. Particular attention was paid to part handling and movement from station-to-station since that can be a significant source of flow time variation and potential bottlenecking. Additional human factors considerations, such as keeping work within the "strike-zone", were investigated so as to limit awkward postures for the mechanics as well as to support general efficiency towards meeting defined takt-times. Kinematics were applied to the models as feasible given project time constraints in order to visualize sequencing and assess ergonomics.

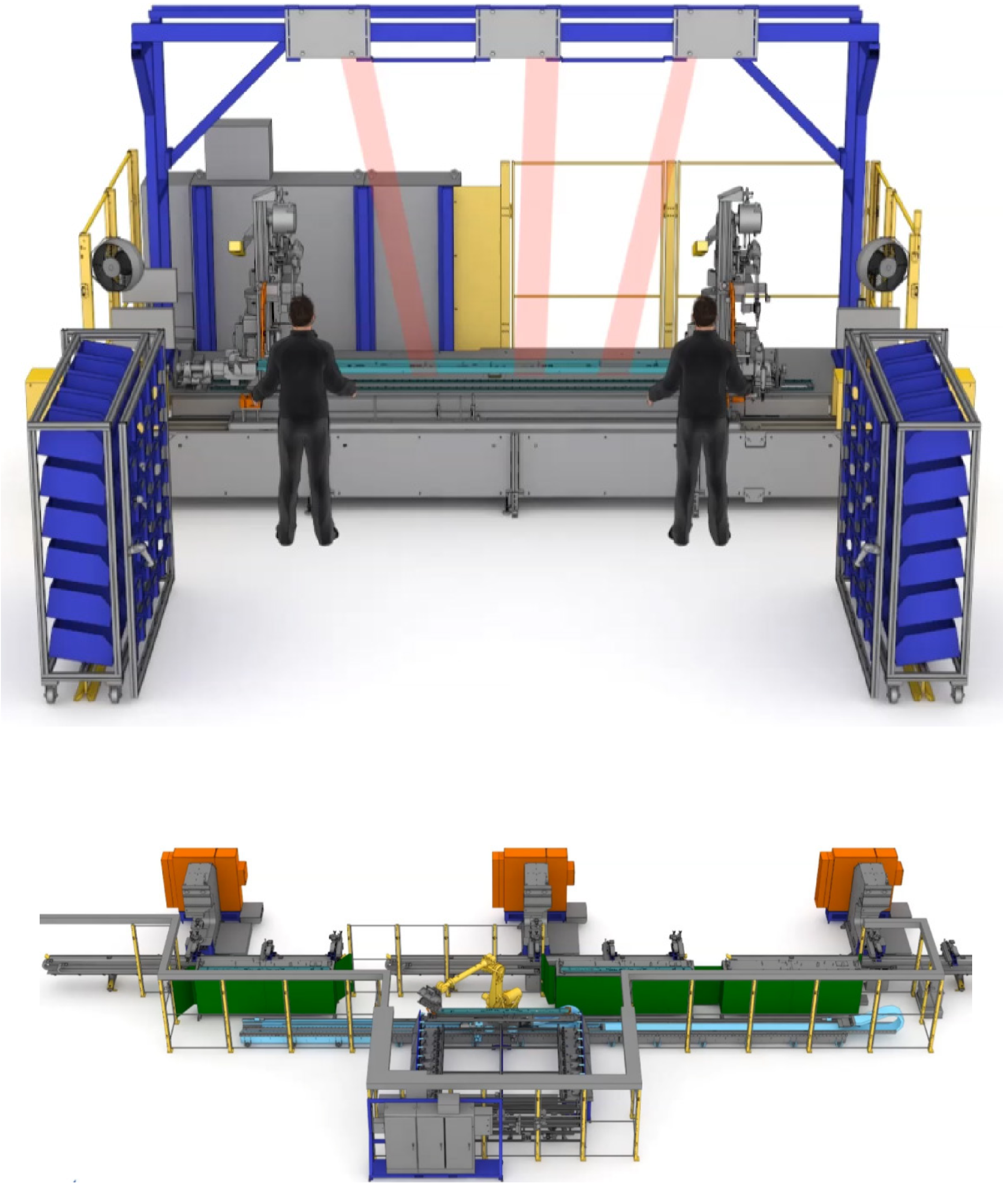


Figure 9: Physical process models developed for manual and automated stations of the line.

