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Implementing a Complete Digital Thread: The Need for Data Element Mapping and Analysis

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ABSTRACT In the age of digitalization and the fourth industrial revolution, the concept of the digital thread has captured both the attention and resources of countless organizations. However, despite its growing popularity and a plethora of technologies being offered that promise to create the digital thread, this research revealed that no current techniques allow for the systematic uncovering of data and information flows in a way that reveals individual threads of data elements. Therefore, data element mapping and analysis (DEMA) is proposed as a tool capable of identifying all the data elements at the granularity necessary to connect digital threads. DEMA is a technology agnostic approach that allows an enterprise to move from a functional, document-centric view of data and information flows to a data element level view, with the data elements serving as the connectors of the digital thread.

INDEX TERMS Data element mapping and analysis (DEMA), digital engineering, digital thread, functional analysis.

I. INTRODUCTION

Manufacturing is undergoing a fourth industrial revolution centered upon the integration of cyber-physical systems [1]. The concepts of Industry 4.0, such as digitalization, have major implications beyond manufacturing for both business and society [2], [3]. Some have used the term “Industry 5.0” to describe a vision for industry that includes the well-being of society [4]. Others have coined the term “Industry X.0” to describe the impacts of Industry 4.0 beyond manufacturing to include all industries [5]. Regardless of the terms used to describe future systems, digitalization is a key component. Although the full impact of digital transformation is still unfolding [3], [6], it is estimated that digital transformation will create value in the trillions of dollars [7], [8]. Digital technologies go beyond monetary value to provide significant enhancement in national security [9], [10], [11]. Therefore, there are initiatives across industries to enable and realize the advances brought on by the fourth industrial revolution and digital transformation.

Despite a growing recognition of the importance of digitalization, there is no consensus in defining the key terminology [12], [13], [14], [15]. The terms "digitization" and "digitalization" are often confused with one another and used incorrectly [10]. Digitization is the computerization of manual activities; digitalization is the fundamental restructuring of an existing process to improve connectivity and information flows while taking advantage of digital capabilities [10]. While digitization is a perquisite for digitalization, digitization by itself does not result in a more efficient, secure, and advanced process. Therefore, despite popular belief, digital transformation cannot be achieved by simply digitizing information or implementing standalone digital technologies [3], [10].

The digital thread is a concept within digital transformation that has been long discussed and desired [16]. It is reported that the term digital thread originated during the development of the F-35 with Lockheed Martin and the Air Force Research Laboratory [17]. The digital thread is defined as the connection of data and information flows throughout a product lifecycle [16], [18], [19], [20]. The name "Digital Thread" is actually a misnomer as it implies a single thread connecting all data. In reality, terms such as "Digital Tapestry" [21] or "Digital Quilt" [22] are more suitable names as their connotations more accurately convey the complex nature of connecting

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heterogeneous lifecycle data. Regardless of what the most appropriate name may be, the term "Digital Thread" is most common and is used in this article.

Within the manufacturing industry, connecting data and information flows are estimated to have annual savings in billions of dollars [16], [20], [23], and establishing the digital thread across supply chains should reduce cycle time by up to 75% [20]. In this research, data element mapping and analysis (DEMA) was created as a generalizable method that utilizes known and novel systems analysis and elicitation techniques to identify and visually map data and information flows as a means of enabling the digital thread. DEMA is a novel approach for the standardized capture, mapping, and analysis of data flows for digital system understanding of the current state and developing the architecture of the improved state. This article describes the development of DEMA along with its application in a product realization environment at a prototyping organization.

The rest of this article is organized as follows. Section II provides background information and summarizes the review of literature. Section III describes the methodology used in the development of the approach. Section IV provides information on the application of DEMA in a product realization environment. Section V presents the results of the application. Section VI provides discussion of the results. Finally, Section VII concludes this article.

II. BACKGROUND

A. TECHNOLOGICAL ENABLERS OF THE DIGITAL THREAD

Although the implementation of digital technologies does not compel digital transformation [3], it is a key enabler of its realization. Several technologies have risen as popular choices in enabling digital transformation. From industry, various types of software for the storage, transmission, and management of data are presented to realize the digital thread. Product lifecycle management (PLM) software is used to manage information and processes across lifecycles [24], [25], [26] and is advertised as the "foundation" of the digital thread [27]. Even computer aided design (CAD) systems have evolved to incorporate capabilities to capture knowledge for reuse in the product lifecycle [28], and various cloud platforms have entered the manufacturing domain to enable instant access to data and collaboration [29] as well as product customization [30]. Virtual reality has also been presented as a technology for enabling collaboration and knowledge management [31].

Research has been conducted into the technological requirements to enable the digital thread. There are three significant periods in the evolution of data exchange standards that show a progression from developments such as standard for exchange of product data, extensible markup language, and unified modeling language (UML) to the development of system modeling language (SysML) and ontology-based data standards [32]. There are diverse efforts in employing data exchange capabilities such as these. For example, a standards-based approach has been proposed as an alternative method for linking data as opposed to costly and often siloed PLM systems [26]. Within the field of software engineering, methods for model-based software synthesis [33], [34] and model and tool integration platforms [35] have been put forward as solutions for integrating disparate systems.

Other work has focused on means for integrating modeling languages [36] and creating novel data structures [37] in line with existing data integration standards as a means of enabling the digital thread. Various technologies for capturing and reusing knowledge across product lifecycles have also been proposed [28], [38]. In terms of cyber-security, blockchain technology has emerged as popular means of securing data traceability in digital thread applications to ensure data authenticity [39]. It is worth noting that many works focusing on data exchange technologies for enabling the digital thread [37], [39], [40] are specifically within the additive manufacturing domain. There is also a recognition that the digital thread is a concept that can be implemented alongside Digital Twins to enable collaboration between manufacturing units [41].

Overall, the review of literature shows that many digital thread efforts conducted by academia and industry have been focused on the software, syntax, standards, and semantics necessary for data exchanges. There is also a popular belief that the digital thread is the infrastructure in which data reside and are connected [26], [42]. While the work that has been done to enable this infrastructure is essential to the realization of the digital thread, in this article we assert that infrastructure itself does not constitute or automatically create the digital thread. Therefore, analytical tools are needed that can be used alongside infrastructure technologies to successfully realize the digital thread [43].

B. PREVIOUS WORK IN ANALYTIC TOOLS FOR ENABLING THE DIGITAL THREAD

There is a growing understanding of the need for new processes and tools beyond physical technologies to enable digitalization [9], [10] and recognition of the importance of understanding data and information flows [44], [45], [46]. One novel concept in this area is the application of Lean Manufacturing principles to eliminate wastes in data and information flows [45]. There is also a recognition that a systems engineering perspective is essential to the realization of the digital thread [16], [18], [19], [47]. Improvement of the process prior to digitalization is critical, as "adding digital capability to a bad process only creates a bad digital process" [10]. Akay et al. [48] proposed a “Push-Pull” digital thread solution concept for knowledge sharing.

