Creating and Deploying Digital Twins In The Process Industries

ARC White Paper
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This white paper provides guidance on digital readiness, preparing the process industry for successful digital transformation. Readiness includes a minimum threshold of digital maturity in resources, systems, organization and culture, upon which digital activities can be built, aligned with business strategy. Constructing digital twins as part of the digitalization process can improve performance in engineering, operations and maintenance, among others, provided there is a company-wide, consistent approach that is supported by corporate digital strategy. The white paper discusses skills and competencies, IT architectures, collaboration, and culture change, required to support the successful application of digital twins.

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VISION, EXPERIENCE, ANSWERS FOR INDUSTRY

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Executive Overview

A digital twin is a representation of a physical asset that has a level of completeness and accuracy and includes context information that allows the user to understand its behavior and performance. We differentiate project digital twins used in engineering and construction, and performance digital twins used in operations and maintenance.

The basis for a digital twin is accurate, up-to-date and accessible asset information. Properly managed and deployed, the digital twin changes over the asset lifecycle time line to reflect the asset changes such that the user can see crucial information about how the physical asset is or was performing in the real world. On top of this basic digital twin, more sophisticated aspects of the twin can be constructed, such as engineering calculations, process simulation, 3D models, construction modeling, and immersive simulation. The different aspects of the digital twin are highly interdependent and their accuracy and currency impact on each other's performance and thereby project or plant performance. Therefore, data integrity and quality of data making up the digital twin must be managed efficiently through data governance[1].

This white paper provides guidance on digital readiness, preparing the process industry for successful digital transformation. Readiness includes a minimum threshold of digital maturity in resources, systems, organization and culture, upon which digital activities can be built, aligned with business strategy. Constructing digital twins as part of digitalization can improve performance in engineering, operations and maintenance, among others, provided there is a company-wide, consistent approach that is supported by corporate digital strategy. The paper discusses skills and competencies, IT architectures, collaboration and culture change, required to support the successful application of digital twins.

In our view, an organization is digitally ready when it has reached a minimum threshold of digital maturity in resources, systems, organization and culture that are required to achieve success through digital transformation. The organization can leverage this digital foundation to build digital infrastructure and activities to reach the levels of digital maturity required to execute its strategy efficiently; and maximize the performance of the organization by supporting digital or traditional activities. Every organization should determine which level of digital maturity and digital performance is optimal for its situation.

[1] DiStefano, R.S. and S.J. Thomas, "Asset Data Integrity Is Serious Business," Industrial Press, 2010.

The white paper discusses minimum threshold digital maturity, how digital twins can be built based on asset information, and how they must be maintained and kept consistent. As collaboration in company networks and value chain ecosystems gain importance in the digital era, an effective IT architecture facilitating collaboration and data federation (rather than replication), are open connected data environments. The white paper describes what culture is, and how it can enable or destroy digital transformation. We suggest starting points in changing culture, mindset, and behavior. The white paper discusses skills and competencies required to create, deploy, and maintain a system of digital twins; and concludes with possible applications and expected benefits of using digital twins, which include:

- Improved operational and asset performance
- Improved engineering and maintenance efficiency
- Increased quality time for engineering and less time spent on data and IT tasks
- Reduced downtime, less equipment damage, and most likely a reduction in information-related incidents and accidents
- Reduced operational and IT risks

Digital Readiness and Digital Twins

Before diving into Digital Twins, it is useful to consider how Digital Twins fit into a company's digital strategy. Strategy should define the level of digital maturity necessary to execute the company's general strategy. Digital strategy must therefore be a subset of general strategy. Therefore, digital strategy should focus on creating value for the business and not be restricted to technology implementation or use.

Skills are abilities and competencies are a set of behaviors motivated by an intent and selected to optimally fit a situation. Skills can be technical abilities, whereas a competency can be the way these are applied to reach an optimum result[2].

A digital foundation is needed to build digital activities upon to support digital and traditional activities. Together these are called digital transformation. This foundation or digital threshold maturity may have been underestimated by companies. The foundation includes:

- Digital competencies of employees.