As with the discrete event models, initial assumptions about cycle times, machine motion speeds, and other time-based process factors were made in the interest of meeting project management deliverables. And as with the discrete event models, these process models were intended to be treated as a digital twin and subsequently updated as design changes were made but eventually were overcome by resource pressures and became another example of point-in-time digital representations and orphaned digital assets.

3.1.1.3 Data Process Modeling

Data process modeling proved to be a crucial tool in innovating a way to successfully leverage the legacy data sources to derive digital work instructions and to utilize them throughout the dynamic orchestration of the line. Although multi-layered and complex, the data and data flow process became the engine that drove the line.

The first step in data modeling was to architect a means by which to generate the process data needed to run the production line. Because of the nature of this product family's evolution across three major generations of engineering design spanning five decades, part definition and process data was located throughout a number of different systems in several different formats. The data needed to run the production line as well as the frequent need to create content for new beam configuration introductions required the development of a series of software applications to automate the creation of this information. This led to a significant process and application development effort by Spirit's Knowledge Based Engineering (KBE) team working collaboratively with Manufacturing Engineering (ME), the internal customers of the applications. Figure 10 provides a high-level representation of the overall resulting process flow to achieve automated work instruction (AWI) authoring.

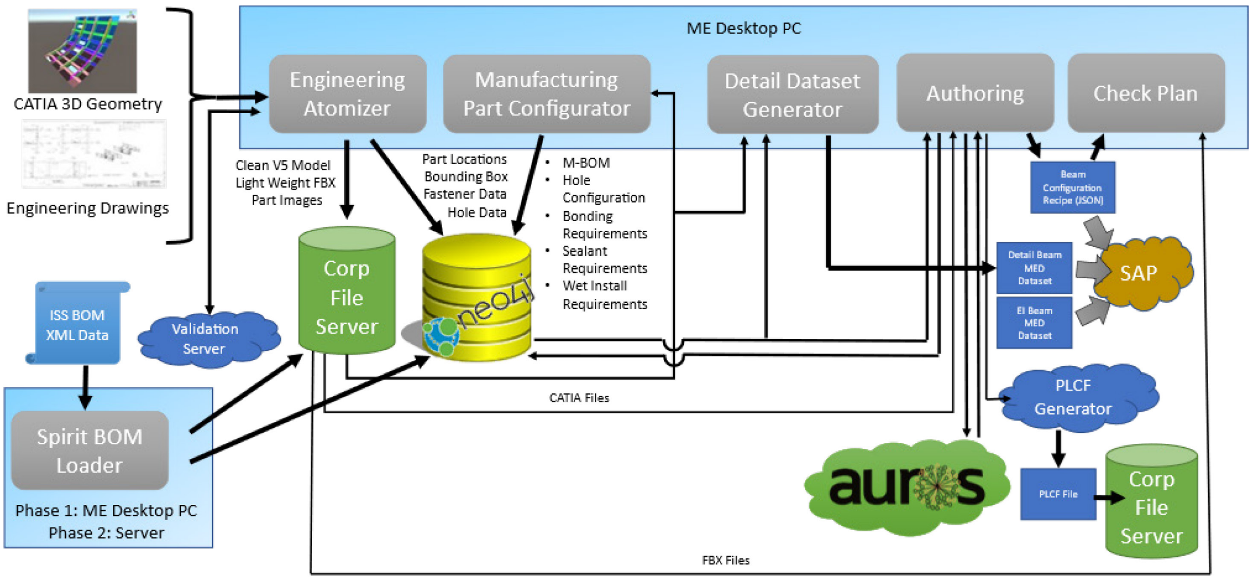


Figure 10: High-level data process flow for automated work instruction authoring.

