Indiana TIM – Digital Thread for Supply Chain

Team Top Gun Final Report

September 2021

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1. Executive Summary

This is a final project report reflecting work completed by "Team Top Gun" (Team) led by prime contractor Mursix Corporation (Mursix) and collaborators, including Cummins, Purdue Polytechnic, ICTT System Sciences and IntelAdvise on the Indiana Digital Thread for Supply Chain contract through the State of Indiana (Sponsor) as initiated by the Indiana Defense Network and the USAFRL.

Using a real-world part as defined by Cummins (OEM) and Mursix (SMM), this project demonstrates the use of the digital thread to advance the capabilities of enterprise learning systems in parallel with individualized workforce development. Within this report, the Team illustrates semantic interoperability between the OEM/SMM process and information stacks using available integrative agnostic model-based frameworks to fulfill the goal of creating a better supply chain ecosystem that enables stronger networks for all stakeholders.

2. Collaboration Scenario

The pilot demonstration illustrates use of the Digital Thread across an example scenario occurring during a product life cycle that involves both the OEM and the SMM. The details of the specific scenario are presented below and compare and contrast historical versus future forms of collaboration and information-sharing using the pilot Indiana Digital Thread for Supply Chain.

Figure 1 below illustrates the range of ecosystem processes contributing to the manufacturing life cycle of a part. The following summary of the scenario merely illustrates one type of scenario chosen for this project and was utilized for highlighting the potential efficiency gained by incorporating innovative digital thread features.

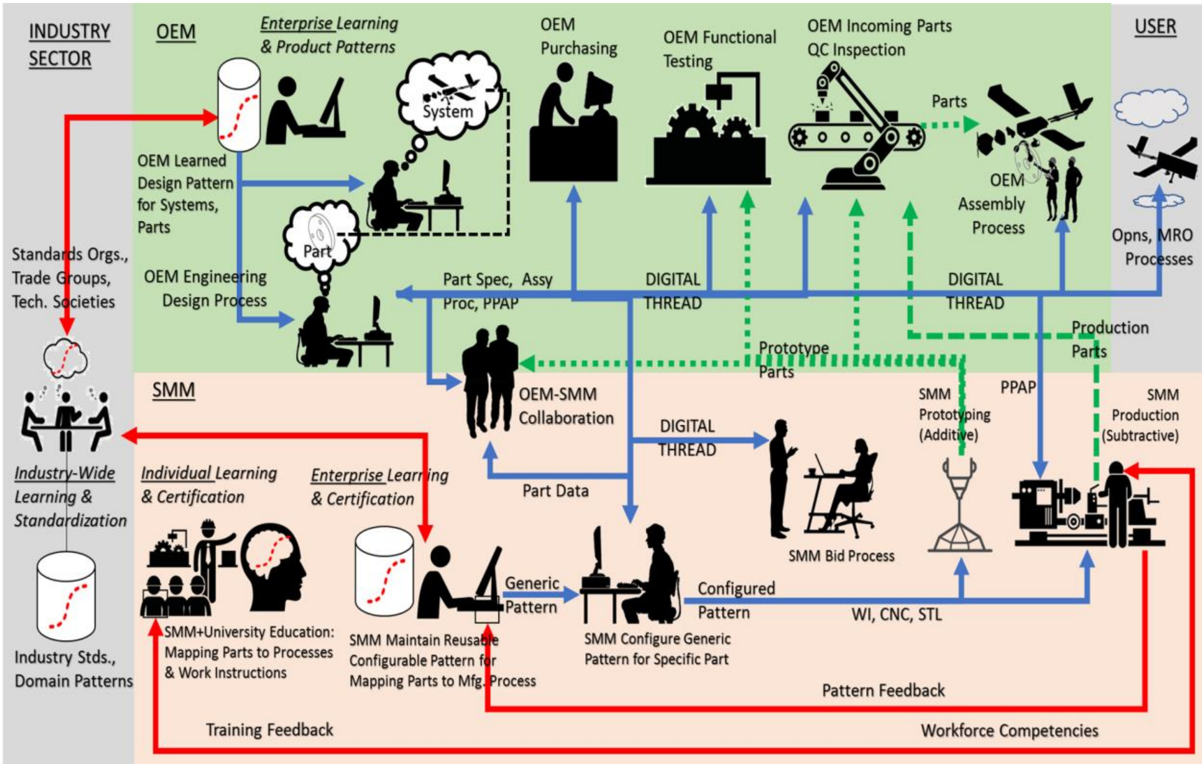

Fig. 1 – Scope of Business Processes Included – A summary view

The exchanges summarized below involve use of digital parametric models supporting the traditional artifacts listed, along with “model wrappers” (configurable metadata for the models) that travel with the parametric models across the life cycle. Such a scenario drawn from real experience includes potential for a design change, a reversion back to the original design, and a part failure under warranty after introduction to the market.