While the total cost of inefficient data and information flows may be hard to quantify, anecdotal data quickly uncovers its immensely negative impact. For example, within the United States Department of Defense acquisition process, obtaining test data from test ranges regularly takes 60 days because of the disparate data repositories, manual data searches, and unstandardized data formats [47]. Also, the variety of digital tools used in engineering processes result in significant gaps in design flows that are bridged by ad hoc, manual user interventions that result in increased labor costs and risks [35]. The difficulty and costliness in managing heterogeneous data and information is true for manufacturing [6], [45], [49]. It is usually taken for granted that such manual and costly data tasks are unavoidable, and consequently initiatives for improvement are neglected [46].

While integration technologies can potentially serve as mechanisms for connecting the digital thread, they themselves do not provide methods for analyzing data and information flows. Therefore, analytic tools are needed to better understand and quantify performance metrics for data and information flows. Previous research has employed data collection and analysis techniques such as surveys [44], workshops [28], and comparison studies [50] to determine the necessary data flows to create a model-based definition and the model-based enterprise. Although efforts such as these provide valuable insights, their results are narrative in nature and do not provide detailed architectures of data and information flows. A technique is needed for uncovering, mapping, and analyzing the complex and disconnected data and information flows found in real-life systems.

C. VISUALIZATION OF SYSTEMS

Visual mapping techniques are a viable solution to investigate data and information flow discovery and analysis. The process chart evolved into functional visual mapping techniques such as functional flow block diagrams (FFBD) and data flow diagrams (DFD) [51]. The Toyota production system [52] progressed with the information and material flow diagrams which were created and made popular by the book Learning to See as value stream mapping (VSM) [53]. *N*2 diagrams were created to develop system interfaces by incorporating system function blocks with the interface inputs and outputs between each function [54].

Visual mapping techniques continued to evolve as the computer introduced a revolution in communicating, capturing, and managing information. The need arose for analytical tools that could also be used to better design, understand, and improve digital processes. Tools such as the architecture of integrated information systems and business process management software helped couple information technology with process modeling [52]. Standards for the integration definition for function modeling (IDEF0) [55] and other versions of IDEF have been introduced for various purposes [51]. Business process model and notation (BPMN) was created to ensure standardization of various business process modeling techniques and to enable such models to be executable [56].

Systemigrams are visual mappings that represent complex systems using natural language [57], and they are used in various settings such as creating conceptual views of the DoD acquisition enterprise as a means of enabling the digital thread [47], [58]. IDEF0 diagrams have been used to describe data flows in the digital thread in the work [37] and [59]. There have also been efforts in mapping information flows in ways inspired by VSM [60], [61]. Analysis of data and information systems is essential, as it cannot be taken for granted that a system's current state of capturing, storing, and utilizing data is optimal.

The visual mapping techniques used in previous research are suitable for evaluating functional, document-based, and software-centric views of data and information. However, such methods do not consider the access of individual units of data, or data elements, that are contained within the documents. It is also difficult to isolate and analyze threads of data elements, which is the actual desired outcome. When mapping objects such as functional blocks are used, it is impossible to see clearly where there are breaks in individual threads. Also, past methods assume that format and organization of data elements into documents are in the optimal form. Therefore, previous visual mapping techniques are suited for digitization (manual computerization of activities [10]) rather than optimizing the flow, form, and handling of data elements to enable digitalization [43].

III. METHODOLOGY

The review of current literature identified the need for a visual mapping technique that moves beyond a functional and document view to achieve a data element level view, and therefore the methodology began with a review of past visual mapping techniques. This analysis was conducted while attempting to analyze the data and information flows of a prototyping organization to the level of data necessary to implement the digital thread. Process flow charts, IDEF0, control flow diagrams (CFD), DFD, functional flow diagrams (FFD), FFBD, BPMN, VSM, and *N*2 diagrams were evaluated for suitability in isolating threads of data elements (the individual units of data such as part dimensions, meeting times, and requirements). Two major issues were quickly discovered when using these techniques [43].

First, although the mapping techniques could be used to visualize the flow of documents and the alignment of processes, their functional perspective inhibited the ability to isolate threads of data. Second, although the organization's work procedures provided valuable information about the stakeholders, functions, major documents, and governing standards of organization activities, they did not capture all data and information activities that drove the processes. Therefore, traditional visual mapping techniques were found to be insufficient on their own, as they do not offer a systematic method for uncovering the complexities in hidden data and ad-hoc information flows that are found in real-world systems [43].

The results of the analysis of past visual mapping techniques are shown in Table 1. In columns C1–C4, an "X" is placed if the mapping meets the criteria outlined in the column header. The criteria for column C1 is that the technique has an object that could be used for mapping places of data storage. The criteria in column C2 is that the technique has an object that could be used for mapping actors that access data. The criteria of column C3 is that the mapping makes data element thread identification both possible and practical. The criteria for column C4 is that the technique has a systematic method

TABLE 1. Evaluation of Past Visual Mapping Techniques for Data Element Thread Isolation

Mapping	C1-mapping to data storage	C2 – mapping actors to access data	C3 – Data Thread identification easy to see	C4 – holistically uncovers hidden data flows
Process Flow Chart	-	-	-	-
CFD	-	-	-	-
DFD	X	X	-	-
FFD	-	-	-	-
FFBD	-	-	-	-
BPMN	X	X	-	-
VSM	X	X	-	-
N2	-	-	-	-
IDEF0	-	-	-	-
IDEF1	X	X	-	-
IDEF1X	X	X	-	-
IDEF3	X	X	-	-
IDEF4	X	X	-	-
IDEF5	-	-	-	-
SysML	X	X	-	-
UML	X	X	-	-

for holistically uncovering hidden processes, data, and information flows that are found in actual real-life systems [43].

It was determined that traditional mapping techniques are helpful in enabling digitization of standardized documents, but not true digitalization. However, decomposing complex systems into smaller categories is very useful in managing complexity and promoting system understanding [46], and functional visual mapping techniques such as those described do provide valuable insights, albeit at a superficial level.

This led to the realization that current tools were not sufficient to achieve the needs for analysis that leads to a complete digital thread. Industrial and systems engineering subject matter experts were consulted to combine various components of traditional functional mapping techniques with systems engineering elicitation methodologies and data mapping techniques to provide a wholistic perspective of the current state of data and information flows in an effort to identify and map data elements of the prototyping organization. A three-step approach was taken to accomplish capturing a wholistic view of data and information flow, and the rest of this section presents each step.

