

NASA's Four-Layer Cake: Systematic Approach for Developing a Digital Transformation Tactical Plan for Organizations

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With the current industry movement to “digitally transform” there is much fervor to do something, to change in some way, to do things differently and digitally; however, the last decade has shown that most organizations do not know where to start or abandon transformation efforts. And often the approaches taken fall in the realm of “low-hanging fruit” or “easy wins” which rarely result in the foundational change needed. NASA was no different in the early years of its digital transformation and this drove the development of what eventually became known as the “Four-Layer Cake”. The Four-Layer Cake provides the critical approach for determining the core areas for investment to gain the greatest return without having to boil the ocean or hope that the low-hanging fruit will provide the foundational elements for a domain’s transformation.

I. Introduction

For organizations wanting to take on elements of digital transformation to address some key business or organizational goals, either wholesale across the board, or some subset, one of the biggest challenges heard repeatedly is, “Where do we start?” And often the approaches taken fall in the realm of “low-hanging fruit” or “easy wins” which rarely result in the foundational change needed. Over the last decade we have seen that many organizations never realize the desired results soon enough and result in the organization failing to meet their goals, with Forbes reporting that approximately 84% of companies fail at their digital transformation [1]. NASA was no different in the early years of its digital transformation [2] and this drove the development of what eventually became known as the “Four-Layer Cake”. The Four-Layer Cake provides a critical approach for determining the core areas for investment to gain the greatest return without having to boil the ocean or hope that the low-hanging fruit will provide the foundational elements for a domain’s transformation.

The four layers represent key focus areas for establishing a digital, or “data-centric / model-based” approach to managing work related to a specific domain, or “system of interest”. The domain can be an organization (i.e. a program or project office), a process (i.e. systems engineering), a physical system (i.e. a science mission system), software system (i.e. flight software system), or any other business unit.

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This paper lays out the four-layer construct which can be applied to a given domain to identify opportunities for investment, design, and implement a “Digitally Transformed” approach to performing the work of the domain and right-sized to the resources available. The four layers are: Domain Layer, Domain Architecture Layer, Data Construct Layer, and the Infrastructure Layer. This paper lays the purpose and content for each layer and provides a concise, yet simplified, example of this technique applied to creating a partial digital transformation analysis for Project Management reporting process.

The top layer, the “Domain Level” represents the mission of the given domain or business unit. As such, the Domain Layer captures why the domain (i.e. program, project, or organization) exists: to produce some explicit product(s), provide service(s), or provide capabilities. This layer also captures the external requirements on the domain (i.e. customer needs), the business value chain, any overarching external standards, and the deliverables from the domain (i.e. product(s)), or capabilities. The Domain Layer address the “What” that the domain is going to produce, and the constraints placed on it from outside the domain.

The second layer, the “Domain Architecture” layer, represents the internal description of the Domain, how it functions, how it goes about generating what it produces, along with the associated processes, constraints, and principles that shape its activities and governance. The Domain Architecture is constructed by defining the domain elements, their behaviors and activities (processes and performance measurements), and the internal requirements/constraints that govern its function. The domain architecture articulates product/service outcomes, quality, safety, security, efficiency – generally the desired ‘ilities’ of the value chain.

The third layer, the “Data Construct” layer, is a digital description of the domain architecture, such that when instantiated (i.e. the domain performs its role digitally) data and associated information products are consumed and acted upon by the domain and processes, products, services and/or capabilities. The Data Construct Layer defines the formats, curation, and governance of the data flowing into, through, and out of the domain. The Data Construct Layer also defines how external and internal stakeholders interact across the domain interface.

The fourth layer, the Infrastructure layer, is a definition of the infrastructure and encompasses the digital implementation of Data Construct and enables the external interaction with the domain, and the internal implementation of the domain function digitally. This layer describes the “Digital Enterprise Architecture”, consisting of infrastructure, model management and governance, and tools to enable the Data Construct layer to operate as part of performing the domain’s duties.

It is critical to understand each of these layers and their interdependence before performing the analysis to identify areas of investment with the goal of digitally transforming some, or all of the domain. Through mapping of each layer and the connections between them and the desired performance outcomes, organizations can quickly identify hot spots of inefficiency or missing capability. It is through the process of defining, mapping, and analyzing the first three layers and designing the fourth that the domain discovers why document centric processes need to evolve to accommodate digital processes, and thus realize the agility (awareness and flexibility) provided by digitally transforming the domain. This approach is foundational and is scalable from a small office all the way up to a government agency or large corporation.

II. Domain Layer

The top layer of the cake (Fig. 1), the beginning of the digital transformation journey, begins with the Domain layer. The domain layer captures the domain’s mission, any externally leveraged requirements, or constraints, as well as the inputs to and the outputs from the domain. The domain’s mission is usually captured by a well-defined set of need (or mission statement), goals, and objectives. Externally leveraged requirements and constraints impose rules on the domain’s operation and governance and can also include elements required by external stakeholders for monitoring and control purposes. Defining the domain in this manner can be seen as similar to describing a “system” in the traditional systems engineering process.