The following scenario summarizes information exchange over the life cycle, emphasizing the overall business purpose of the interactions that the information supports. Details may be found in the Digital Thread Items Tracker of Attachment I.
The product lifecycle simulation began with the OEM (Cummins) selecting a part to outsource to a supplier. This part is an idler shaft insert and is illustrated in various views in Figure 2.

a. For the simulation, a group of 4 students from Purdue Polytechnic Columbus represented Cummins (OEM) and a group of 4 students from Purdue Polytechnic Anderson represented Mursix (SMM). These two groups of students were registered in a two-semester capstone class at each location.

b. Each team communicated frequently with employees of Cummins and Mursix to learn about the product lifecycle process. However, all communication related to the production of the part were between the student groups and were cataloged by both teams in a single document. This tracking allowed an evaluation into the effectiveness of the communication and identified avenues of improvement with the digital thread.

This part has been outsourced by the OEM for a number of years so drawings, standards, and processes from the OEM perspective are already established. The SMM (Mursix) is not the current supplier.

i. OEM prepared Request For Quote (RFQ) for the idler shaft part and designated supplier(s) to receive the RFQ.

   1. ***Artifacts:*** ***Request for Quote (RFQ) (OEM)***
      - i. ***System Product Requirements***
      - ii. ***System Product Design***
      - iii. ***System Performance Parametric Model and Wrapper***
      - iv. ***Part Drawing***
      - v. ***Material Standards***
      - vi. ***Inspection Standards***
      - vii. ***Engineering Standards***
      - viii. ***Consensus Standards***
      - ix. ***Process Standards***

ii. OEM allowed potential suppliers to provide 2 quotes if desired:

   a. The first quote asks suppliers to match the tolerances, materials, requirements, dimensions and overall features of the part as specified in the RFQ and system requirements artifacts.

   b. The second quote allows suppliers to modify some of the features in (a) to lower the overall price of manufacturing the part. This could include material changes, slight modifications of tolerances that could include geometric dimensioning and tolerancing specifications or surface finish specifications, and any other features of the part that would lower the price.

   1. ***Artifacts:*** ***Quotes for manufacturing part. (SMM)***
      - i. ***Could include a second quote that modifies requirements to lower piece price.***

iii. OEM review of quotes from suppliers to determine the optimal approach to manufacturing the part. This includes evaluation of all quotes received and determination if proposed changes in the quotes modified to achieve a lower price are acceptable.

   a. Included communication among OEM team to determine if modifications are acceptable.

   b. Included communication with supplier(s) in an iterative approach to implement modifications or if only a subset of modifications is acceptable.

iv. OEM selected SMM to manufacture 32 of the parts, which represent a short manufacturing run with limited quantity of the part. This limited quantity played a large role in how the SMM dedicates resources to produce the part. OEM created a Purchase Order to begin manufacturing process.

1. ***Artifacts:*** ***Purchase Order***
   i. ***Product Failure Modes & Effects Analysis (FMEA)***
   ii. ***Product GANTT Chart***

v. SMM utilized their resources to produce a prototype of the part using subtractive manufacturing while simultaneously developing the process flow, the process Failure Mode and Effects Analysis (FMEA), and the production process control plan.

1. ***Artifacts:*** ***Balloon Drawing***
   i. ***Process Flow Diagram (SMM)***
   ii. ***Process FMEA***
   iii. ***Production Process Control Plan***

vi. SMM sends the prototype part(s) to OEM for validation (Fig. 2 below)

a. Validation of SMM capability regarding subtractive manufacturing and overall quality of the part. This includes
   i. Part geometry, dimension and tolerance inspection
   ii. Functional capability of the part in the intended product system
   iii. Cost information supporting commercial viability

1. ***Artifacts:*** ***Product Test Results (OEM)***
   i. ***Dimensional Results (OEM and SMM)***
   ii. ***Cumulative Costs***

vii. OEM issues PPAP (Production Part Approval Process) and releases that to SMM.