A. STEP 1—FUNCTIONAL LEVEL MAPPING AND ANALYSIS

The first step in wholistically capturing data and information flows of the prototyping organization was functional level mapping and analysis. In this step, high-level functional areas and corresponding subfunctional activities were identified and visually mapped. It was critical that the analysis begin here as all captured data and information flows had to be traceable to high level functions so that the data and information flows identified could be traced back to organizational requirements. In this step, hidden (ad hoc and undocumented) functional activities were also identified and recorded. The functions identified in Step 1 served as a foundation to establish the flow of data vessels in Step 2 and without them, the end-goal of the data element level view in Step 3 could not be achieved.

The high-level functions and their subfunctional activities were identified using several approaches. In the application at the prototyping organization, the program management data and work procedures were available, so they were used to identify the different functions. Elicitation techniques and round table discussions with system stakeholders were also essential in ensuring that the captured functions accurately reflected the real-world data and information systems. Once the functions and subfunctions were identified, they were visually mapped using functional block diagrams (FBD) and FFBD. A generic example of a functional level mapping is shown in Fig. 1; the high-level functions of the system are shown on the left, the identification of the subfunctional areas is shown in the middle, and then the functional activities are filled in on the right. Once the visual mappings were verified by the system's stakeholders, the functional level view and mapping was complete.

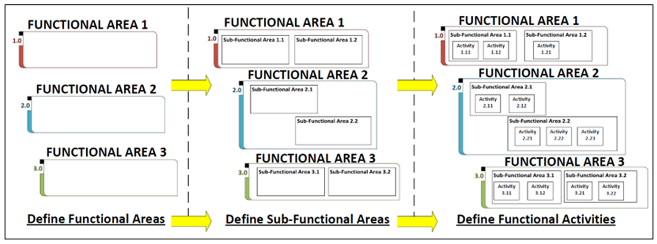


FIGURE 1. Generic functional level mapping example.

B. DATA VESSEL LEVEL MAPPING AND ANALYSIS

In this step, a visual mapping was created that showed the flow of data vessels across the functions and subfunctional activities identified in Step 1. Data vessels are documents, emails, personal notes, drawings, CAD files, and any other possible container (i.e., vessel) of data. Although the functional level view in Step 1 was essential to gain insight into the system and establish a foundation for the flow of data vessels, it did not address the data and information exchanges between the subfunctional activities. Therefore, Step 2 had to be conducted to identify the flow of data vessels so that full digitalization was enabled.

In this step, representatives from each of the functional areas of the prototyping organization were presented the initial functional level mapping from Step 1. Informed consent was obtained from each interviewee prior to conducting the interviews. They were asked to identify which of the high-level functions and subfunctional activities that they were involved in and to provide transparency in the functional mapping. For systems where the subfunctional activities are not clearly defined and standardized within the system, the interviewee should first be asked to describe the system activities in which they participate and their responses recorded. It may be helpful for the interviewer to start by asking about the activities at the end of the process and then work backwards from there to have the interviewee describe the process. This method of working backward through a process is deployed when conducting VSM [62].

Once the interviewee identified the functions and subfunctional activities they were involved with, they are asked to report the data vessels that were the inputs and outputs of

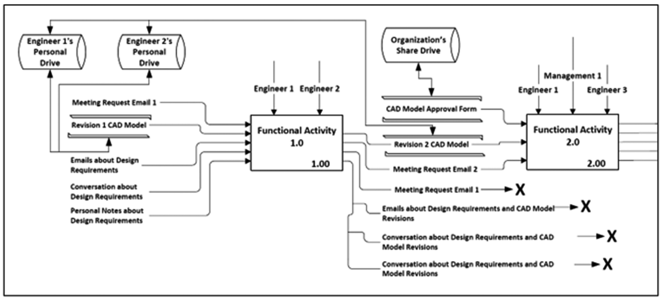


FIGURE 2. Generic data vessel level mapping example.

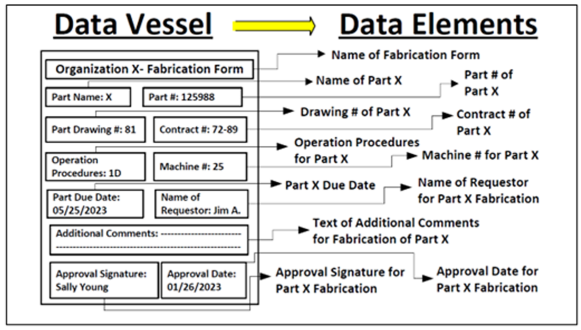


FIGURE 3. Generic example of data element identification.

each subfunctional activity. Information on each data vessel's place of storage, form, means of transfer, and the actors involved in handling the data were recorded in a standardized questionnaire template. Data not contained in vessels such as conversations and visual observations were also identified and recorded. Important knowledge that can be reused throughout the product lifecycle is often not captured in an easily searchable digital form [38], and the ultimate goal for data and information flows is to enable the right people to have the right data at the right place at the right time and in the right form to make the best decision [45].

The interview results were then visually mapped using a technique derived from an integration of IDEF0 and DeMarco's DFD to record the flow, storage, and access of data vessels across the high-level functions (see Fig. 2). One finding from the interviews may be that different actors within the system conduct different patterns of data exchanges while performing the same functions within an activity. In these instances, separate mappings should be created from each process. Deviations such as this may reveal a need for standardization in activities and data exchanges.

However, the analysis did not stop at the data vessel level view and mapping. A document-centric view of data must be overcome to enable digitalization [21], [63] since data elements are contained within the data vessels, and it is the data elements, not the data vessels, that matter. The data vessels were instrumentally important to the extent that they enabled organization, traceability, security, and appropriate access to the data elements.

C. STEP 3—THE DATA ELEMENT LEVEL VIEW

The data element level view was the final step of the analysis. The data element level view was necessary to determine the actual system requirements and architecture needed to build the digital thread or systems such as the model-based enterprise. The output of this step was the identification, capture, and listing of the data elements in each data vessel as they flowed through-out the system functions. The data vessel level mapping in Step 2 recorded each of the data vessels involved in the system as well as where they came from and were stored. Therefore, the data vessel level mapping was used to seek and retrieve the data elements contained within each of the data vessels. From there, the flow of data elements were listed and visually mapped using the flow identified in the data vessel level mapping. The data element level view captured the current state of data and information flows to the level of detail necessary to determine what must happen for the right people to access the right information, at the right time, and in the right form.

Data elements themselves are the smallest units of data contained within a vessel. For example, an engineering drawing may consist of data elements including but not limited to dimensions, tolerances, revision numbers, approval signatures, date of approvals, and drawing titles. An example of data elements is a meeting invitation email that includes data elements such as email addresses, name of sender, name of receiver, meeting date, meeting time, meeting location, and other texts. In Fig. 3, an example is shown of the data elements being identified in a generic form.