Systems engineering has been long recognized as a successful approach to aid in the execution of programs and projects by clearly defining the scope and minimizing the unforeseen issues in complex systems. As stated in NASA’s Systems Engineering Handbook: “The objective of systems engineering is to see that the system is designed, built, and can be operated so that it accomplishes its purpose safely in the most cost-effective way possible considering performance, cost, schedule, and risk.” [3, 4] The premise then is if systems engineering is the recommended approach

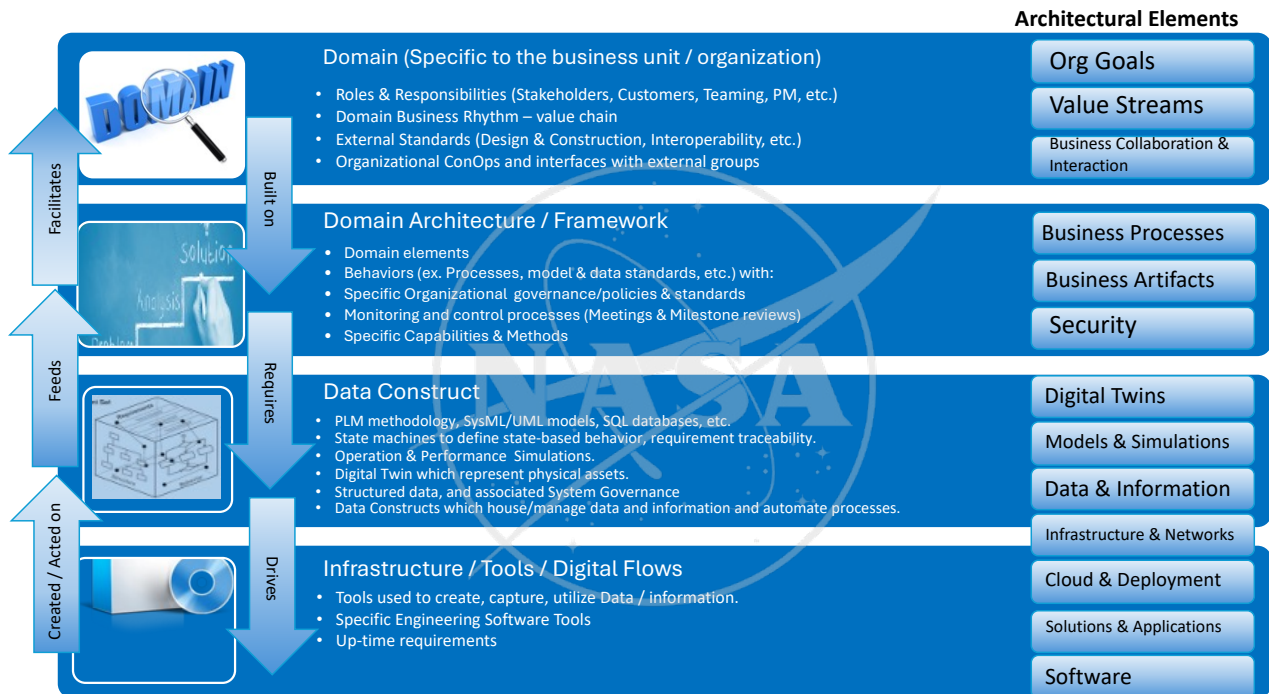


Fig. 1 NASA’s Four-Layer Cake providing a systematic approach to identifying opportunities for digital transformation investment.

to achieve those goals to deliver a product, vehicle, space craft, factory, etc., why would it not be an appropriate approach to treat the transformation of an organization as a finite project and apply tried and true systems engineering principals?

The Four-Layer Cake is simply a framework to communicate the systems engineering process to non-systems engineers, within the context of their domain. The phrases “system” and “systems engineering” often carry specific meaning to individuals and organizations, although they do not necessarily mean the same thing to everyone involved. The words Domain or Business Unit, rather than system, were found to be a more effective way to communicate with various organizations and lends itself to generalizing the systems engineering approach to be embraced outside of the traditional NASA systems of interest.

When establishing a new domain, teams will often start with a clean sheet of paper which can make the development of concept of operations and later system-level requirements easier. However, digital transformation of an existing organization doesn’t provide that luxury, and the larger and more complex the organization the harder it is to identify where to start with digital transformation. Even trying to determine if a proposed change would be effective becomes daunting, incredibly difficult to quantify, and usually involving multitudes of people with their own backgrounds, biases, and agendas. Think untangling a two-hundred-foot-high pile of Christmas lights and requiring one hundred people to detangle and change out the bulbs. It is no wonder most organizations give up on that approach and default to easy wins and low-hanging fruit. NASA has discovered that leveraging this framework with its own organizations, or domains, that are exploring transformation of their business processes has been helpful to bring cultures together and chart an implementable tactical plan. But it is equally important to be able to execute this approach at the lowest appropriate business unit via the Four-Layer Cake approach while understanding its interfaces with the next higher level, to make it a manageable endeavor.