1. ***Artifacts:*** ***PPAP Level III instructions from OEM***
   i. ***Signed Warrant (OEM)***

viii. SMM develops tools for PPAP.

1. ***Artifacts:*** ***Qualified Laboratory Documentation***
   i. ***Validation of Fixtures/Gauges/Measurement Aids***
   ii. ***Measurement System Analysis (MSA)***
   iii. ***Process Capability Study***
   iv. ***Production Performance Parametric Model and Wrapper***
   v. ***Submission Package***
   vi. ***Supplier Packaging Approval***

ix. Collaboration – OEM inspects the part, analyzes the results and begins an iterative process with the SMM incorporating modifications (dimensional, material, manufacturing etc.). SMM re-fabricates the part and sends to OEM to continue the validation process. This iterative process continues until both parties have agreed on part quality, manufacturing processes, and continuing work.

x. OEM gives SMM confirmation of part integrity and SMM moves to production.

1. ***Artifacts:*** ***Check Sheets***
   - *i.* ***SPC Charts***
   - *ii.* ***Work Instructions***
   - *iii.* ***Set-up Sheets***
   - *iv.* ***Production GANTT Chart***

xi. At the OEM, responsibility is transitioned from product engineering to Product Life Cycle (PLM) management system

1. ***Artifacts:*** ***Continuous Quality Improvement (CQI) Plan***
   - i. ***Warranty Materials***

xii. The part application was simulated into the assembly with the engine then introduced into the market. A field failure launches an investigation using the Digital Thread to retrace the design and production history.

xiii. The investigation identifies errors, challenges, and improvements to augment the original design and manufacturing of the part with digital communication and digital transfer of data utilized efficiently.

xiv. This failure also provides an opportunity to highlight when in the cycle the SMM representatives requested data or asked questions and if the OEM provided the correct data and answers promptly and without much superfluous information. In other words, did the OEM provide the right data, at the right time, in the best manner available?

xv. Post-simulation analysis allows for discussion of the results and the lessons learned during the simulation. This includes the advantages and disadvantages of using the digital thread and places where it might be used to effectively change the product life-cycle process. An example illustration in this project would be in the case of the warranty claim provided by the OEM indicating a cause as “O-Ring Torn”, the data captured and stored in the digital thread showing that the lead in angle was not identified as critical and was therefore not monitored during manufacturing. The identification of that angle as critical would then be configured into the pattern used for initiation of future O-ring seal projects. An engineering study would yield an addition to the O-ring standard accessible to all future appliers.

Fig. 2 – Idler shaft sample produced by the Team

3. Digital Mapping

Figure 3 illustrates how the “Digital Thread Items Tracker” (Attachment 1) produced within our project provides the data map overview of both traditional and model-based artifacts within the configurable modern patterns to improve performance across the supply chain. These improvements include enhanced collaboration, learning at individual and group levels, and better decision-making.

As further described in the presentation of Attachment 2, this project was carried out with reference to the overall ecosystem-level reference model provided by the INCOSE Agile Systems Engineering Life Cycle Management (ASELCM) Pattern, appearing in Figure 3 in its Level 0 summary form.

This framework includes the use of embedded models and wrapper metadata as a form of integrating “glue” to improve consistency of understanding and action across the ecosystem and product life cycle. This includes use of models of decision-making in the presence of uncertainty and progressive incoming signals. The approach is analogous to the aircraft pilot decision-making process that is integrated through a Heads-Up Display (HUD) that brings together only the minimum information needed for the decision-making situation at hand, such as release of a weapon.

In the case of this OEM-SMM Digital Thread Pilot, the "purchasing agent" depicted in Figure 3 is using the digital information in a similar manner as a pilot would use the HUD display to make an on-time decision in a cockpit--except that in the supply chain ecosystem, we are releasing a purchase order. As further illustrated in Attachment 2, this framework was also used to illustrate enhanced collaboration between the SMM and OEM, based on their respective use of separate OEM and SMM models of product and production, linked differential game and modular game frameworks to enhance collaboration while protecting separate interests and illustrating both shared and unshared information across federated Digital Threads.