[2] Boyatzis, R.E., "Competencies as a behavioral approach to emotional intelligence", J. Management Development, 28 (9), pp. 749-770, 2009.

- Digital information provided by assets in research, development, production, and supply chain, by ecosystem partners and by smart products in use.
- Information systems provide sufficient quality and quantity of information required to make decisions in all functional areas, that is, provide sufficient vertical and horizontal integration. These systems should support the organization and the processes to analyze information locally or centrally and visualize relevant, contextualized, and role-based information to those who need to use it.
- In terms of organization and management, the agility and flexibility required by global and transparent supply chains requires flexible ecosystems, both inside the enterprise and in its supply chain network.
- Agile, flexible ecosystems can only be effective with less emphasis on hierarchy and more on processes, and rules, performance goals and autonomy, decision latitude and limits, and responsibility of employees in those ecosystems. The cost of centralized decision-making and optimization is justified where global synergies can be obtained, but the cost effectiveness and speed of local decision making is preferred in other cases.
- Culture is a key ingredient of Industry 4.0 or Smart Manufacturing. Collaboration and open communication used to be an advantage, but they are becoming key requirements. These patterns of behavior are built on trust, group identity and group efficacy, requiring modern people management approaches.
- Employees must be willing to review and adapt their behavior in response to a changing environment. They may have to adjust their skills and competencies in domains they could not anticipate in the past and this may be at odds with their professional identity. Willingness to change cannot be imposed, but must be coached, which defines a management capability for digitally transforming companies.
- Employees must be willing to be guided by data and fact-based systems, which requires tribal knowledge to be examined and transformed into observation-based standards. For acceptance and optimal usage, employees need to understand how systems generate recommendations and give them the opportunity to enrich and improve them.

We discussed the elements of digital readiness starting with technical aspects and ending with human and cultural aspects. A roadmap for implementation should follow a reverse order, to prepare the organization to implement the technical and organizational changes. A summary of criteria of digital readiness is provided in the Appendix.

With this foundation, companies can choose for which topics or projects, they want to reach their ideal level of digital maturity: digitalization, connectivity, visibility, transparency, predictive capability or self-optimizing adaptability. A systematic approach could include a maturity assessment and road mapping[3]. Behavior, norms and culture have been discussed by the author at Bentley's Year in Infrastructure conference 2018.[4]

Bentley Systems serves process industries, power generation, utilities, and mining, as well as transportation infrastructure, and smart cities, with digital engineering modeling capabilities throughout the project and asset lifecycle.
Digital engineering models can be used for design, structural analysis, construction planning, or asset information, integrity and performance modeling. Beyond engineering technology (ET), these models are also linked to information and processes in enterprise information technology (IT) and operational technology (OT).
Bentley Systems provides a range of products for process industries including PlantSight™, OpenPlant, PlantWise, AssetWise™, ProjectWise™, ContextCapture, and iTwin™ Services.

The digital strategy must work hand in hand with governance that identifies resources, financing, reviews results, and provides input to strategy adjustment. It is important not to get overwhelmed with technology choices[5] but to experiment and innovate with a business focus, and scale-up promising proofs-of-concept to generate enterprise-level benefits. This needs to include cost-benefit estimations, cash flow calculations, and prioritization of digitalization projects.