The original content and format of engineering and process requirements includes bill-of-material (BOM), part lists, 2D drawings, and various levels of Model Based Design (MBD) from CATIA V4 and V5 of various versions depending on the time the initial design was developed. The intent was to generate a digital thread where individual engineering requirements for manufacturing processes like drilling of holes, wet installation of fasteners, and torquing collars can automatically be traced from the engineering drawing to execution on the production line.

The approach developed begins with extracting individual requirements from the multiple data sources and formats in a process termed "atomization" in order to create derivatives of the requirements and standardize the content into a 3D format along with associated information. A critically important initial step of the process includes automated 2D drawing clean-up and CATIA batch conversion utilities to funnel engineering data into the intended MBD end-state (i.e., V5, STEP, ...) and storing them in a repository. The subsequent standardized data content is normalized into a Spirit data model and stored in a graph database (neo4j) which also facilitate interaction with a newly incorporated knowledge management system (Auros). Both the derivative MBD and standardized content organization are depicted in Figure 11.

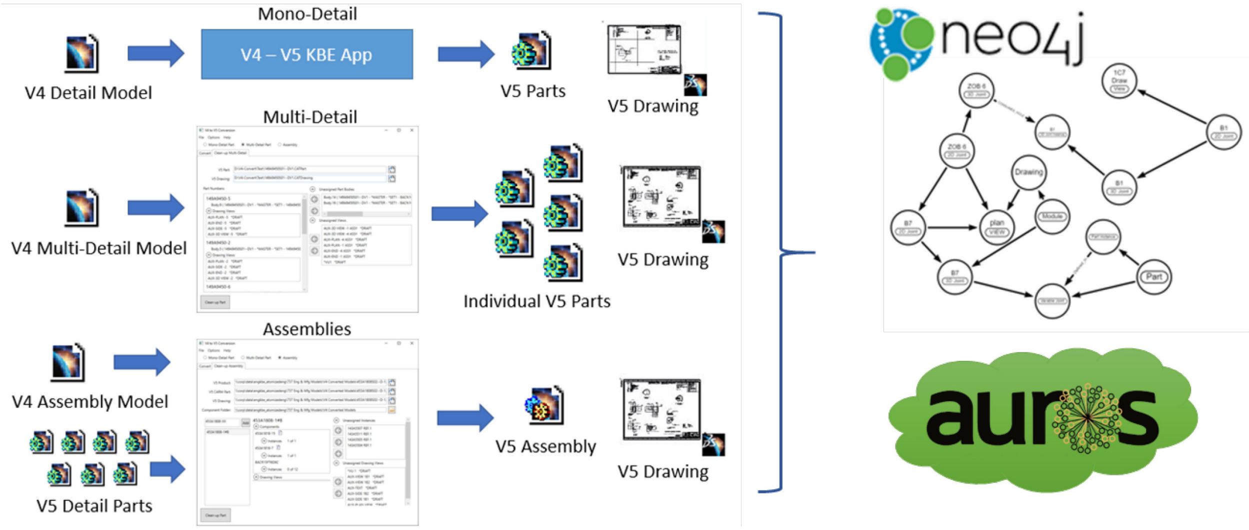


Figure 11: Collating data and requirements into standardized derivatives facilitated by a Neo4j graph database and Auros knowledge management system.

The process of generating derivative data creates many new data elements down to the feature or requirement level, far more granular than a part number level. The addition of process information and association to formalized objects like derivative information or CAD elements represents an exponential increase in total data as well as its value. Traditional product lifecycle management (PLM) systems typically use relational database systems that are not conducive to this information structure. This large set of information elements and relationships also required the creation of more than 300 new formal objects or parameter names. The incorporation of manufacturing process information magnifies the challenge because it is many times more likely to change over time than the product definition itself. The graph database system was selected to facilitate this large, complex, and dynamic set of data objects and relationships.