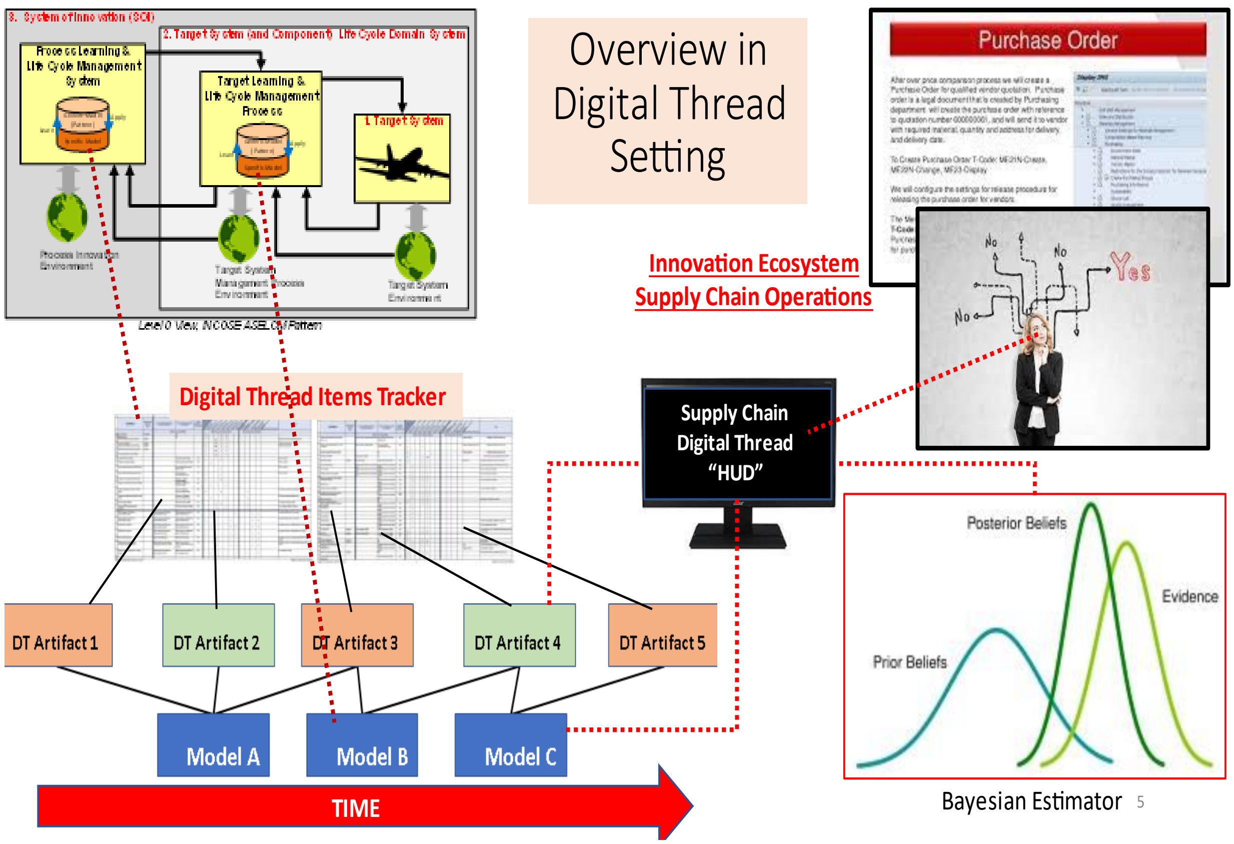

Figure 3: Embedding the Pilot Digital Thread in the Ecosystem Reference Pattern Setting

Figure 3 also summarizes the use of underlying digital models that link more traditional artifacts such as those described in contemporary life cycle threads (References). The demonstration pilot made use of parametric models of integrated system product level performance as impacted by the manufactured part dimensional tolerances, and production capabilities associated with those same tolerances. As an aid to transition, this approach provides for continued use of traditional artifacts familiar to the supply chain but integrated and supported by the digital models which make their interdependencies explicit. Integrating models illustrated in the project also included the use of configurable metadata to enhance the semantic interoperability of the Digital Thread. The configurable metadata "wrappers" used made use of the Model Characterization Pattern (MCP), a universal configurable metadata framework for describing models of any type, detailed in Attachment 4. The use of such intermediate patterns on a standardized basis forms a part of the recommended approach to enhancing the interoperability of complex evolving Digital Threads. In the case of the project scenario described in Part 2 of this report, one could imagine that the post-simulation analysis would lead to an improved configured pattern from which to begin the next project.

4. Regional DT Economic Value Study

i. In-Depth Interviews – one:one

IntelAdvise facilitated a series of (9) in-depth interviews for the Team to gauge stakeholder perceptions and gain feedback on the implementation of "digital thread" (DT) in manufacturing. An executive summary can be found as an attachment to this report (Attachment 3).