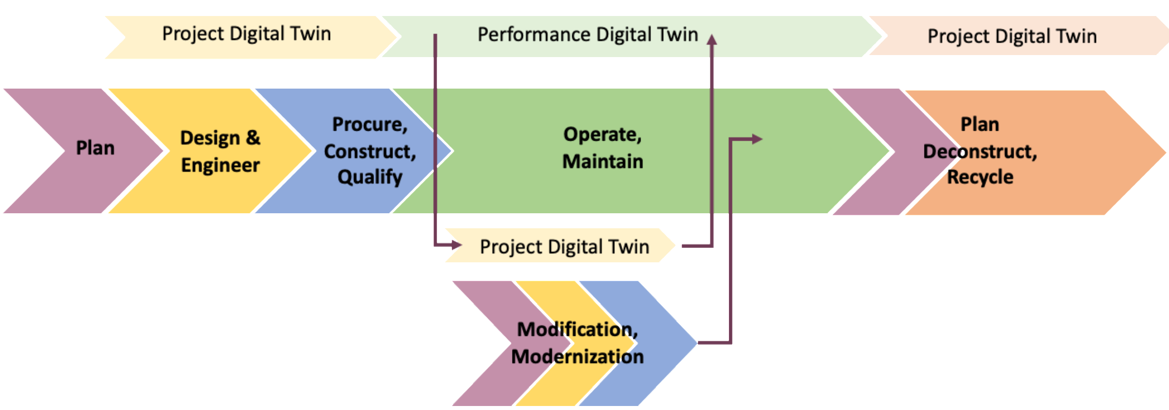
Digital projects or initiatives can include the implementation of new technologies applied to improving or innovating business processes, new, possibly smart products and services. The latter can lead to new sources of income. Creating and managing digital twins can be one of the initiatives that a company embarks upon. What these are, how they can be constructed and maintained, and which value adding applications can use a digital twin is the subject of the remainder of this white paper.

[3] Schuh, G., et al. (Eds.), "Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies" (acatech STUDY), Herbert Utz Verlag, 2017.
[4] De Leeuw, V., "Digital transformation In The Process Industry."
Asset Lifecycle Information Management" presentation at Year In Infrastructure, London, 2018.
[5] Guilfoyle, M., "Developing and Executing Digital Transformation Strategies," ARC Advisory Group, January 2019.

Digital Twins

Representing a physical object digitally is a starting point of digitalization. Every day we scan documents, or we take pictures with our smart phones of documents and assets, but these are not digital twins. To be a twin, these should reach a level of completeness and accuracy, and include context information that allows the user to understand its behavior and performance. A digital twin can be continuously synchronized from multiple sources, including sensors and continuous surveying, to represent its near real-time status, working condition or position. A digital representation reflecting the state of an asset at a point in time in the past may provide useful information to understand which decisions and actions led to the current state.

The lifecycle of an industrial asset can be broken down into "*design and build,*" "*operate and maintain,*" and if relevant, "*deconstruct and recycle*" phases. In this paper we distinguish *project digital twins* used in construction and deconstruction phases, and *performance digital twin* used in the operation phase. In the case of greenfield plants, rare in the developed economies and more common in developing economies, the project digital twin can seamlessly transition to its role of performance digital twin. The engineering information, enriched with detailed equipment and qualification information is handed over to operations, and further enriched with operations and maintenance information. This process is far from perfect in the large majority of handovers and there is consensus that the average cost of poor handover is several percent of the total capital expenditure![6]



Usage of Digital Twins Along the Industrial Asset Lifecycle

[6] Gallaher et al., "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry," NIST report GCR 04-867, 2004.

Today, it is possible to handover the complete digital twin and keep it evergreen. This *performance digital twin* starts deviating over time from the project digital twin because if equipment is modified or replaced, equipment performance changes due to fouling, wear and tear, etc. When modification, modernization, debottlenecking or turnarounds are planned, it is necessary to create a new project digital twin (based on the most current performance digital twin) and engineer the modifications in parallel with the operation of the plant, until shutdown. At the point construction and qualification take place, any changes in construction compared to design are captured in the project twin, after which a reconciliation step may be necessary to combine the latest changes in the performance twin with the information from the project twin to serve as a starting point for the updated performance twin. This is easy to do in a side-by-side view of differences and a step-by-step process for approval or rejection of changes.