IV. DEVELOPMENT OF DATA ELEMENT MAPPING AND ANALYSIS

During the application of the methodology, the researchers discovered that the three-steps deployed in the methodology created a new visual mapping technique that meets all the criteria outlined in Table 1. This three-step process was named DEMA. DEMA enables the standardized capture, mapping, and analysis of data flows for digital system understanding and architecture development. Each step of DEMA is essential and must be carried out sequentially to achieve the end-goal data element level view. The first step of DEMA is the functional level view, where system decomposition takes place. The second step is the data vessel level view, where all containers of data are identified and visually mapped. Valuable insights and opportunities for system improvement are uncovered at each step of DEMA, but the final step, the data element level view, is unique in that it isolates the flow of individual data elements across the system that serve as the connectors of the digital thread. Fig. 4 presents an overview of each of the steps of DEMA with simplified examples of the graphical representations associated with each step.

DEMA is based on system decomposition methods and elicitation techniques. The concept that a hierarchy of

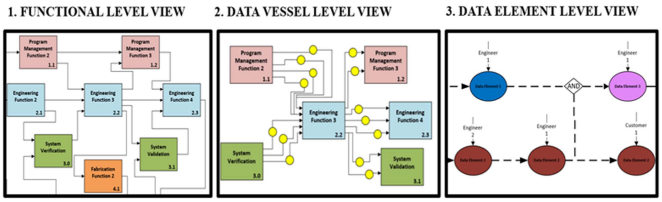


FIGURE 4. DEMA overview.

elements (related subsystems and components) exists within almost any system is an established concept that is well understood [64]. It is recognized that man-made systems have now reached complexities never experienced, and data are a key system element along with humans, software, and hardware [65]. However, all currently known methods for system decomposition and visual mapping are unsuitable for decomposition to the data element level. DEMA can be applied to any system that involves the flow of data, with data being defined as any fact or information that can be used to make decisions, analysis, or calculations [66].

There may be concern for using DEMA if the system to be analyzed is not well understood and is without clearly defined processes or if the system in question varies greatly depending on its application. In reality, DEMA is suitable for application in both situations, as DEMA offers a standardized method to uncover the complexities of such a system, and mechanisms can easily be added to each step to account for system variability. Therefore, DEMA is suitable to analyze all types of systems with data, regardless of the current level of system understanding, digitalization, and variability.

In the application presented here, DEMA was utilized in a product realization setting within a prototyping organization with high-mix, low-volume product types with both engineering and production functions. DEMA was created while analyzing the data and information of the organization, and therefore the organization's prototyping process was chosen as a case study in the application of DEMA. Within such an environment, proper management of lead times, process milestones, quality, operational costs, and flexibility are crucial to maintaining a competitive edge [67]. It is also important to remember that the product realization process involves process design, process execution, and process improvement [68]. Such complexity and variability in a product realization environment provides many opportunities for the identification and elimination of nonvalued added activities [69].

Knowledge management, the management and use of data and information, is a critical enabler of competitiveness in product realization environments [38], [70]. The actors in an organization hold knowledge of both products and the processes used to create products [71]. In practice, organizations rely heavily on highly skilled employees utilizing siloed tribal knowledge to accomplish functional activities. Such systems contain great risks and are not sustainable as they rely on a system based on heroic effort from its employees, dependent on employees doing the right thing every time and remaining indefinitely within the organization. DEMA was applied with the intent to identify opportunities for improvement in data and information flows to assist in developing well documented standardized processes and to reduce the cost and lead time for getting finished products to the customer.

V. RESULTS

The overall findings from this work are the following: Even with detailed work procedures, over 90% of the data vessel handling and exchanges were nonstandard and undocumented (hidden to the organization) and driven by the tribal knowledge of the actors in the system. Approximately 88% of all data element instances involved manual handling and transfer, indicating a lack of connectivity (breaks in the digital thread). Because over 25 000 data element instances were identified in the product realization process, the magnitude of need for digital connectivity is apparent. However, just under 75% of the data vessel handling and exchanges involved unstructured data vessels—that is, data vessels not in a format amenable to having their data elements digitally connected.

This application showed that the results from each step of DEMA captured the current state of data and information flows in a way that allowed nonstandard (hidden) and unconnected data vessels and elements to be identified. Due to the nature of the research, due to ethical reasons, a full set of the supporting data is not available. Example mappings with sensitive data removed are available throughout this report, and they fully demonstrate the methodology.

A. FUNCTIONAL LEVEL VIEW AND ANALYSIS

The purpose of the first step of DEMA, functional level view and analysis, is to identify and visually map the high-level functional areas of the system to be analyzed, along with their corresponding activities. This was accomplished by evaluating program management and work instructions from a previously executed product realization project. More specifically, the Microsoft project integrated master scheduler (IMS) from the project was provided to the team.

The IMS along with stakeholder roundtable discussions discovered that the high-level functional areas were program management, engineering, verification and validation, fabrication, quality assurance, and final delivery. The timelines of each functional area were also identified to be used in potential critical path analysis of the data and information flows. The map of the functional areas is presented in Fig. 5.

The functional activities within each functional area were determined from the IMS and mapped using FBD. The IMS was used to determine the functional flow between the functional activities and mapped using FFBD. The functional level view and analysis revealed a total of 65 functional activities, with fabrication having the most activities at 27. Moving from six functional areas to 65 functional activities showed increasing levels of system complexity. After including functional flow, 77 dependencies were identified between the activities, with Fabrication having the most dependencies at 43.

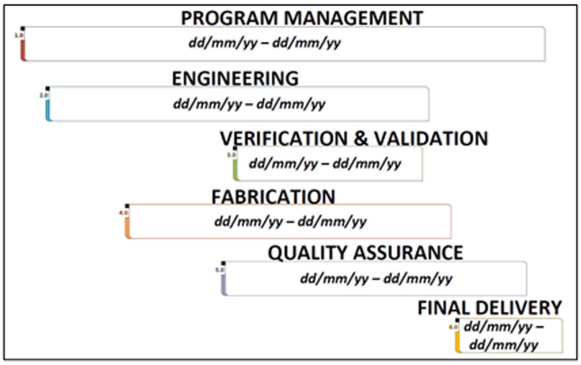


FIGURE 5. High-level functional areas of the system.

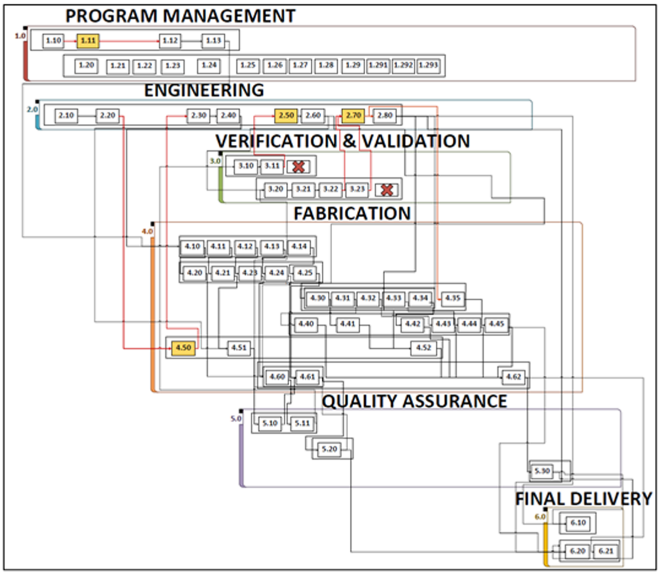


FIGURE 6. Functional flow block diagram of functional level view.