The leveraging of the Four-Layer Cake as an enabling framework for transforming existing domains into digitally transformed versions of themselves has proven useful at NASA. To that end, one of the key tenants of systems engineering is the identification of the boundary of the system of interest and establishing well defined interfaces and standards by which it interacts with other systems. Perhaps surprisingly this layer often receives the least amount of discussion at the outset of a digital transformation activity. This is often due to assumptions that an existing organization requires minimal elaboration. NASA has found that regardless of the pre-existence of a given domain, discussion at this layer is often fruitful, to clarify why the domain exists, what products or services it produces, who their customers are, and their organizational requirements and associated performance goals. This clarification, in the

context of using digital means to improve performance, often articulates new requirements on the domain, particularly at its interfaces, where data enters the domain, and data, products, services and capabilities are delivered from the domain. Where digital transformation is part of a significant shift in the organizational business model, starting with the new capabilities or performance metrics is most appropriate. By understanding the desired end state, one can then work backwards in the temporal nature of their business operations to identify the needed changes or additions to processes, capabilities, data collected, and technology.

Starting with a robust exploration of the Domain Layer is usually fruitful because while the domain of interest is transforming to work digitally, the external stakeholders (or external domains) are taking this journey; likely most of your suppliers and competitors are as well. When looking to transform a domain to a digitally implemented domain, it is very important to pay attention to the data formats for inputs and outputs (both physical and digital) that cross the domain boundaries. This ensures external stakeholders provide products and data in formats that the domain can interpret digitally and provide digitally in formats ready for the external stakeholders to consume. Therefore, it is important to understand those external interfaces which may have digital components as well and will need to be addressed. This is often where modern tools and methods that already exist can be applied to an existing domain and ease the transition to Digital Implementation.

Further analysis on the Domain Layer will lead to questions about business relevance and internal vs. external change. NASA Engineering exists in many organizations throughout NASA, and work across the Government-Contractor interface. Many specific NASA Engineering processes in place have been honed over decades of programs, successes, failures, and lessons learned. Many think that to digitally transform such a domain, which is multi-organizational and multicultural requires individual organizations and specific roles to change how to they execute their work. In some cases that might be true, but what has been observed is that most of the cost and schedule associated with business lines is centered around people and how they spend their time. There is a study performed by a Harris Poll which states that most employees spend 25% of their average work week looking for information [5]. And in the Age of Information the leveraging of such is more and more important to our daily work and personal lives. So, if high-valued Engineering resources are spending time trying to find information in order to perform their jobs, one can start the digital transformation of Engineering domains by asking if changes on how the information flows to a domain may benefit work inside the domain. Changing the quality and format of data into the domain may have a profound impact on the ability a domain has to perform its work. Therefore, before mandating that a specific domain change its behavior, it is best to analyze what is expected of that domain, and how to best feed data and products within that domain.

This first step should thus be considered a significant element of the overall processes of your organization, but such analysis is just the beginning.

III. Domain Architecture / Framework Layer

The second layer in the cake, the Domain Architecture Layer, is a description of the domain's architecture, its elements, its behaviors and the internal constraints.

Similar to the Domain Layer, an existing domain will have much of this defined, and applying the four-layer framework is an opportunity to re-visit the existing architecture through the lens of modern-day tools and methods. Examining a domain's current "pain points", which cause the most significant time sinks and iteration may be re-defined as an enabling force behind a digital transformation.

Constructing the Domain Architecture Layer requires an understanding the workflows, with a focus on the content of physical products and data each element works upon, what content and form of physical products and data is required for the next step in the workflow and how data and product quality is monitored and controlled during the domain operations.

When the workflow is understood, an organization can then begin asking what kind of digital construct for which to manage the data and information and can enable the flow of products and information within the domain to improve the quality and speed of the workflow by ensuring consistency of information to all parts of the domain. Digital workflows, which minimize the amount of human in the loop data transfer and manual transformation from one format to another can improve speed at which data is shared, and ensure proper context associated with the data – representing improved knowledge flow, rather than simple data flow.

NASA has discovered that in most cases re-visiting the domains process as a team, facilitating the common understanding of organizational processes and the flow of information throughout and across the lifecycle of the products and services is critical. This shared activity often becomes the core catalyst of digital transformation, as the team's re-visiting of the domain's approach to work, within the context of its mission is explored with goals of leveraging digital technologies to free humans from the burdens of tasks better performed by computers.

While digital transformation is often associated and confused with upgrading software, building models, or basic digitization of paper processes, such a characterization is an oversimplification that can lead to upgrading software to perform work in the traditional manner and resulting in little to no benefit. It is the flow, sharing, and contextualization of information which is at the heart of successful digital transformation efforts. As such, evaluating the foundation of your organizational business rhythm (the heartbeat of your organization), and your core business practices associated with the business unit in question is so extremely important.

NASA has found that best practice is to analyze each existing process and must look at who is creating information, how are they delivering it, in what format, to what repository, who consumes that information, what format do they need to receive it, how is that information transferred from creator to consumer, what will the consumer of the information do with it, what will they deliver, and so on and so forth. Additionally, older organizations which relied first on paper to execute their processes and act as the data construct then later digitized to electronic documents, there's a high probability they didn't significantly change the nature of their processes during the digitization. Their processes thus remained largely serial because when it was executed by paper, only so many people could hold the piece of paper at one time which was actively part of the process as that was primarily where the information associated with the process was managed, and thus the process is highly serial until it came to the dissemination of the information. This level of analysis will inform high-value organizational or enterprise changes in terms of process automation and movement of information, but also interoperability requirements between systems and tools which will drive requirements for the lower two levels.