Asset Information as Foundation for Digital Twins

The basis of a digital twin is asset information that is needed to understand and model the asset. As shown in Table 1, ARC considers assets in the

Physical Assets		**Human Assets**		**Virtual Assets**	
Primary	*Support*	*Program-centric*	*Asset-centric*	*Reference data*	*Activity records*
Facilities	IT HW / SW	Project Management	Operations	Functional Design	Commercial Status
Equipment	Mobile	Engineering Design	Process Engineering	Procedural	History
Remote	MRO	Procurement	Maintenance		
	Material	Construction	Reliability		

Table 1: Asset Categories

broadest possible way[7], to make sure to take all interdependencies in the main business processes portfolio, project and asset performance management into account. Beyond physical assets, we consider human and intellectual assets. While up-to-date engineering information is most critical to understand asset performance and make maintenance decisions, other virtual assets besides engineering information are included in a digital twin.

Examples of asset information types needed by business processes are listed in Table 2. Once this basic digital twin is complete, up-to-date and accurate, the enterprise can start using the information. To be usable, the information must be easily accessible to those who need it. There are several aspects of access that need consideration:

Project Performance Management	Asset Performance Management	Portfolio Management
Schedules	Operational data	Asset and project performance
Budgets	Analyses	Risk profiles
Analyses	Permits	Resource availability
Design, Equipment data	Procedures, practices	Company strategy
Bills of material	Recipes	Etc.
Purchase Orders	Materials	Etc.
Contracts	Equipment data	
Status	Contracts and Warranties	
Etc.	Maintenance history	
	Etc.	

Table 2. Asset Information Needs by Business Process

- During the *design and build* phases, owner-operators interact with engineering, procurement and construction companies, equipment builders, ground and road work companies, regulators, and auditors, etc. During *operate and maintain* phases, equipment providers, maintenance service providers, licensors, instrumentation and automation providers, and others may interact in a network setting. As many parties and stakeholders contribute to the asset information (project or performance twin), it is important to have agreements about property, access, and decision rights

[7] De Leeuw, V.V. and S.R. Snitkin, "Asset Information Management, From Strategy to Benefit," In: Proceedings of the 7th International Conference on Product Lifecycle Management, Berlin, 2010.

in place, and ideally these must be enforceable by the software solution used (see: A Cloud-based Collaborative Environment).

- To improve effectiveness and reduce the cost of asset information exchanges, a standardized information model can be used, specifying the content of specific information and where it is stored. The recent increase in the number of publications on the topic indicates its importance across industries. The main international standard is ISO 15926. In this article we recently summarized the status of standardization activities in this domain. There are many variants and extensions of ISO 15926 being worked on, many of which are specific to industry sectors. We discuss most of those in this overview that also includes asset performance management standards. While ISO 15926 and its extensions can be perfected, extended and aligned, they are able to deliver benefits in the current state.[8]

As the amount of data for a basic digital twin is huge and the importance of accuracy and currency is high, it requires a data governance process to monitor the degree of completeness, accuracy, integrity, and currency including management of changes. With modern dashboarding tools, this is not as daunting a task as it may seem. The effort spent will pay off in more accurate operations and maintenance decisions that will improve performance, process and occupational safety, and environmental impact. Reliability will likely increase, and maintenance costs will decrease.

Consistency Among Different Aspects of Digital Twins

With this basic digital project or performance twin in place, the user can start building more sophisticated aspects of the digital twin. Depending on the company's priorities and expected benefits, this could include steady-state process simulation and optimization, transient process models, predictive maintenance and asset performance management, immersive operator training, reality mesh based on surveying and/or 3D models or supply chain models. These would all be based on a single basic digital twin[9] (see also: Applications and Benefits).

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[8] De Leeuw, V., "Standards-based Asset Management, Information and Performance Management," ARC Strategies, October 2016.
[9] Otten, W. et al., "Engineering without structured Data?" Presentation at the NAMUR General Assembly, November 2018.