The functional level view mapping was presented to stakeholders from each of the functional areas. The stakeholders were asked to identify the functional activities they were involved in, and their answers were documented. The stakeholders were also asked if any functional activities were incorrect or missing from the mappings. These interviews found that two activities were missing, and two were placed in the wrong functional area, resulting in 67 activities. The resulting mapping is shown in Fig. 6. The yellow boxes represent the two missing and two misplaced functional activities, and the red lines represent the new functional dependencies.

Whereas a high-level functional view of the system showed six functional areas, a subfunctional level view shows increasing complexity with 67 functional activities. Program management and work procedure data are helpful, but not sufficient for identifying all activities, nor was it always correct. After the stakeholder interviews, four functions and three functional dependency corrections were found. Although the functional level view provided insight into system processes, it did not address the data and information exchanges between the functional activities. Therefore, the results of the functional level view and analysis indicated that methods are needed beyond functional analysis to capture the current state of data and information flows within a system.

B. DATA VESSEL LEVEL VIEW AND ANALYSIS

Data vessel level view and analysis was then conducted to identify the flow of data vessels across the functional activities. The functional level view was essential to gain insight into the processes and to establish a visual structure for the flow of data vessels. However, as previously shown, this does not reveal the data and information exchanges between the activities. The data vessel level view is captured to identify the flow of data containers.

Representatives from each of the functional areas of the prototyping organization were presented with the initial functional level view mapping and asked to identify the data vessels inputted and outputted at each of the functions in which they were involved. Their responses, as well as information on each data vessel's content, place of storage, form, means of transfer, and actors involved in handling the data, were recorded in a standardized questionnaire. The end results of these interviews were standardized documents that recorded data vessels (as well as information about each data vessel) as they flowed through each of the functions. From there, the interview results were visually mapped using a technique derived from a combination of IDEF0 and DeMarco's DFD to record the flow, storage, and access of data vessels across the high-level functions. To manage the size of the mappings, individual mappings were created for each functional area (six total). Functions outside of the functional area considered are shown only to the extent that they have direct data vessel inputs or outputs into the functional area considered in each data vessel mapping.

In a data vessel mapping, the boxes represent the functional activities, and the name of each data vessel is recorded on the arrows going into and out of the functional activity boxes. The labels on arrows going into the boxes are data vessel inputs to the function, and those going out are the data vessel outputs.

The actors that handled the data are recorded on the arrows going into the top and bottom of the functional activity boxes (there is no difference in actors based on whether the arrow is at the top or bottom of the function box). The data vessel retrieval or storage locations are indicated by the cylindrical database shape. The data vessels are connected to their place of retrieval/storage by lines connected to brackets grouping data vessels to their respective place of retrieval/storage. When a data vessel is connected to an "X" it means that the data vessel was not stored in an official place of storage. When a data vessel is connected to a highlighted "???," it means that the place of storage or retrieval was unknown. For this application, mappings were created in Microsoft Visio for each of the six functional areas. A figure that shows the syntax used to create a data vessel mapping for a generic functional activity is provided in the Appendix as Fig. 11. An example

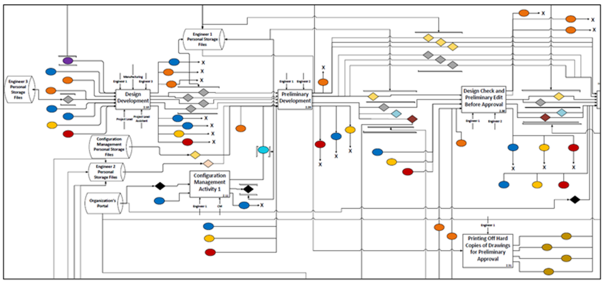


FIGURE 7. Representative section of color-coded engineering data vessel mapping.

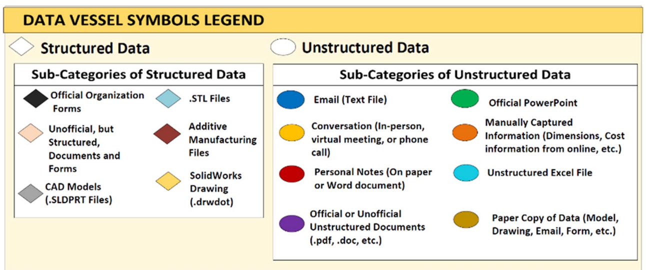


FIGURE 8. Legend of colors and shapes for data vessels.

of the data vessel mapping of a function from the engineering functional area is also provided in the Appendix as Fig. 12.

Each of the six mappings were then created with the data vessel names on each input and the output arrows replaced with color coded shapes. A section of this color-coded mapping created from the engineering functional area is shown in Fig. 7. The ovals represent unstructured data, and the diamonds represent structured data. Structured data are in a format compatible for processing and analysis with digital tools, and unstructured data are not in a format compatible for such use [72]. The colors of the shapes represent the types of structured/unstructured data represented and the legend is shown in Fig. 8.

The results of the data vessel level views established a current state flow of data vessels across the organization's lifecycle functions within the functional areas. The fabrication function had the most data vessel inputs, outputs, and dependencies with one of the lowest percentages of structured form, standardization, and data storage for reuse. This result indicates that manufacturing systems are ideal candidates for DEMA application as they have ample opportunity for improvement.