Interviewees identified several strengths of the DT:

- Better decisions in design and operations, and consequently fewer changes in production and faster delivery.
- Better logistics management (e.g., spare parts provisioning) throughout the supply chain
- Talent is not wasted on menial tasks or correcting mistakes; because customers, OEMs, and SMMs can coordinate and work efficiently, talent can instead be deployed to maximum effect
- Streamlined processes and record-keeping prevent wasted time and improve quality for immediate and long-term needs (e.g., repairs or replacement parts). This may lead to gains in safety (e.g., the history of a part is tracked in the event of failure).
- Aggregating information about parts also allows for a more rapid design cycle
- Small manufacturers can use DT to expand reach in a global marketplace

Stakeholders also identified key challenges in implementation. First, establishing uniform processes is difficult. As one interviewee said, "we are just not ready to tell the supply chain, 'Here's how we expect you to do business.'" Navigating relationships with OEMs and SMMs can be delicate, who may also have IP concerns. DT requires a culture of "collaboration over competition," as one interviewee put it, which poses barriers to adoption.

ii. Structured Discussions – group setting

Additional qualitative analysis took place in the form of weekly Team meetings where participating contributors had the opportunity to share their value perspectives on the usefulness of this pilot and how future DT implementations might impact their respective roles. The following is a collection of "key-takeaway" quotes from the members:

"The Top Gun project was a great opportunity for me and the Purdue Polytechnic Anderson students. Not only were the students exposed to the collaborative process between two impactful central Indiana companies in Cummins and Mursix, but they were able to work with students from the Purdue Polytechnic Columbus location. While the students are generally presented many of the concepts the encountered during this project in many of their courses, the opportunity to experience them first person from within these companies is invaluable. For me as the instructor and mentor for these students, I was able to learn more about how the content from my courses is applied in industry and see where I may need to improve on some of those concepts. All in all, this was a tremendous opportunity for everyone involved."

Jeff Heiking, PE
Clinical Assistant Professor, MET
Purdue Polytechnic Anderson

"The importance of the digital representation of a physical system that is used to communicate properties and live status to other systems and applications is integral to the future of smart factories. As an SMM, we need to be able to provide the OEM access to the right information at the right time. This project was a stepping-stone to providing a framework that takes technical data and analyzes it to provide actionable information."

Susan Murray Carlock
Vice President of Business Development
Mursix Corporation

"Cummins is thrilled to work with private and public entities, including IEDC, Purdue and Mursix, to transform manufacturing to benefit the state's economy and drive job growth in the digital age," reads a statement from Cummins Inc. "This project has incredible potential to increase the pace of design, product development, manufacturing and the launch of products – potentially taking years off the process. For Cummins, it furthers our industry 4.0 efforts by expanding our knowledge and use of digital manufacturing and a digital supply chain. These types of projects drive collaboration, cultivate the leaders of tomorrow and help us attract and retain talent in our state."

Steve Stahley
Director Measurement Excellence
Cummins

Further insights from the project contributors can be found in section 2 of Attachment 3.

iii. Digital Questionnaire

Lastly, supplemental quantitative data was collected via a digital questionnaire distributed to key stakeholders within the regional manufacturing base. The target audience represent the (5) stakeholder segments that the project team has used to identify the collaboration ecosystem addressed in this report, which include: DoD- Target System Purchaser (the end customer), OEM, SMM, Workforce Development and Economic Development. The results indicate recognition of digital thread business value and a willingness to participate in collaborative efforts to advance digital transformation among the manufacturing ecosystem. The analysis also indicates a gap between a perceived high level of importance in data management systems within their organizations and low level of satisfaction with both their model-based simulations in engineering design capabilities and their actual implementation of an IoT roadmap.

The willingness to address this gap by respondents in executive leadership roles within OEM's and SMM's creates a near term opportunity to foster collaboration through programs that support DT learning and adoption. A full review of the analysis is provided in Attachment 3 with this report and offers "Next Steps" suggestions that dovetail with the recommendations from the project team offered in Part 5, Section C of the following pages.

5. Observations, Analysis and Recommendations

This Indiana TIM pilot as completed offers an illustrative example of how independent enterprises can utilize existing frameworks to strengthen the digital thread across the supply chain, leading to better decisions throughout the life-cycle management of a manufactured part. The team itself, by virtue of the stakeholders represented within this project, showed that with the right incentives there is promise that key decision makers within the manufacturing ecosystem will collaborate in a manner conducive to a holistic manufacturing base digital transformation thereby "raising all boats".