This analysis lends itself to the reconsideration of any form of 'paperwork' generation – real or digital. Where paper, reports or documents are used to transfer information from one element of a domain to another – the underlying reason should be explored. Where a document may be used today to signify an agreement, and thus shared information, a digital artifact may suffice just as well. And where a document must be read, interpreted and then the resulting knowledge gained leveraged to do additional work within the domain, information transferred from one element of a domain to another should be machine interpretable, where the next element can ingest it and work on it directly. Humans needed for decision making may still be required, or, where a set of rules can be established to process data and work on it directly.

Processes and associated workflows should already be in an existing ecosystem, and how often do such legacy processes require people enter data into forms which already exists somewhere in your domain? How often does one go to the doctor's office, and be asked to write on paper forms information you know already resides in their computer system? Wouldn't it be more value added for the patient to update/add new information to a record directly into their system? How many processes do you have within your organization like this? The creation of artifacts should now be considered for information sharing by exception, almost as a disposable medium, and only as a snapshot in time as part an authoritative source of truth repository until you're able to manage official data records in a structured format vs electronic documents or artifacts.

Another analogy that has become common at NASA is referring to "riding the satellite", looking at an organization's products and services from the top down logically, with document trees, product catalogs, forms, spreadsheets, schedules, rosters, and organizational charts. Challenging this approach to one where one "floats the river"; meaning put oneself in the viewpoint of the data, how it flows through various processes and associated systems across the temporal nature of a process, and thus understanding data and knowledge creation through a fully executed process resulting in the desired products and services. This approach allows a more deliberate exploration of chokepoints for the information flow, delays (manual or semiautomated transmission of information), disconnects (incompatible data format to allow automated processes or access from different tools), and the creation of redundant data sources. Similarly, it can be discovered that certain deliverables (such as documents and 2D drawings) may no longer add value to the organization, or more importantly, to those outside of the organization but may be necessary for data transformation within one's own domain as intermediate products or services. Ideally information flow should be unimpeded and gather in data reservoirs of which tools and workflows can pull from and add to fluidly and without interruption. It would be fair to say what is proposed here is not unlike both Lean Six Sigma and Kaizen methodologies which would be reasonable approaches if done from the perspective of the information flow in question.

Consider Domain D with two internal Business units A and B. If in a legacy process Business Unit A requires a set of heat loads for its office spaces (in Btu/hr). If it were to transfer the desired temperatures of each office to Business Unit B, in °F, and Business Unit B calculates heat loads from temperatures in °C, there could be a legacy role in Business Unit B that transforms all of the temperatures to °C and then passes them along to another role in Business Unit B that calculates the head loads (let's say in W). The heat load information is then sent back to Business Unit A – who may then need to have a legacy role to convert them to Btu/hr. In this circumstance, a digitally transformed workflow for Domain D may re-visit and establish that Business Unit A will deliver data to Business unit

B in °C, and receive them in W. This would then free Business Unit B to avoid the unit conversion step – and minimize an extra step (speed) and possible errors (effectiveness).

Understanding aforementioned disconnects due to incompatible data exchange formats will now serve as a basis for design in the third layer, Data Construct layer. Moving information in and out of common data repositories, rather than sending it to individual domain elements to operate on is duplicative work and can lead to inconsistency.

IV. Data Construct Layer

The information required to execute the processes and associated performance metrics has historically been managed on paper or similarly non-digital forms such as microfiche, with the last two to three decades resulting in the digitization of the paper to electronic versions but with the information still largely being managed within the digital document and not in a structured data construct. As discussed previously, the serial nature of the process builds in inefficiencies and completely orthogonal to the advantages gained via the digital approach. Instead of employees and system waiting to get information and then having to spend time converting it into a useful format, the analysis of the driving process should inform the Data Construct layer of where individuals could access the data on demand, in parallel, and in the format needed.

Early in the age of digitization, we thought we slayed that dragon by emailing out copies of the documents to hundreds of people at a time, who then forwarded on the information to hundreds more. Within a few years of this modern approach to sharing information at the speed of electrons, it was realized that ultimately people had outdated copies sent to them, and we then started including notes on the cover pages stating the consumer needed to verify it is the latest copy before using, which in turn required the consumer to search out the actual authoritative sources of truth (ASoT) of which may or may not be in the format they needed. This is a prime example of how many employees waste time every day and how the document-centric approach to information management facilities inefficient chasing of information. Therefore, in cases where the same information is needed by multiple consumers, opportunities for an ASoT, or federation of ASoTs, can be identified and investments made.

Understanding a process's data and information sources, format, consumers and corresponding required format, mechanism of the transference from one party to the next (manual vs. automate vs. on demand), and the associated transactional time cost and opportunities for injection of errors with every transaction requiring translation or reformatting of the data, will provide the basis for identifying high-value investment targets for digital transformation.