Another interesting outcome was that although there were around 1000 data vessel inputs and outputs identified from the data vessel view, there were only around 500 data vessel dependencies identified. This finding implies a large amount of the data vessels did not transfer directly across the functions because some data vessels are being created and then not transferred across the lifecycle for reuse. Although the data vessels are not being reused, the data elements within them are

TABLE 2. Definition of Data in Data Element Level View Excel Sheet Columns

Data Element Level View Excel Sheet Column Table	
Column Name	**Definition of Data**
Instance ID	A unique identifier for the data element instance.
Data Element ID	A unique identifier for the data element accessed in the instance.
Data Element	The name of the data element accessed in the instance.
Functional Activity	The functional activity under which the instance takes place.
Data Vessel Name	The name of the data vessel (as listed in the Data Vessel Mapping) in which the data element is accessed in that instance.
Link to Instance ID	The Instance ID of data element access instance that directly precedes the current data element instance.
Data Vessel Type	The type of data vessel in which the data element is accessed in that instance (Email, Digital Document, Non-Digital, CAD Model, etc.).
Data Format	The format of the Data Vessel in which the data element is accessed in that instance (Text, PDF, Excel, Paper, Native CAD, etc.)
Place Where Data Resides	The place where the Data Vessel in which the data element resides and is accessed in that instance.
Actors 1, 2, and 3	The first, second, and third person, software, or any other possible actor who is accessing and/or handling the data element in that instance.
Manual Transfer Involved	A "Yes" or "No" answer as to whether the transfer between the instance of data element access that directly preceded the current data element instance (referenced in the "Link to Instance ID" column) was manual (transferred between human actors). A "No" answer indicates that some form of digital connectivity exists between the instances.
New Data Element	a "Yes" or "No" answer as to whether the transition between the instance of data element access that directly preceded the data element instance (referenced in the "Link to Instance ID" column) introduces a new data element.

being manually transferred across the lifecycle into different data vessels. Overall, the results of the data vessel level view proved DEMA effective in capturing and mapping data vessel flows.

Although the data vessel level view provided insight into the containers (i.e., vessels) of data, it did not address the data elements that would serve as the connectors of the digital thread. Also, the data vessel level view only showed what data vessels were required for each function, so it did not show all data exchange and reuse that occur in real-life for each function. Although data vessels are useful in that they can be used to organize data elements and facilitate their flow throughout a system's lifecycle, data vessels themselves are not intrinsically valuable as they do not directly create value—they are instrumentally valuable. Therefore, a data element view is necessary to isolate and identify the individual threads of data that actors directly use to make decisions that create value within a system. The final step, data element level view, provides the identification, capture, and listing of the data elements within each data vessel as they flow through the system functions.

C. DATA ELEMENT LEVEL VIEW AND ANALYSIS

To achieve the data element level view, the data vessel level mappings were used to locate and investigate data vessels to capture the data elements contained in the vessels. From there, the flow of data elements is listed using the flow captured in mappings from Step 2. These flows were recorded in Microsoft Excel. Each row in Excel corresponds to one instance of data element access by an actor in the lifecycle. The instance ID in column A and the data element ID in column C are assigned manually. The data shown in each column in the Excel Sheet show are shown in Table 2.

The purpose of the data element level view listing in Excel is to isolate and identify individual threads of data. This allows visualization of how the data element is passed throughout the lifecycle between actors, functions, and data vessels, and the visualization of how much of the data flow is driven by manual intervention such as email exchanges, moving data elements from paper notes to CAD models, and retrieving data from

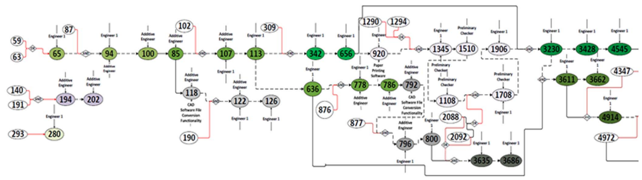


FIGURE 9. Data element thread of nomenclature of additive part.

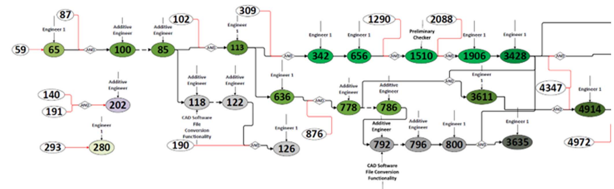


FIGURE 10. Improved data element thread of nomenclature of additive part.

various places of storage. From another perspective, it shows where data are currently stored and retrieved as well as which data elements are not stored at all. An example of isolating the flow of a data element by using the filter function on the data element column C is provided in a figure located in the Appendix.

The data vessel level view revealed approximately 1000 data vessel inputs and outputs across the functional activities with more than 500 data vessel dependencies. The data element level view revealed over 2500 unique data elements in the 25 000 total data element instances. The engineering functional area produced the largest amount of data elements with around 1500 unique engineering data elements and with just under 12 500 data element instances. Over 90% of the data element instances were manually exchanged, therefore less than 10% of data element instances were digitally connected.

The filter function in the data element level view listing can be used to isolate threads of data. An example showing how to create a visual mapping of the flow of data elements from the data element level view listing is available in the Appendix as Fig. 13. Fig. 9 shows the data element thread of the nomenclature of an additively manufactured part. Altogether, this thread was made of 157 data element instances, but for the sake of simplicity, only a segment from that data thread is shown in Fig. 9.

This mapping is made by creating an oval for each row in Excel and labeling it with both the instance and the data element name (Fig. 14). The color of the oval is darkened as the data element matures across the product realization process. Arrows are then added to either the top and/or the bottom of the oval with the actor/s that are accessing the data element in that instance. Connecting lines are added to describe the flow and digital connectivity of the data elements. A relationship between the current data element and past data elements is established by the referring to the "Linked to Instance ID" in Col. F. This column presents the previous data element instance or instances in which the current data element is directly linked. If the current data element is directly linked to multiple data element instances, "AND" and "OR" logic, or some combination of the two, are used to describe the relationship between the multiple instances.

After determining that a relationship exists between the current data element instance and the data element referenced in Col. F, it must be determined whether the relationship involves some form of digital connectivity or not. A lack of digital connectivity is described by a dotted line connecting the data elements, and some form of digital connectivity is described using a solid line.

Fig. 10 shows how the data thread shown in Fig. 9 would be improved if a digital technology such as a PLM system were used to digitally connect the elements when possible. It was found that implementing a connective digital technology to reorganize the flow of instances for this data element could reduce the total number of data elements in that digital thread from 157 to 111 (a 29.1% reduction). Digital connectivity could be increased from 22.3% to 75.4%. Therefore, DEMA was proven to be an essential tool in enabling digitalization.

According to the works of Sztipanovitz et al. [35], the most critical kinds of design knowledge for reuse are that which relates to system model and testing/verification methods. It is interesting that this application of DEMA revealed that data related to verification and validation were the most likely to be unstructured (5.3% structured) and the least likely to be saved for reuse (2.9% saved for reuse). The example data element thread shown in Figs. 5 and 6 showed that through the application of DEMA digital connectivity could be increased from 22.3% to 75.4% for an additive manufacturing data element. Additive manufacturing is an inherently digital process, and it is likely that other data elements start with less connectivity than this example's 22.3%. Therefore, the results of this study make sense considering the findings in paper [50], that a transition from a drawing-based process to a model process would reduce cycle time by 74.8%. More research is needed to confirm the improvement metrics.