Another foundational element of the overall architecture that links the source data and instruction authoring to production line execution is the abstraction and modeling of explicit manufacturing process knowledge outside of the KBE applications. Spirit used a knowledge management system which includes mechanisms to model granular actionable knowledge and insert it into the workflow process. This facilitates the capture and continuous improvement of knowledge by creating a single source for people and applications as well as enabling feedback learning by tracking knowledge use. The basic elements of the system are Knowledge Packets (K-PACS), Sets of K-PACS, and Assessments which are like execution records of knowledge models. The knowledge management system provides APIs that allow application interaction with the knowledge, which for this application is exclusively explicit knowledge.

Outputs from the AWI authoring process include multiple CAD datasets, kit box BOM, work instruction operation graphics, and a JavaScript Object Notation (JSON) file that includes step-by-step work instructions for both manual and automation components of the system.

The production line itself is orchestrated via a data architecture that incorporates a large-scale SCADA system called the Assembly Management System (AMS). It is integrated with all the physical elements of the line including work instruction projectors, pick-to-light systems, NC controlled machines, smart hand tools, and inspection systems. As depicted in Figure 12, it is the central hub interacting with multiple data systems and other equipment controllers.

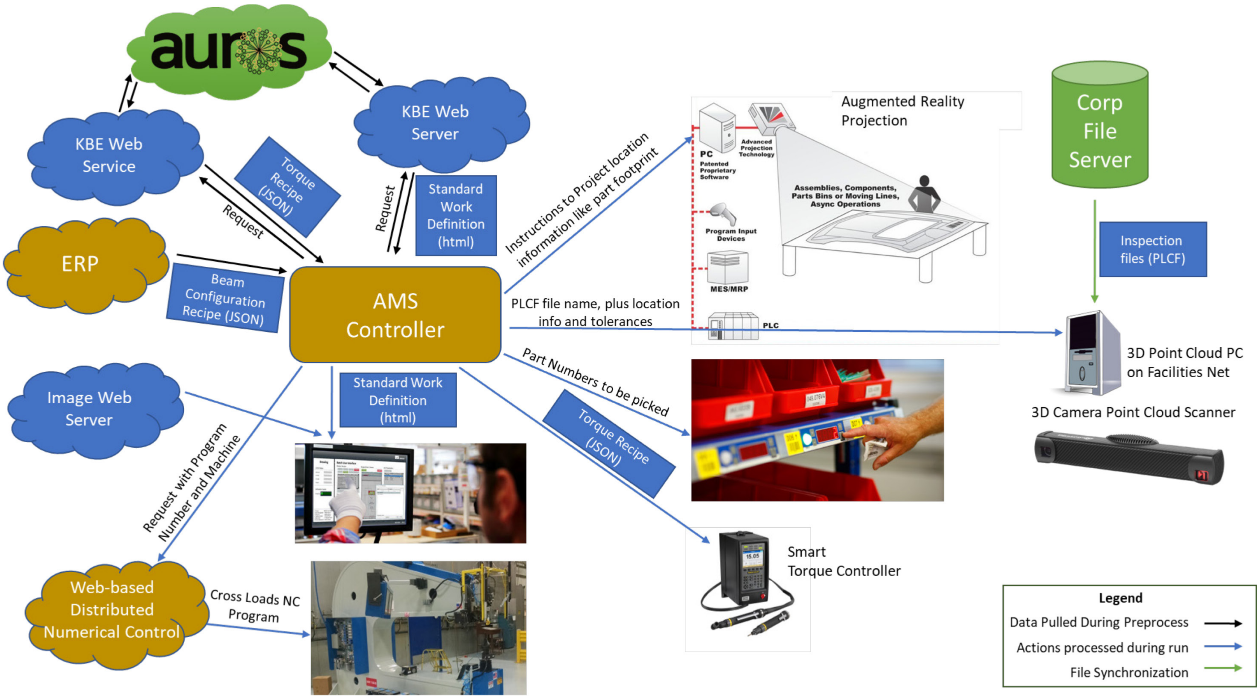


Figure 12: Data process architecture for production line work instruction execution.