The identification of one or more ASoT drives the requirements to the Data Architecture layer in terms of transformation planning along with any additional metadata needed to provide greater leverage of corporate knowledge, which then manifests in changes to the process data constructs. It's also important to note the management and ultimately the curation of corporate engineering knowledge must first be both human readable, but also machine readable and tagged with the appropriate meta data. The latter is critical if ever knowledge mapping, ontologies, semantic search, a graph technology landscape, machine learning or artificial intelligence capabilities are to be fully leveraged. The data interoperability and automation requirements from the Domain Architecture process analysis inform the enterprise/infrastructure layer and only then should new tools be selected and implemented. This approach ensures the required capital investment will be rightsized and directly support the desired digital transformation outcomes; no more, no less.

These are not your father's databases. Simply put, simple database tables of yesterday will not provide the data construct needed in the next five to ten years. Referencing the Data-Information-Knowledge-Wisdom (DIKW) Pyramid, ultimately organizational decision making informed by wisdom is a layering of knowledge and information which all have a foundation on data. If your data isn't in good shape, well tagged, structured properly such that one layer of the pyramid is traceable forwards and backwards, then you will never have the appropriate information available to move at the needed speed of business going forward. Depending on the age of the organization, data systems and repositories may be home-grown and will need to be migrated to commercial solutions or at a minimum modernized to provide standard Application Programming Interface (API) exchange of information with the tools which will ultimately be selected in the assessment of the Infrastructure Layer [6]. Additionally, as the size of the data sets and sensitivity therein grows, taking Role-based Access Control (RBAC) and/or Attribute-based Access Control (ABAC), in addition to compliance with industry authorization standards like OAuth 2.0 (allows the granting of permissions to an application based on a user's credentials to access data in another application), increases in importance and the associated forethought should be applied as you walk through the analysis of the different cake layers.

There is no getting around the fact that our data assets can grow exponentially in the foreseeable future which will stress all aspects of infrastructure in addition to associate overhead costs, to say nothing of the fact that management and curation of said assets will largely not be humanly manageable via historical approaches and having a data scientist

as a friend definitely won't hurt either. In all seriousness, this is a skillset needed by medium-to-large organizations going forward to not only know how to leverage the organizational data to best inform decisions, but how to use the analytical tools required to provide the insight to fuel the desired competitive advantage or needed efficiencies. A data scientist perspective, informed by the organizational goals, on what information will be required to be managed, curated, analyzed, and combined to feed the DIKW pyramid is extremely important whilst assessing the Data Construct layer and will also form requirements placed upon the Infrastructure Layer not only in specific tool capabilities, but in the capture of new information not currently in the environment.

V. Infrastructure Layer

Ironically the Infrastructure Layer is where most organizations mistakenly start their transformation journey. Updating, replacing, adding new tools to an organization's environment and portfolio will do little in changing the digital transformation required for success and survival in the Fourth Industrial Revolution underway which is blurring the lines between the physical and digital world and wholesale changing society and how business is done. And keeping an eye on the emerging Fifth Industrial Revolution, which "encompasses the notion of harmonious human-machine collaborations, with a specific focus on the well-being of the multiple stakeholders (i.e., society, companies, employees, customers) ... and how humans and technology can collaborate, rather than one replacing the other". [7] Therefore, understanding the pace of change in technology and customer's expectations will continue to accelerate, a critical part of the analysis of this layer of the cake is the need for "plug-and-play" capability (compatible with recent promotion of Modular Open Systems Approach (MOSA) within the Department of Defense) with minimal disruption to the organization to allow nimble updating, augmentation, and pruning of the infrastructure and tooling. Understanding the aforementioned layers and the logical, process, data and associated interfaces is extremely important, and that they are done intentionally and not happenstantial.

Thus, understanding the roll-up of requirements from previous layer assessments has to take place in addition to resisting the urge to "just do something" prior to executing investments in the infrastructure. Of all the areas to manage as part of assessing the different layers, this may be the most difficult as it is much more closely linked with people's curiosity to explore new things and chase shiny objects, and emotions relating to a sense of pressure and urgency, or fear of being left behind, and on the opposite end of the spectrum the emotional resistance to change as many arrived in the place of authority via the ways business has been done in the past and when you change that it instills a subconscious insecurity of not being valued in the future with the new ways of doing business. Therefore, taking the emotion out of this effort is paramount, as every manager around can attest how many of their employees are emotionally attached to their preferred tools. Changes in tools or how tools are used as part of transformation also requires a level of dialogue with those affected by change. Having a clear message from senior leadership defining what the organization's objectives are, where the organization needs to get to, by when, and what success looks like, and what their world looks like if success is not obtained, is a very important first step. Follow on engagement with implementation managers and personnel as to how to achieve those organizational goals, either with current tooling or other, now makes them part of the journey and after which point their fingerprints will be part of the eventual solution and the organization benefits from the institutional, undocumented tribal knowledge of what works and what doesn't from those required to actually create and deliver the organizations products.