In greenfield plants there is an opportunity to build sophisticated aspects of the twin when the basic digital twin is complete. The aspects of the twin can link shared parameters, to ensure consistency over time. Many brownfield plants may have created some of these sophisticated models, before the basic digital twin existed. Asset information is often scattered over systems, files, paper and other disconnected sources. It does represent an investment to reconcile those models with the basic digital twin, and to link parameters, and re-establish consistency. The pay-off is the increased value of those pre-existing models and the improved accuracy of their results. It will also ensure the consistency of the different detail models. For example, if a transient model runs until steady state is reached, the results obtained should be identical to those obtained from steady-state process simulation running at the same conditions. This will only be the case if the asset and material information used is identical, that is, based on one and the same basic digital twin. The management of consistency of those models should be part of the data governance activities.

A Cloud-based Collaborative Environment

Looking back through the different requirements for managing asset information and digital twins, we must conclude that we need a cloud-based environment enabling different stakeholders and partners in the ecosystems to collaborate efficiently and safely. This includes cybersecurity and protection of intellectual property and data.

Bentley System's iTwin Services enable users to incorporate engineering data, reality data, and other associated data—from diverse design tools and other sources—into a living digital twin, with no disruption to their current tools or processes. Users can track and visualize changes including real-world conditions from instrumentation, sensors, IoT devices, or drones. iTwin Services facilitate actionable insights for decision makers across the project and asset lifecycle. This can lead to users making better and more informed decisions, anticipation and avoiding issues before they arise, and reacting more quickly and more accurately, resulting in cost savings, improved service availability, lower environmental impact, and improved safety.

Bentley Systems has developed iTwin™ Services as an open, scalable platform for digital twins. The set of cloud services enables organizations to create, visualize and analyze digital twins of projects and assets. iTwin™ Services include reality modeling, 3D web visualization, and 4D change synchronization technologies within an open, connected data environment (CDE) for efficient and safe collaboration.

In the capital project phase, different parties may work with the data they are allowed to see, use or modify, they can add their proprietary information, part of which may be hidden for others if they decide so, and they may share parts of the results of their work under conditions they have agreed upon with the other parties. Each party accesses a different subset of the total available information, depending on their rights.

In the operational phase, engineering, operations and maintenance have access to one federated source of asset information, and can aggregate and analyze multiple conditions from traditional and IoT connected devices to facilitate actionable insights for decision makers across the organization and asset lifecycle, anticipate and avoid issues before they arise, and act more quickly with confidence, resulting in cost savings, improved service availability, lower environmental impact, and improved worker safety.

Bentley Systems and Siemens have collaborated to develop PlantSight™ to deliver the digital twin environment for process industries, built upon iTwin™ Services. As a set of microservices, PlantSight includes a web portal view for collaborative process engineering and functional asset information management (that is, 1D information such as specifications and data sheets and 2D schematics), to 3D design and physical asset modeling (such as physical layout, positions and location). Furthermore, it provides line of sight from asset and project management perspectives including design

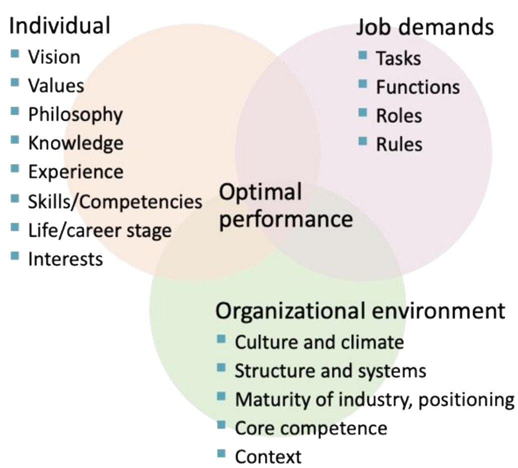
A Reality Mesh Model with Functional Context: Highlighted Areas Are Identified Process Units with Properties (Image Courtesy: Bentley Systems)

specifications, maintenance history, reliability data and failure mode analyses, plus analytics services to aid in making timely and informed decisions.