ERP routing master data is delivered to the AMS controller as a production order in the form of a JSON file that describes the specific beam's configuration or "recipe". The AMS controller performs a preprocess on the data to get current torque programs and standard work instructions from the knowledge management system as indicated in Figure 12. The AMS then further communicates to the production line's systems like augmented reality projectors, pick-to-light systems, smart hand tools, web-based distributed numerical control (DNC) which provides NC programs under configuration management, and the human-machine interface (HMI) systems in each station.

3.2 Floor Beam Assembly "2.5"

Additional beam product variants continued to be introduced to the new line acting as a type of stress test of the various elements and functions of each workcell and the overall production system. Subsequently, a number of system weaknesses appeared that had not been identified in design and commissioning of the line, even with the use of digital modeling (intended to be extended into digital twins) during development described previously.

3.2.1 Production Ramp-Up Provides Lessons

As the new production system was brought online (Figure 13) and more beam configurations introduced, a number of lessons began to manifest. Collectively, the topics relate to all three primary digital modeling categories and range from underestimation of the overall complexity of configuration variation to overly optimistic assumptions of equipment or tooling availability within the process. Some of the most important lessons include:

- Assembly variant complexity. Every new beam configuration results in a potential for capability shortcoming within the line. For example, one new beam (of the 400 previously processed configurations) in one workstation required the use of four unique fasteners. This in turn required an inventory plan revision and update to pick-to-light capability.
- The level of detail to which initial discrete event modeling was conducted did not account for task-level actions such as the time to pick fasteners from bins or to place a grommet. Instead, the DES assumed resources to be optimally available and tasks to be completed within a pseudo-optimal specified time.
- As the process within each station evolved, physical process models and discrete event models were not consistently updated and validated prior to changes being implemented on the line. This resulted in:
  - Inaccurate assumptions about optimal availability of tooling and associated setup time.
  - Systems designed for one person working in a station (e.g., pick bins, light guide projections, and indicator lights for hand tools) were not easily adaptable or efficient when additional personnel were added in the workcell with the intent of increasing throughput: doubling personnel did not double throughput.
- A virtual commissioning effort that included a detailed factory *data* simulation may have identified the subsequent data and data processing bottlenecks.
  - The controller architecture for managing the production line hinges on a PLC device that runs at or near its capacity limit when the line is in operation. It is used as the memory holder for the AMS database and as the control for most of the tools and machine components on the line. The PLC controller's option providing access for monitoring capability was not included with system procurement. Subsequent required coding by the system provider, who can currently access the PLC and create a bespoke custom report for dashboarding, maintenance, etc., would be a significant and expensive effort.
  - Due to cycle time constraints, the process diverges from single-piece to multi-station batch flow at the automated fastening position mid-way through the line in a hub-and-spoke fashion. The material handling robot (i.e hub) used to transfer beams from the buffer queue station to one-of-three automated fastening systems (i.e., spokes) and back again frequently receives time-conflicting commands and must queue tasks, which adds delays in line operations. This typically manifests as network errors with the web-based DNC or the AMS database causing delays of approximately three minutes at the material handling robot, delaying all actions within the material transfer queue and automated fastening systems until errors are resolved.
- Committing to the recurring cost of staffing with requisite skills to update and maintain digital twins would provide a means of virtually validating planned improvements prior to deploying them on the physical production line. This has a tendency to be viewed as additional cost with indeterminate benefit as long as the process is running smoothly. Only when problems arise does it receive full recognition as a value-added capability.
- Instances of siloed digital models that are not linked to an authoritative source of truth (ASoT) and that do not connect via a robust digital thread are ultimately of limited use. The effort required to manually identify changes to the ABL, and individual workcells' designs, processes, and associated data flows was considerable and a major contributing cause in abandoning, or at least deprioritizing, upkeep of the digital assets for discrete event, physical process, and data modeling.

Figure 13: The ABL includes a mix of manual/semi-automated and automated workstations in a takt-based hybrid single-piece flow arrangement.