Don't be afraid to pick new tools. There are some cases when going with the new solution provider – with demonstrated agility and ability to keep pace with rapidly changing data/digital thread environment – is worth consideration. And as mentioned before with a long-term plug-and-play approach, this will provide greater flexibility to keep pace with technology while minimizing the disruption but must be baked into the infrastructure architecture and strategy as linked to the organization data management strategy and constructs. A few things to also consider in this new data-centric approach and the needed interoperability which the associated industry standards should support, is that when a software vendor reports they are compliant with said industry standards, often they are not fully compliant and should be evaluated before making any significant organization infrastructure investments. This non-compliance or lack of complete compliance with industry interoperability / data exchange standards can result due to a few reasons, some of which are outside the control of the vendors. There is natural tension between the industry standards bodies, comprised of the vendors and their customers, to create an agreed-to approach which allows the industrial private sector to be able to do business with multiple customers and multiple software solutions. However, these organizations which are largely voluntary with their participating members often with their own motivations, take a good deal of time to release and make changes to said standards, at which point the software vendors then make some attempt of compliance. This dance between vendors and standards is further complicated by competition pressures which drive innovation, which in turn drives new capabilities, which eventually will be desired by industry to be interoperable across the different tools.

Another facet of the current digital thread landscape is the usage of third-party software solutions to provide the connectivity between tools and ASoTs. Often referred to as ‘glueware’ or ‘data brokers’ (however this term has historically been used to refer to companies that collect and sell information), this rapidly evolving industry is creating capabilities at a surprising rate. Many in this field can create domain ontologies through the very process of creating the data mapping between each connection endpoint and by extension semantic search / graph capabilities. Much the same cautionary tale should be made in this area as was made with the interoperability standard compliance; not all company capabilities are the same, it is not guaranteed they will have out of the box connectors for the tools your organization uses, etc. However, the key things to remember in this area are: firstly, tool-to-tool connections sans glueware quickly create a n-squared connection overhead of which the math and associated labor cost to maintain become untenable; and second, until most if not of all the software vendors you use can freely interoperate with the other tools, some form of glueware will be in your organizational life. For most organizations trying to keep up or outpace this industry via home-grown efforts likely will not be value added.

It doesn’t go without saying as the other layers are being reevaluated, so too should the associated cyber security elements. Since the threat of cyber-attacks have been with us since the very beginning, many an organization’s approach to deal with this constantly evolving threat is to apply layer upon layer of security defenses and metaphorically build the city walls higher and higher. However, what has resulted after half a dozen decades of this approach, are organizational cyber environments where it is increasingly difficult and time consuming to connect their own assets which greatly retards, or all out hinders, their ability to undertake transformation at the pace of the overall industry. The current industry-recommended approach revolves around Zero Trust methodologies, and like digital engineering transformation, it is a unique journey for all of use depending on the current organizational state of affairs. But it should not be a missed opportunity to, in continuing the metaphor, fortify the external walls, but take down the vestigial organizational security barriers which were put in place decades ago. This is brought up at this level, simply because some of the zero-based approaches are applicable at this layer because of the need to understand what information is needed, like employee credential management, which needs to flow throughout the processes, be the backbone for allowing information to be accessed through the digital thread, facilitated by the toolchains, and of course a good plan of where this information will be originate and be managed.

VI. Example: Digital Project Management Cost & Schedule Reporting Transformation

Digital Transformation can be a little messy, particularly when different organizations participate in the same domain. To help bring life to the application of the Four-Layer Cake framework, a short example is provided here. In this example, we focus on a Project, called Science Observatory, that wants to improve the consistency and automation of projecting schedule changes as a function of a workflow change. This example defines a Domain Layer that is limited in scope, highlighting that digital transformation can be performed on a variable scope, it need not be comprehensive to be effective.

In this example, the Project Manager approaches the project team and asks them to perform a Digital Transformation on the ability to understand how the project schedule and costs may change when the Payload provider needs to change their delivery dates. Therefore, the Domain of this particular activity is a relatively small part of the Project Office – and the external stakeholders are the Payload Deliverer and the Project Manager.

Figure 2 shows an application of the Domain and Domain Architecture layers for this simple example. The Domain Layer identifies the external stakeholders to this specific Domain and constraints on the domain. The Domain Architecture Layer then identifies the architecture elements including the associated business processes and recommended changes of the Digital Transformation effort to achieve the desired results defined by the Project Manager.

For the Data Construct Layer, the individual elements of the domain (Systems Engineer, Project Scheduler and Project Cost Manager) must establish how they manage their own data, including the formats that it enters and leaves their individual Digital Constructs and the larger business process. Figure 3 shows an application of the Digital Construct Layer.

The interface between the Data Construct Layer and Infrastructure layer can often be confusing to teams looking to employ digital transformation. Often individual people and/or business units may have software that they are comfortable with and may be reluctant to change. It is therefore important to ensure that the Data Construct Layer applies tool agnostic behaviors and methodologies which can be performed a multitude of different ways. It is the role of the Infrastructure Layer to establish how to meet the data collection and management of the Data Construct Layer (Fig. 4). It is also important to note, that good communication between the team members establishing the appropriate use cases associated with how the perform their duties with respect to the organization’s business processes and the associated logic of the Data Construct Layer and the developers of the Infrastructure Layer. This helps ensure proper

discussions take place about legacy tools and activities, and how they may want to evolve over the course of the Digital Transformation.