Many functionalities draw on software and accumulated know-how and experience that both companies Bentley Systems and Siemens bring to the market today. The user will be able to use pre-existing 3D plant models or projects authored in most available 3D design tools and mix and match those with models based on photogrammetry or 3D point clouds to create a "reality mesh." [10]

The solution facilitates the construction of the digital twin as a federation from many sources, that will not only include project and operations repositories and files, but also information in IT systems, such as an enterprise asset management system, usually part of the ERP. The operating plant has the possibility to connect the digital twin with operational technologies (OT), such as automation software asset health or production performance dashboards or build their own apps based on information in the twin.

The iTwin™ services record the changes made over time to the digital twin, and a user can rewind to any desired point on the time line. The solution has several tools to view difficult-to-access data, mechanisms to validate (or invalidate) those data, thereby increasing the trust in the information and facilitating data governance.



A Contingency Model for Performance (Source: R. Boyatzis)

[10] De Leeuw, V., "Bentley's and Siemens' [Vision for Cloud- based Distributed Engineering and Operations,]" White Paper, ARC Advisory Group, June 2018.

Mindset, Culture, and Behavior

Mindset and culture are essential ingredients of smart manufacturing operations. During the introduction of lean manufacturing and six sigma similar effects have been observed. If plans for change, such as introducing Industry 4.0 or collaborative cloud-based engineering are at odds with culture or team norms, the symptoms can include resistance, demotivation, turnover, absenteeism, productivity drops, and destroy the best-laid plans. This happens when the fit between individual or group characteristics have drifted away from job demands and the organizational environment have drifted apart[11]. For example, it is often said that tolerance for failure and willingness to learn from mistakes is essential in the era of digitalization, but it is easier said than done to change the fear for being perceived to be inadequate.

The challenge with culture and mindset is that they concern deeply ingrained values, beliefs, habits and rules most of which are implicit or subconscious. This subconscious content could be compared with dark data about industrial assets. They are not impossible to access and validate, but it requires a methodology and a certain effort.

Resonant leaders are capable of having open conversations with individuals and teams, and make subconscious beliefs, values, identities and implicit rules explicit[12]. Brought to awareness, the individual and collective beliefs, values, and operating philosophies can be discussed and changed through consideration, coaching, training, role modeling, appropriate performance goals and reward systems, and human-centered work design where people are assigned tasks where they provide unique added value. Organizations are multi-leveled complex systems, which implies they do not behave linearly but can flip their behavior according to tipping points[13]. This implies that the organizational culture should be changed for the enterprise as a

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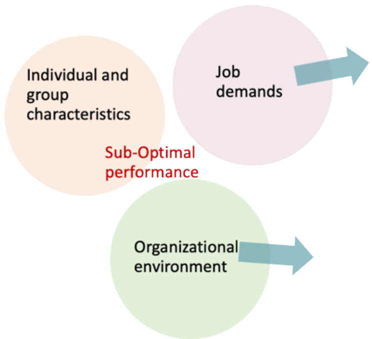
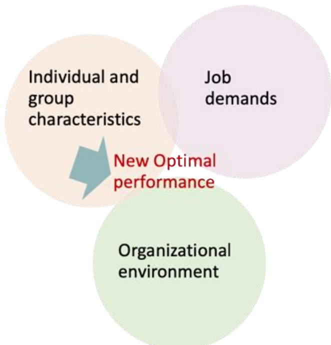
[11] Boyatzis, R.E. "The Competent Manager, A Model for Effective Performance," John Wiley & Sons, 1982.

[12] Goleman, D. et al., "Primal Leadership," HBR Press, Boston, 2004, Ch.9.

[13] Boyatzis, R.E., "Coaching Teams For Sustained Desired Change," In: De Vries, M.K and L. Guillen (Eds.), "Beyond Coaching; Creating Better Leaders, Teams, and Organizations," p. 168-180, 2010.



whole and that managers at all levels need high levels of competencies[14] in modern management, to reach the tipping point of global behavioral change.