3.2.2 Digital Twinning Improvements for V2.5

A supplemental effort has been initiated to review and assess the existing digital models and to identify specific aspects for revision and improvement to move towards more true digital twin capability. Three recommended areas for focus are described in the following sections.

3.2.2.1 CAD Modeling

As production ramped up, bottlenecks due to actual flow of tasks and events on the line became more evident and resulted in additional changes to workcell configurations. While disruptive to deployment, this provided an opportunity to update CAD models to more accurately reflect as-installed equipment and workcell configurations. These updates will also support additional potential uses including performing supplementary detailed human factors simulation for specific workcell and sequences. The updated layouts will also be usable as a basis for visualization related to both DES and factory data monitoring.

A specific CAD modeling update involves a new process for creating light-weight digital models supporting the in-process digital inspection process (see 3D point cloud scanner in Figure 12). This is accomplished using an opensource parametric modeler to generate Polygon File Format (PLY) files that are used as the nominal comparison for the 3D point cloud scanner inspection process. Because PLY files are ASCII or binary in nature, object files are also created in this process for lightweight viewing on HMIs during the inspection process. Figure 14 shows the web application user interface used for this purpose.

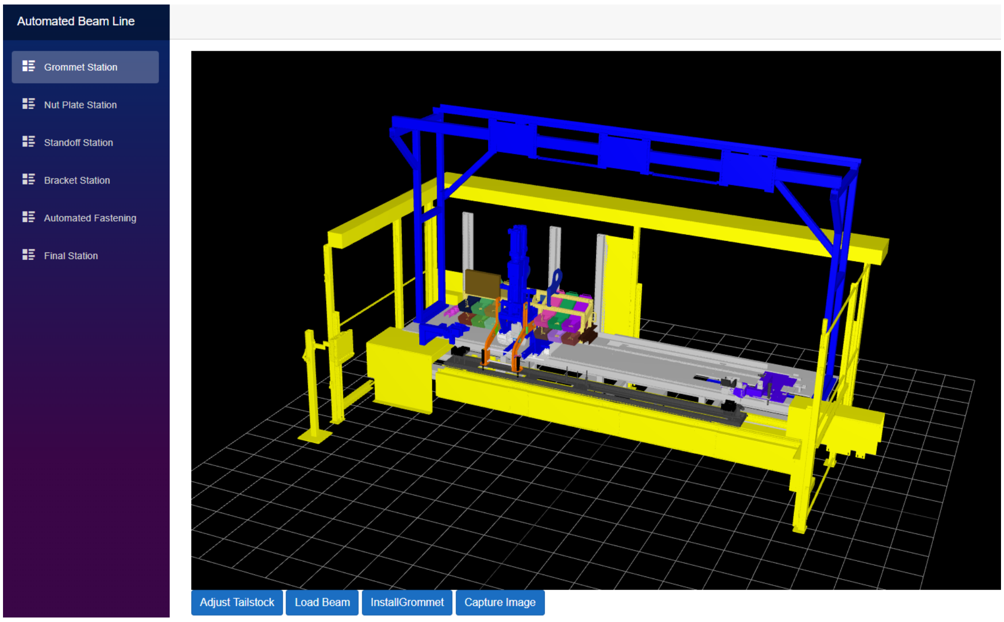


Figure 14: A web application user interface enables generation of light-weight PLY and object files in support of 3D scanner inspections.

3.2.2.2 Discrete Event Modeling

Spirit's standard software for discrete event modeling and is used frequently as the tool of choice in support of complex problem-solving including root cause / corrective action (RCCA) type activities. Spirit also has experience with nearly all other industry leading DES software tool sets and has also begun using some with broad and complimentary CAD and kinematic modeling capabilities.

While a preliminary discrete event model was constructed using Spirit's standard software near the start of the ABL project, the model was not updated as the project progressed and the production line and its workcells were revised. A third-party consulting firm created a second discrete event model using a different software tool as part of a point-in-time assessment, but assumptions were not robustly documented, and it too was not updated over time and was eventually abandoned. The effort to establish an enduring discrete event model with improved fidelity and based on the current as-built production line configuration is underway, again utilizing Spirit's standard DES software environment. Multiple DES and ABL production system subject matter experts internal to Spirit are collaborating to develop this model and are coordinating with the production industrial engineering team that will have responsibility for using and updating it going forward.