Toward that end, the team has specific recommendations the project reveals as prudent for the continued evolution of digital thread capabilities throughout the US manufacturing supply chain.

A. Standardization

The next step in proliferating US national manufacturing base participation in a digital thread capable supply chain is to evolve the applicable standards. There are some relevant standards in place (ISO, AS, OSLC), others in development and still more yet to be created. The team supports contributions to a consensus standard configurable set of fields for describing the ontology of product and process specifications over life cycles. There is ongoing work that we feel DoD should support including the ASME VV50 Guideline in development, which is about managing credibility of advanced manufacturing models over life cycles. Our team used the INCOSE Model Characterization Pattern (MCP) meta-data wrapper which is utilized by ASME in the VV50. Another standard is in draft stage referred to as Model

Identity Card (MIC). The team proposes the establishment of a community to contribute to these standards efforts to include logical, appropriate standards bodies such as NIST and ISO.

B. Model Repositories - Framework Focus

This section addresses the problem definition of "how to move to a truly model based system?" Models are acquired and accumulated across a variety of enterprise systems which represents the fragmentation of data that the digital thread hopes to address. Since the technology for housing the data already exists in the form of various model authoring, PLM, and other (sometimes proprietary) management systems software platforms and data storage hardware, it is the recommendation of the team to focus on the open-source development of frameworks that define the data requirements. An example of this strategic approach would be comparing it to when UNIX was at one point a proprietary AT&T language until it was opened up, at which time affordable servers were proliferated everywhere, benefitting the whole server market, which grew rapidly.

It is important to address a recurrent commercial barrier to DT adoption around the issue of intellectual property. IP rights are determined by contract and the industry seems more likely to accept a limited rights of use license-based model, whereby the commercial developers of the models retain ownership. The ongoing proposed additions to the DFARS whereby contractors are required to attach line-item costs associated to the data is a practical solution as comprise to ongoing DoD needs for access to that data (Nagel and Hayes, 2020). Of note in the context of this project TIM, the "cost" primarily associated with a disconnected DT is a pace of bringing new target systems online that is untenably slow rather than a traditional dollar cost. Price is always a concern to an acquisitions office, but it is also recognized as an inadequate way to value the supply chain when appropriate weight is given to losing ground to adversaries.

Put another way, the question of who owns the data may be less important than agreeing on standards around how the data is stored, how access and permissions are granted, the cybersecurity protocols (CMMC of all stakeholders), model credibility (VVUQ), the length of time data is stored and maintained and other critical features addressed by the framework.

C. Adoption

i. Awareness to Adoption – There is an opportunity to create a community network contributing to the evolution of DT standards and accumulation of ever improving patterns. Publication of project results and whitepapers with associated presentations to trade organizations, workforce development and economic development are suggested modes of evangelism from the TIM outcomes. Raising awareness in this manner leads to consideration from leadership, consideration leads to trial and trial leads to adoption. The adoption phase is where the agile process iterates into the feedback loop that improves the patterns, something that is illustrated in the ASELCM System 3 framework of the whole ecosystem, i.e. a configurable System 3 pattern for aircraft innovation systems versus a configurable System 2 pattern for aircraft.

ii. Training – The project illustrates the benefits of utilizing university partnerships in standing up a digital thread capable workforce. The team suggests research in identifying regional campuses to provide resources for materials production (curriculum, web, print, video), accredited certification, instructors and modes of delivery i.e., online video modules, in-person capstone courses and business enterprise workshops. The content of this report, references and attachments contains the basis for creating the necessary tools for advancement of learning at the individual, enterprise and ecosystem levels.

Pictured – Purdue Polytechnic, Anderson Campus DT Capstone Student Team

References

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8 ISO 10303-243 – MoSSEC: "Modelling and Simulation information in a Collaborative Systems Engineering Context" http://www.mossec.org/ 2021.
9 Lu, Morris and Frechette "Current Standards Landscape for Smart Manufacturing Systems" https://www.nist.gov/publications/current-standards-landscape-smart-manufacturing-systems , NIST, 2016.

Attachments From This Project

Attachment 1: Digital Thread Tracker
Attachment 2: Explanatory Slides from IDN June 9, 2021, TIM
Attachment 3: Regional DT Economic Value Study
Attachment 4: Model Characterization Pattern for Universal Model Metadata Wrappers
Attachment 5: Educational Workshops
Attachment 6: Project Proposal