VI. DISCUSSION

One of the benefits of DEMA is its system-agnostic nature. The three-step methodology of DEMA allows clear deliverables and benefits to be realized at each step. Because DEMA is an analytical method, in-depth knowledge of other engineering disciplines is not a prerequisite, thus making the DEMA concept and methodology understandable and attainable to those without such knowledge. DEMA integrates principles from industrial engineering, lean manufacturing, and systems engineering to create a novel digital engineering tool. The remainder of this section continues this discussion within the concepts of systems engineering, the principles of lean manufacturing, and digital engineering.

A. DEMA WITHIN SYSTEMS ENGINEERING

DEMA can be applied to an existing system such as in this research or in a system that is under development. There are many ways in which DEMA can be leveraged by the systems engineering process. Within systems engineering, there is often a lack of integration between the involved disciplines such as engineering, management, science, and finances [65], and DEMA can serve as an invaluable tool in defining the data relationship across the functional activities that correspond to these disciplines. DEMA can thus serve as an enabler of cross disciplinary system integration.

The definition of external system interfaces and their elements is one of the most important yet often overlooked systems engineering requirements tasks [73]. DEMA could be used in this context as a systematic method to uncover and define the data requirements for system interfaces for systems requirements specifications. Graphical tools such as FFBD are encouraged for use when developing concept of operations [74]. Therefore, DEMA can be integrated into the system engineering process by applying DEMA Step 1 the development of functional mappings for the concept of operations.

Within the concept of system science, there is the concept of "black box/white box" system representation. The "black box" view is that of the external system, and the "white box" is an internal view of system that shows the structure of the elements [75]. An understanding of both the "black box" and "white box" view of the system and the relationship between the two is essential for system understanding [75]. DEMA is a tool to systematically determine and manage the data relationships between system elements and the functions to which they correspond, thus marrying the "black box" and "white box" views.

Within the model-based enterprise, model-based systems engineering (MBSE) has captivated diverse sectors including defense, commercial, and healthcare industries [76]. Delligatti [77] has defined three pillars, or enablers, of MBSE as modeling languages, modeling methods, and modeling tools. There have been three significant periods in the evolution of data exchange standards that show a progression toward the SysML and ontology-based data standards [32]. This evolution moves toward user-friendly modeling tools for exchanging data that have aspects of visual mapping techniques. Within the field of MBSE, SysML has emerged as the “de facto standard” [78]. A system model in SysML defines and shows the interconnections between elements of the system that represent key aspects, and there are various diagrams within SysML to accomplish this [79].

SysML is both a language for data exchanges and a tool to create visual mappings, further proving the interdisciplinary nature of digitalization. Whereas SysML is primarily a language, DEMA is an approach, and SysML and DEMA could be used synergistically to enable digitalization in systems engineering efforts. SysML could potentially be used as a tool to visualize the mappings created during the DEMA steps, but SysML alone does not offer the DEMA methodology. DEMA could be used to identify the inputs that could be used with other SysML diagrams. Therefore, DEMA and SysML can be used together to fully define a system model that accurately reflects the data and information of the system.

B. DEMA AND THE PRINCIPLES OF LEAN MANUFACTURING

Past visual mapping techniques have relied on functional, document, and software-centric views of data and information. This is a problematic view given that data elements, and not documents and software, are used to drive value in an organization. In the Toyota Production System, there is the idea that some activities in manufacturing are value-added, and others are nonvalue added, and the 7 Wastes of the Toyota Production System developed by Ohno [80] are used to identify the nonvalue added activities [45].

The data vessel is analogous to a physical container that is used to move and store materials in a manufacturing facility. In the same way a physical container is used for inventory management and transportation in manufacturing, the data vessel is used to facilitate the manual storage and transference of data elements across the project lifecycle. This reality hints at the possibility of wastes categories existing for data and information flows as Ohno’s waste categories are for the analysis on physical processes, and research is actively being conducted to develop such categorizations [45], [46]. Research has also been conducted in utilizing VSM to eliminate waste in manufacturing information inefficiencies, but these efforts also do not address the data element level [70], [71].

VSM, like other traditional mapping techniques, is suitable for functional and document-centric views of data and information flows as opposed to a data element level view that enables full digitalization. Therefore, DEMA offers a tool uniquely suitable for application of lean manufacturing to data and information flows. Waste categorizations for data and information flows could be used to assist in identification and elimination of waste in both the data vessel and data element level views. Two of the most important philosophies of the "Toyota way" are continuous improvement (kaizen) and respect for the people [81]. In almost all cases, it is not feasible to assume that all waste can be removed from a system, but continuous improvement allows a system to gradually be improved and optimized over time. This mindset is important to the application of DEMA, as the final mappings created by DEMA will uncover many suboptimal and nonstandardized data flows.

Although new technologies and the application of artificial intelligence and machine learning may eventually enable real-time optimization of data and information flows, no such technologies currently exist to enable this at the data element level. Therefore, a kaizen approach is necessary for incremental improvement to a system. Future work will examine the application of DEMA to optimize data and information flows alongside the development of a system.

C. DIGITAL ENGINEERING

The definition of products is becoming exceptionally complex and two-dimensional drawings are unsuitable for properly capturing this complexity [28]. Model-based definition has been proposed as an alternative to meet the needs of the modern enterprise. There is an ongoing effort to establish common information models as a means of enabling the model-based definition [44]. Persistent identification of product-definition elements was identified as a research gap in enabling model-based manufacturing and inspection [50]. DEMA can systematically reveal these elements and their relationships.

DEMA has been shown as a means of capturing all relevant data and information flows within a system and can be used alongside model-based definition to realize the model-based enterprise and establish complete product definition. Errors are more likely to accumulate as drawing based definitions are passed throughout the lifecycle [50]. Given that this research revealed thousands of data element instances related to the use of engineering drawings, this realization is even more impactful. Therefore, each instance of data element exchange and interaction is critical, and the realization of the digital thread and the model-based enterprise would eliminate thousands of single point failures in data elements.

DEMA can also be used to facilitate augmenting connected data with semantics. The purpose of the DEMA process is to capture the current state of the data flows so that they can then be fundamentally re-organized using digital technologies (digitalized). Therefore, DEMA does not dictate how semantics will ultimately be augmented in the final digitalized system, but it provides a means by which the semantics can be identified. DEMA accomplishes this by capturing the relationships between data elements in the data element level view, and through the interview process used to create the data vessel level view which captures the context in which the data element originates and are used.

VII. CONCLUSION

DEMA is a novel approach for the standardized capture, mapping, and analysis of data and information flows to enable digitalization. Whereas past visual mapping has taken a functional, document, and software-centric views of a system, DEMA connects the system functions, data vessels, and data elements in three concrete steps. The DEMA process also systematically uncovers the invaluable tribal knowledge of the people who work in the system and uncovers hidden and undocumented processes and data. By utilizing the current state mappings at each of the DEMA steps, a kaizen approach can be utilized to incrementally connect the digital thread and eliminate inefficiencies in the system.