3.2.2.3 Data Process Modeling

A lack of visibility into the status and performance of the line's operation resulted in a directive to implement Spirit's standard IIoT platform, specifically to function as a secondary SCADA focused on data collection. The first attempt to monitor the overall condition of the line via the IoT platform resulted in PLC drive clock-sync errors, which desynchronized the logic of the production system. It was theorized and later validated that this was caused by reading 1,200 of the 1,800,000 available tags in the PLC controller through an open platform communications (OPC) unified architecture (UA) asset connectivity server at a 10-second sample rate on the corporate networks. The team subsequently began evaluating the priority of available tags, determining the appropriate polling frequency, and implementing a localized network architecture to optimize the balance of information and system performance and reliability through Ignition.

Spirit's internal team of experts has developed the model for a new architecture concept (Figure 15) that connects the IIoT platform to the main PLC controller, robot, and machine CNC controllers, AMS database, computerized maintenance management system (CMMS), safety-integrated system, and the material movement system. This digital twin of the in-process data flow is designed to provide more responsive analytics leading to an array of diagnostic and predictive capabilities. It focuses on implementing IIoT as the single digital factory gateway and data aggregator between the line and corporate data systems. The robot and machine CNCs will maintain an intermediate connection through the OPC UA server, but all other ABL assets will connect directly to the IIoT platform through the PLC controller. Work to optimize the system's PLCs to accommodate more data transfer is also on-going.