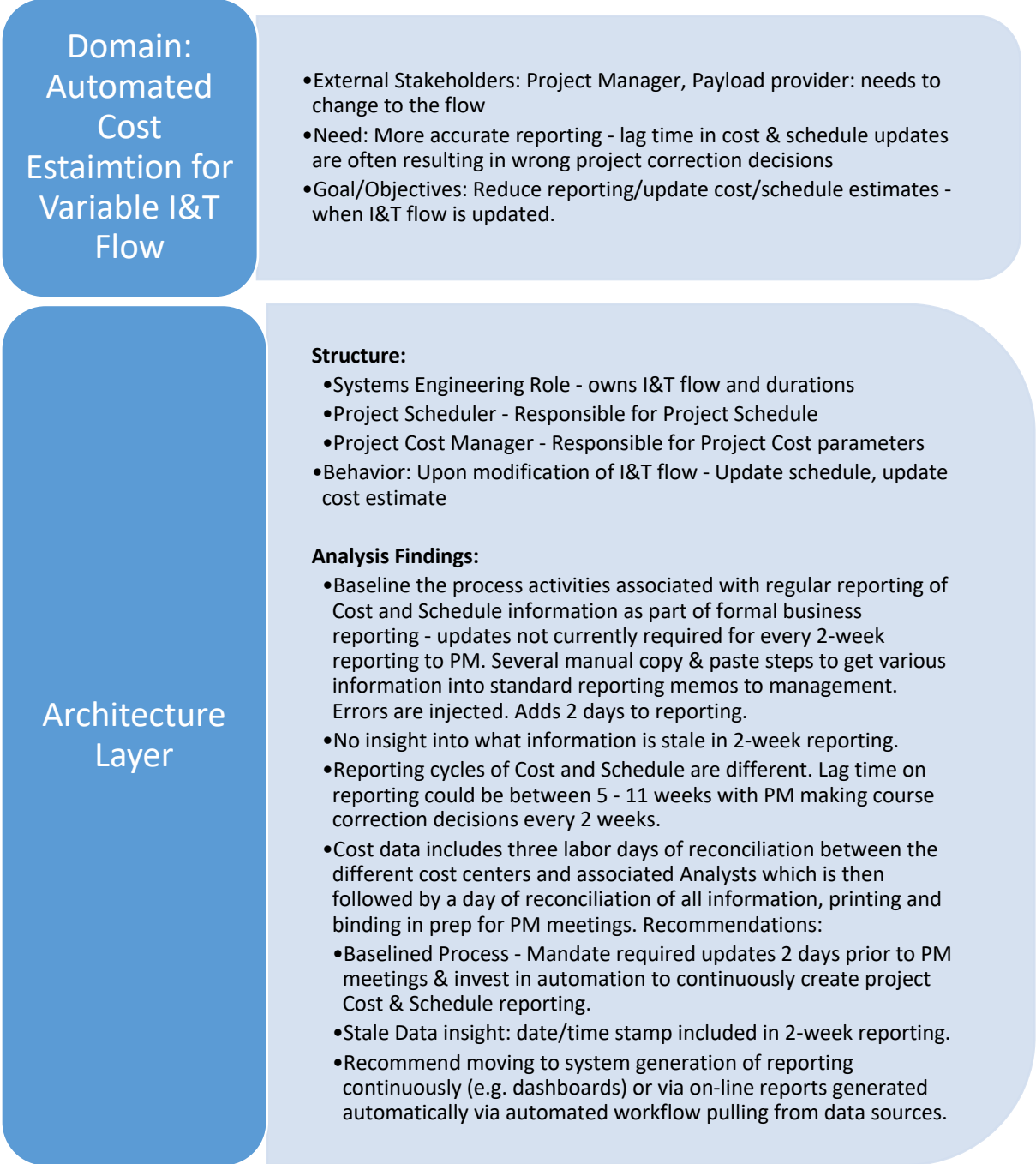


Fig. 2 Example of an application of the Domain and Domain Architecture identifying the external stakeholders to this specific Domain and constraints on the domain along with the architecture elements including the associated business processes.

Data Construct Layer

Analysis Findings:

- SE: Flow diagram, in SysML language, with durations for activities captured as properties of the specific I&T activities which is redundant and often different than durations tracked in project schedules. No connection between project scope (requirements) and Cost and Schedule.
- Schedulers: Schedule managed in project schedules with master files residing on the various computers of the different schedule manager's computers with no linkage to a master company schedule. Often linkages between activities and durations do not exist in different schedules - consistency issue between schedule managers.
- Budget Analysts: Data is managed in spreadsheets which resided on the computers of the different Analysts and not linked to a central spreadsheet or cost accounting system but sometimes done ad hoc for special company reporting efforts. The information tracked and associated level of detail is not consistent across Analysts.
- Output: Information from project schedules must be either printed to a PDF file which is then printed out for PM meetings or must be exported to .csv file which is then opened in spreadsheets and that info is then copy & pasted into a PowerPoint chart which is then printed for PM meetings. Similar efforts for Cost data.

Recommendations:

- SE: Data managed in the SysML model should not be duplicative of information managed more appropriately elsewhere (e.g. task durations in project schedule), but can link to said sources when appropriate.
- Budget Analysts: Consistent information should be tracked and managed across Analysts. Should have a central company cost and accounting system, or at a minimum have linked and synced accounting spreadsheets.
- Digital Thread Requirements to Infrastructure Layer: Minimal investment in glueware tool which will integrate SysML data, project schedule, and spreadsheets via appropriate API integration. If current tools cannot be integrated, recommend migrating to right-sized commercial tool which can.
- Data management: ensure there are key data fields in the company data repositories which are used to link the appropriate information to enable reporting and data mining and future analytics. Related, meta data should be appropriately, and automatically applied by the systems to ensure future leveraging of AI/ML capabilities.