This research was limited to the application of DEMA and did not go beyond the application to realize the improved digital thread. Future work could utilize the results of this application to create a digital thread architecture to be used by the prototyping organization to enable the digital thread using product lifecycle management technology. Other future work could be conducted in applying DEMA to different types of systems. One example of this would be creating the digital thread alongside the development of a new system to enable the model-based enterprise in verification and validation processes. Ideally, software should be created to guide users through the DEMA process and automate the mappings created at each step.

Other future work could involve utilizing DEMA to define the data flows required to be represented in a digital twin. Also, future work may include the utilization of machine learning or artificial intelligence in eliminating wastes in the data and information flows captured by DEMA. This work would also include outputting optimized future states of the flows. In its current state, DEMA is not a language for data exchanges, and work could be conducted to enable DEMA results to be outputted in a way that is readable to languages such as SysML. Broader future work could utilize and evolve the DEMA process to be suitable for analyzing cyber-physical systems, lifecycles for sustainability, cyber-security, healthcare systems, and supply chains.

As the full impact of digital transformation continues to unfold, it is becoming increasing clear that digital transformation cannot be achieved by simply digitizing information or implementing stand-alone digital technologies. Past visual mapping techniques are suited for digitization rather than optimizing the flow, form, and handling of data elements to enable digitalization. DEMA bridges this gap to create a novel digital engineering that allows for the realization of the digital thread.

APPENDIX

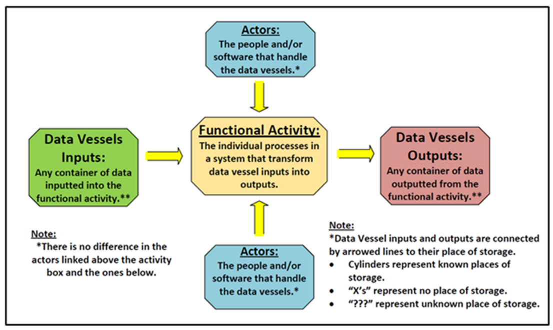


FIGURE 11. Data vessel mapping syntax.

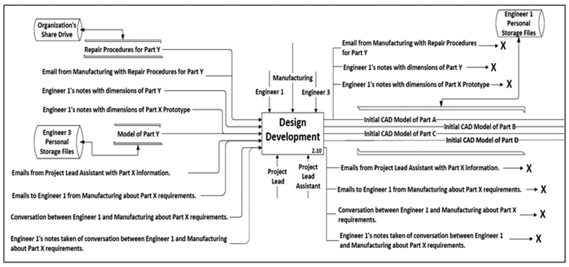
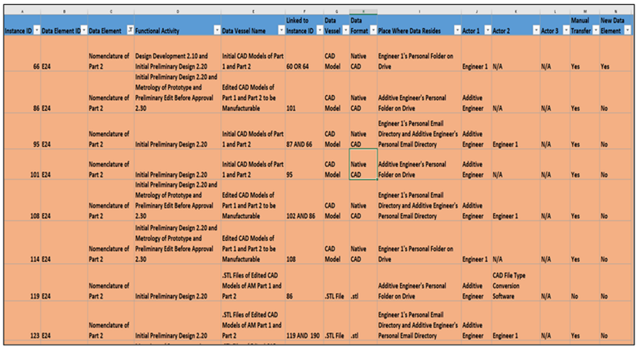


FIGURE 12. Engineering data vessel mapping first activity.



Instance ID	Data Element ID	Data Element	Functional Activity	Data Vessel Name	Linked to Instance ID	Data Vessel	Data Format	Place Where Data Resides	Actor 1	Actor 2	Actor 3	Manual Transfer	New Data Element
66	E24	Nomenclature of Part 2	Design Development 2.10 and Initial Preliminary Design 2.20	Initial CAD Models of Part 1 and Part 2	60 OR 64	CAD Model	Native CAD	Engineer 1's Personal Folder on Drive	Engineer 1	N/A	N/A	Yes	Yes
86	E24	Nomenclature of Part 2	Initial Preliminary Design 2.20 and Metrology of Prototype and Preliminary Edit Before Approval 2.30	Edited CAD Models of Part 1 and Part 2 to be Manufacturable	101	CAD Model	Native CAD	Additive Engineer's Personal Folder on Drive	Additive Engineer	N/A	N/A	Yes	No
95	E24	Nomenclature of Part 2	Initial Preliminary Design 2.20	Initial CAD Models of Part 1 and Part 2	87 AND 66	CAD Model	Native CAD	Engineer 1's Personal Email Directory and Additive Engineer's Personal Email Directory	Additive Engineer	Engineer 1	N/A	Yes	No
101	E24	Nomenclature of Part 2	Initial Preliminary Design 2.20	Initial CAD Models of Part 1 and Part 2	95	CAD Model	Native CAD	Additive Engineer's Personal Folder on Drive	Additive Engineer	N/A	N/A	Yes	No
108	E24	Nomenclature of Part 2	Initial Preliminary Design 2.20 and Metrology of Prototype and Preliminary Edit Before Approval 2.30	Edited CAD Models of Part 1 and Part 2 to be Manufacturable	102 AND 86	CAD Model	Native CAD	Engineer 1's Personal Email Directory and Additive Engineer's Personal Email Directory	Additive Engineer	Engineer 1	N/A	Yes	No
114	E24	Nomenclature of Part 2	Initial Preliminary Design 2.20 and Metrology of Prototype and Preliminary Edit Before Approval 2.30	Edited CAD Models of Part 1 and Part 2 to be Manufacturable	108	CAD Model	Native CAD	Engineer 1's Personal Folder on Drive	Engineer 1	N/A	N/A	Yes	No
119	E24	Nomenclature of Part 2	Initial Preliminary Design 2.20	.STL Files of Edited CAD Models of AM Part 1 and Part 2	86	.STL File	.stl	Additive Engineer's Personal Folder on Drive	Additive Engineer	CAD File Type Conversion Software	N/A	No	No
123	E24	Nomenclature of Part 2	Initial Preliminary Design 2.20	.STL Files of Edited CAD Models of AM Part 1 and Part 2	119 AND 190	.STL File	.stl	Engineer 1's Personal Email Directory and Additive Engineer's Personal Email Directory	Additive Engineer	Engineer 1	N/A	Yes	No

FIGURE 13. Example of isolated digital thread in data element view listing.

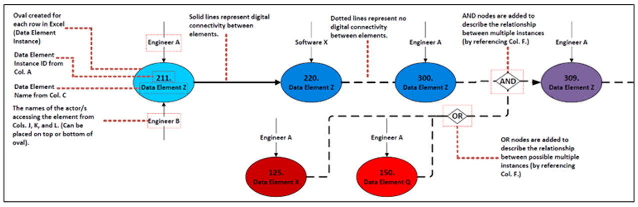


FIGURE 14. Syntax for creating data element mapping.

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