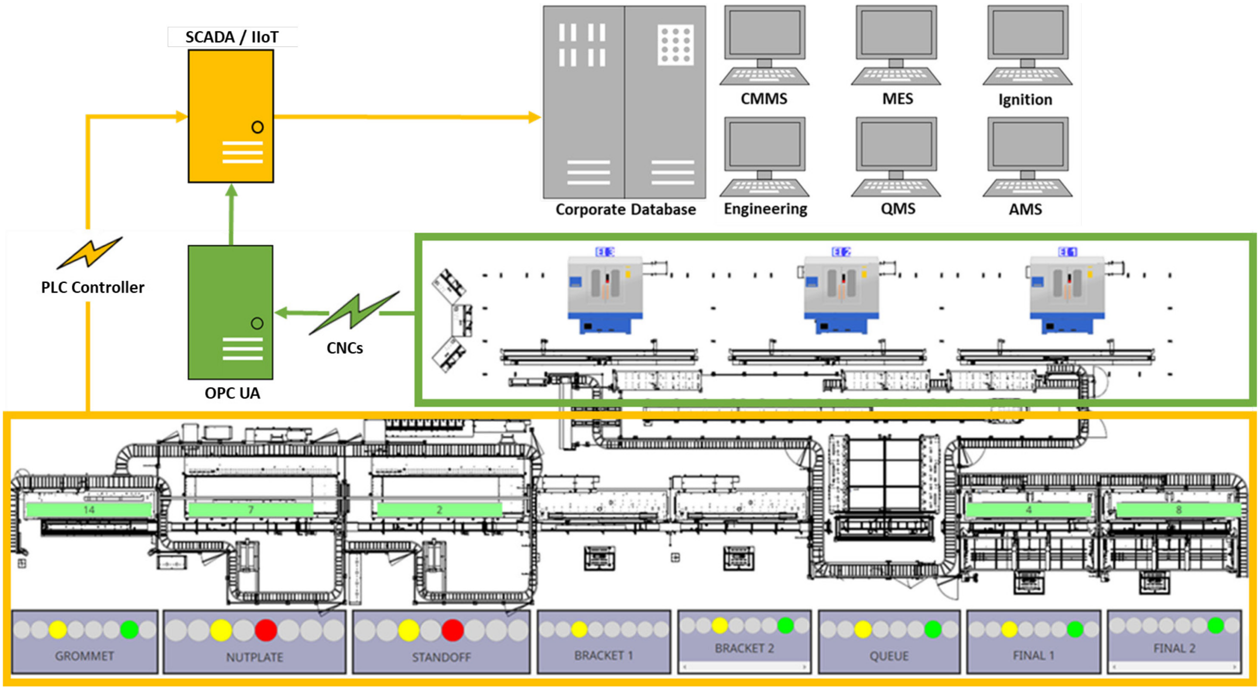


Figure 15: Future state digital twin of the ABL factory data for workcell status using IIoT.

4.0 SPIRIT ONE™

The combination of many of the lessons learned over the time of concepting and implementing the ABL strongly aligns to the benefits envisioned for Spirit's enterprise digital transformation initiative called Spirit ONE™. Launched at approximately the same time as the ABL project, the intent of this program has been to establish Spirit's integrated digital way of working across its various business, engineering, and manufacturing processes which require interaction globally as well as with multiple external customers and suppliers. Based on a foundational Enterprise Architecture (EA) approach (Figure 16), it is designed to ensure future digital twinning can and will be done within a comprehensively connected environment, in large part to address the principal lesson-learned expressed in the final bullet of section 3.2.1: siloed digital models not linked to authoritative sources of truth are ultimately of limited value.

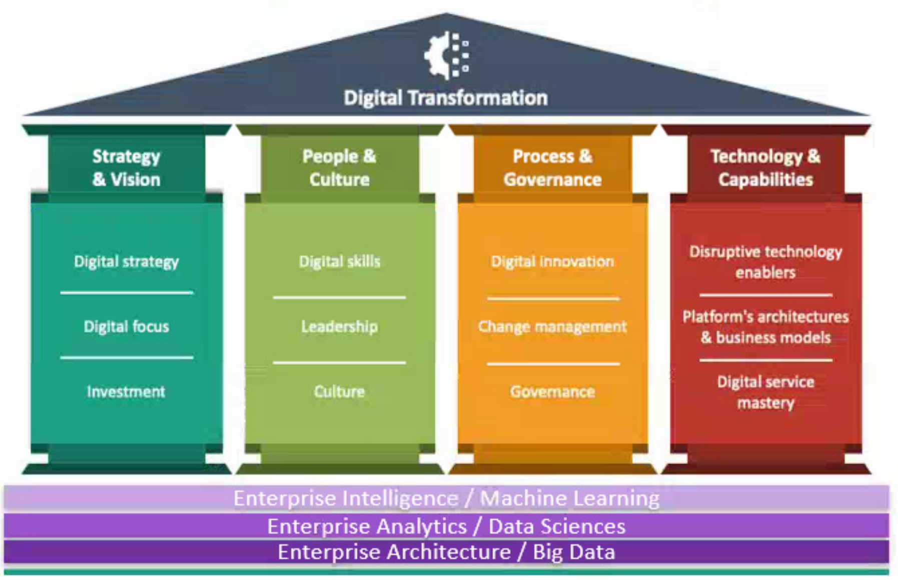


Figure 16: Spirit's digital transformation built on a foundation of Enterprise Architecture, Analytics, and Intelligence.

Following an assessment of PLM platforms against a matrix of requirements referred to as "Factors of Merit", as well as an expansive proof-of-concept to evaluate quantifiable benefits of working within an out-of-the-box (OOTB) integrated digital environment (IDE), members of Spirit's technical fellowship recommended an approach that focuses on a unified architecture that supports multiple CAD data structures, allows robust integration to third-party system components, and robustly integrates to ERP utilizing a baseline platform as a backbone for Spirit's production system. This general approach is an imperative given Spirit's role as a Tier 1 supplier to an array of major OEM customers across commercial, defense, and space market segments. And governance by a federated EA function whose decisions are supported along the digital thread of Enterprise Analytics turned into Enterprise Intelligence is what Spirit envisions to ultimately underpin successful digital twinning.

5.0 REFERENCES

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