With this approach it is feasible to change the mindsets, values and identities of individuals, and increase their willingness to review and adapt their behavior in response to a changing environment. They may for example more easily accept that their jobs will have higher IT content than before, and that they will have more interdependence with members in ever-changing ecosystems. They will more easily accept not to rely on their traditional tribal knowledge but trust the digital twin, and act more consistently according to facts and data. The organization must evolve to higher levels of trust that enable open communication[15], necessary for the agile enterprise in an increasingly transparent value network and market place. Therefore, the quality of relationships between individuals, teams, the organization and outside entities must improve. Only then, people will be capable to become more autonomous, making more decisions locally and work within the constraints, rules, ethics and decision limits rather than explicit directives, or escalate issues when necessary.

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[14] Boyatizis, R.E., "Competencies as a behavioral approach to emotional intelligence," J. Management Development, 28 (9), pp. 749-770, 2009.
[15] Druskat, V.U. and S.B. Wolff, "Building Emotional Intelligence of Groups," HBR, March Issue, 2001.

Applications and Benefits

Most functions provided by the environment and its services, can be fulfilled with today's tools and infrastructure. The breakthrough? An open CDE enables efficiency gains in building and maintaining a digital twin with an ecosystem of parties.

Compentencies and skills for managing and deploying digital twins.
Personnel who create and manage digital twins need technical domain skills (engineering, maintenance, compliance, finance, etc.) and also digital and IT skills. For teams to collaborate and cooperate with success, they need to master competencies such as communicating effectively, managing relationships, resolving conflicts, and understanding one's own behavior and behavior of others and groups related to social interaction. As information in a collaborative environment is used by many stakholders, and impact their results, personnel managing this information need to have a high level of integrity and responsibility and understanding of systems thinking [16].

In the *design and build* stages, engineering conceptual and detail designs can be shared between engineering firms and owner-operators for engineering reviews. 3D models can be easily compared in multi-party teams with point clouds tracing construction progress. The up-to-date and accessible information facilitates cross-disciplinary and cross-ecosystem collaboration, and significantly reduces search time, and errors related to out-of-date information. Project digital twins can be used to reduce risk by simulating logistics and construction. Time to operational readiness can be reduced training personnel before commissioning using immersive operator training. During qualification, regulatory compliance can become more efficient when comparing as-built and progress against requirements. Deviations and action items can easily be shared between owner-operator and regulator. During commissioning, comparison between as-designed and as-built will also be facilitated.

In the *operate and maintain* phases, immersive operator training, or 3D situational information will support maintenance and operations staffs, who can easily compare a location with engineering or operational information. When continuous surveying information for inspection of asset integrity is displayed as a reality mesh, it is far easier to detect and oversee the consequences of material degradation or loss of containment than with traditional methods. Asset performance analyses can be compared quickly and comfortably with engineering design information and situational context information. Trustworthiness of the information enables personnel to make

[16] Boyatzis, R.E., "Competencies as a behavioral approach to emotional intelligence", J. Management Development, 28 (9), pp. 749-770, 2009.

data and fact-based decisions, rather than having to verify facts or rely on implicit knowledge. Artificial Intelligence and Machine Learning applications applied to a digital twin will help optimize operations, assist staff to anticipate behavior, and take preventive action. The performance digital twin can therefore support operational excellence and reliability initiatives. Engineering studies and projects, as well as advanced process control applications will be executed faster.

In the *decommissioning and deconstruction* stages, similar benefits as in *design and build* are found. In addition, 4D deconstruction studies, and environmental impact studies are naturally linked, and combined optimization becomes feasible.

Combining 1D, 2D, and 3D in a single environment provides functional context to physical representations and vice versa. The more "dark data" can be made visible, tagged, validated and linked to other available information, the more valuable and context-rich information will become. Access to operational, business and project, portfolio or product data management software will provide even more context. Context plus more complete and accurate information will improve quality of decisions. ARC would expect to find at least the following bottom line benefits with contributions from the items listed above:

- Improved operational and asset performance
- Improved engineering and maintenance efficiency
- Increased quality time for engineering and less time spent on data and IT tasks
- Reduced downtime, less equipment damage, and most likely a reduction in information-related incidents and accidents
- Reduced operational and IT risks

Recommendations

Digital transformation strategies must be agile and updated regularly. They must be a vital component of the overall company strategy. Technologies are enablers, and business objectives must drive digital transformation.