Fig. 3 An application of the Digital Construct Layer illustrating the type of analysis and associated recommended changes to best facilitate the desired flow of information and increase in reporting accuracy with a decrease in reporting latency.

Infrastructure Layer

Analysis Findings and Recommendations:

- Implementing an Integrated Project Schedule Server would reduce the company operational costs associated with usage of project schedule and associated license costs by 30% and would provide a central reporting, management and integration of different project schedules.
- Moving from individual instances of office/word processing software installed on each employees' computers, moving to an enterprise approach would improve the integration, communication, and data sharing in addition to approx. 10% in overhead savings.
- Implement a glueware server which will:
 - Detect a change to the SysML file that holds the I&T Flow and project scope requirements
 - Pulls activities by name, their linkages and durations
 - Communicate the changes to activities, their linkages and durations to linked dashboards and automated report generation tools and environments to notify changes from baseline / last reporting have occurred and attention needs to be paid.
 - Automatically publish project schedule(s) and link to organizational master schedule.
 - Automatically publish project costs of activities as a function of time and in responses to approved changes to the baseline to get new costs and link to organizational master cost accounting system.

Fig. 4 Example analysis and recommended changes to the organizational Infrastructure Layer considering the requirements from the Data Construct layer in context of the current deployed capabilities of the org.

Highlighting a perhaps oversimplified and limited cost and schedule reporting improvement example, which admittedly is a bit of a nightmare situation of inefficiency, was a deliberate choice in this example as it gives deference to the existing domain stakeholders to maintain their own tools, and likely has semblance at some level of needed improvements you recognize within your own organization. In this example the SE role has declared in the Data Construct Layer that they will manage their information in a more modern SysML modeling tool, while the project scheduler and cost estimator state declare the use of their legacy tools. Of course, through the process of working through the different levels of the cake it will require senior leadership to determine if allowing personnel to stay with legacy systems and all that will be required to achieve the desired results outweighs the investment needed to move to a new tool or platform which can be easier integrated and achieved the desired return on investment.

Therefore, the Infrastructure Layer is following the logic declared in the Data Construct Layer and serving a role of data manipulation and interfacing via APIs for individual software packages to manipulate, transform the data, and connect with the ASoT. This digital transformation has deliberately automated much of what was human-in-the-loop with respect to data collection and transformation. The Infrastructure Layer implements automation (for speed) and communicates directly with the data sources (for accuracy).

Conclusion

To be direct and clear, the Domain Architecture Layer is the critically important initial area to focus on as part of digital transformation, especially for organizations which have been around for more than a decade. This area is the centroid of how your organization operates, drives the flow of required information, how it flows, and will drive all meaningful digital transformation in all the other layers of the cake and your organization. This is where the foundational changes will happen, and it should also be said, this work is not sexy and many will shy away, but it needs to be emphasized this is where the meaningful work happens and will set the course of your transformation. It is not recommended that additional transformation investment be made until due diligence has been paid to understanding your business processes (business, human resources, procurement, engineering, operations, logistics, etc.), associated pain points, inefficiencies, and possible gaps when regarding new needed capabilities.

Digital Transformation is hard. The exercise involves modernizing tools and methods, while analyzing the Domain's purpose, architecture and function and ultimately establishing a data platform to implement digital data streams. While there is no single secret recipe for managing an organizational change of the magnitude of the current digital transformation movement, we can rely on tested methods of framing our problems. NASA has established a Four-Layer Cake framework that is used to frame digital transformation efforts in a common framework and a manageable size/scope which has helped organizations better implement digital transformations.

The Four-Layer Cake has its foundations in Engineering and the systematic development of tiered requirements which then drive execution and procurement plans. Taking a traditional systems engineering approach to mapping the organizations desired outcomes to the business processes which drive the delivery of associated products and services, to the mapping of said processes, identified needed changes to the processes, automation, interoperability, data constructs and finally to the infrastructure will provide an objective scope which can then be mapped unemotionally to an implementation plan informed by the available planned resources. Transforming your organization is no different than any other complex engineering undertaking in the last fifty years.

Outside of bounding the digital transformation effort for your organization, the most challenging part of this is re-thinking your processes from the data-centric perspective and the associated changes to your culture – digital transformation is not a technology challenge. Understanding the flow of information throughout the lifecycle of your processes, who is creating the information, where it is created, where it is going, who will be using it, how it will be used, are all critical points of understanding before getting too far into your digital transformation journey and certainly before you start picking new software and redesigning your enterprise architecture.

Unlike the project reporting example provided, the larger and older an organization is, the more complex the business processes, how they are connected to one another, and more complex still, how and where the support information and data are managed, and even more complex still, the myriad of tools comprising the organization's software portfolio. This complexity is why the systematic Four-Layer Cake approach is important because of its scalability to any size of an organization, or any level of groups within, and doesn't require the boiling of the oceans to define and implement meaningful digital transformation of any domain given limited investment resources.

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