A digital foundation is needed to build digital activities required for successful digital transformation. Digital readiness includes a minimum threshold of digital maturity in resources, systems, organization, and culture.

Companies should consider each of those in their digital strategy. The success of digital transformation and the value of the digital twin depends on their maturity levels.

Digital twins are digital representations of physical assets. Their basic form is accurate, up-to-date and accessible asset information. Companies should consider what information they already have, and what returns they can expect from the investment in the digital twin. These are likely to be significant.

Companies should consider which available information can be used as basis for a digital twin and labeled as "trusted," which information may need verification or updating, and what additional information is needed. Efficiency gains related to using trusted information may pay for validating untrusted information and adding new information.

Sophisticated aspects of digital twins such as simulation or 3D modeling are closely related to each other. They should at least be consistent with the basic digital twin and with each other.

The quality of the digital twin is directly related to project, asset, and operational performance. ARC recommends inhouse data governance to safeguard the value of the digital twin.

Cloud service solutions such as PlantSight™ are the optimal IT architecture to support safe and efficient collaboration across disciplines and across value chain networks.

Mindset and culture are essential ingredients of digital transformation. Specific leadership qualities are required across the organization, to restore the optimal fit between individual and group characteristics, job demands, and organizational environments. This fit predicts organizational performance.

Appendix: Foundational Digital Readiness

Information	**Systems**	**Organization and processes**	**People, Norms and Culture**
People, processes and equipment provide digital information in all enterprise domains (R&D, Manufacturing, Sales...)	Systems are technical (IT and automation), socio-technical (in collaboration with people) or management-oriented (e.g. governance, asset management, quality management)	Rigid and hierarchal systems are de-emphasized in favor of ecosystems and local decision-making favoring flexibility, speed and agility	The variety of competencies of a single person increases and includes technical/domain expertise, IT and automation skills; and relational, organizational and cultural skills
Direct information sources are sensors, instruments, handhelds, algorithms (computed information)	Systems are horizontally and vertically integrated	Organizational forms can include traditional hierarchical organization and increasingly include flexible, internal or cross-enterprise ecosystems that are adapted according to needs	People understand how the systems they use work and contribute in improving them. They are willing to be guided to make fact-based decisions.
Indirect information sources can be retrieved from collaborative data environments	Horizontal integration takes place among plants and value network members.	Hierarchy is de-emphasized and process, performance management and decision latitude are emphasized such that responsible workers can take decisions autonomously (in ecosystems at the edge) where possible	People are trained and assisted by automated systems, remote assistance involving people and face-to-face training and coaching, according to the nature of the competency and the individual needs
Information comes from inside the enterprise and from the value network	Vertical integration connects the edge with enterprise systems, usually in several layers, e.g. line, plant, site, enterprise, value network.	Tribal knowledge is discussed, validated or invalidated and converted to best practices by communities of practice	Open communication and collaboration are promoted by developing norms of trust, group identity and group efficacy
Difficult-to-access information is gradually validated and made accessible	Information is processed locally as much as possible.		People are willing to review their behavior, skills and competences and change them according to involving organizational needs
Information is trustworthy and current, and its integrity is part of governance responsibilities	Higher level optimization and decision making is used where necessary for coordination and obtaining synergies		People understand and share the company vision and goals
			Willingness to change is not imposed but coached
			Norms and culture are brought to consciousness,

			and influenced through discussion and coaching

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Acronym Reference:

ALM Asset Lifecycle Management
APM Asset Performance Management
ERP Enterprise Resource Planning
ET Engineering Technology
IIoT Industrial Internet of Things
IoT Internet of Things
ISO International Standards Organization
IT Information Technology
MES Manufacturing Execution System
OT Operational Technology
PLM Product Lifecycle Management

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