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[*] Smart Manufacturing: Concepts and Methods Editors: Masoud Soroush, Michael Baldea, and Thomas F. Edgar, Elsevier ISBN 9780128200278, 2020

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Abstract

The productivity, precision and performance benefits of Smart Manufacturing are unleashed when there is frictionless movement of information – data in context, at the right time, among systems, operations and people, that can create value within and across all manufacturers and all sizes of plants throughout enterprise supply chains. Line of sight to the full economic potential of Smart Manufacturing requires business, leadership, market and infrastructure realignments for the "democratization" of "smart" business, technology, operational and workforce data practices industry-wide. Access and the ability to effectively use operational data in cyber operations (Operational Technologies, OT) that are enabled by Information Technologies (IT) and the knowhow to deploy Smart Manufacturing solutions are therefore increasingly important to small, medium and large manufacturers, providers, integrators and innovators alike, but increasingly constrained with today's manufacturing infrastructure practices. Addressing democratization, breaking through barriers and transforming manufacturing to a new data centric orientation are key objectives for CESMII, the Clean Energy Smart Manufacturing Innovation Institute, the third Institute sponsored by the Department of Energy and the ninth out of the fifteen Manufacturing USA national institutes (see https://www.cesmii.org).

Key Words: Smart Manufacturing, Technology Democratization, Manufacturing Cybersecurity, Cyberinfrastructure, Supply Chain, Advanced Sensor Controls Platforms and Modeling, Cyber Physical Systems

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1. Introduction

"Smart Manufacturing" is the transformation of U.S. manufacturing that results from disrupting traditional business, organizational, operating, and market structures with a radical increase in the availability and use of real time operations data to produce value in previously inconceivable ways—a transformation process known as "manufacturing digitalization" or "manufacturing digital transformation." There are significant economic and investment opportunities with substantially increased supply chain productivity and far better product design with process and machine precision and performance for higher value products manufactured better, faster, cheaper with less energy and material. Manufacturing processes can be fundamentally improved and made safer with profoundly better use of human, control and automation capabilities. New global manufacturing and market growth opportunities—powered by next generation digital technologies, 3D printing, next generation IT hardware and firmware, 5G, advanced sensors, controls and modeling, including artificial intelligence (AI), deep learning and machine learning—are all expected to exploit data and information in unprecedented breadth and at a previously inconceivable scale. The steady march of digitalization is both accommodating and upending legacy manufacturing business transaction structures and markets (how, where and among whom manufacturing is done) with shifts toward partnership structures for business and operational interoperability and improving what is manufactured.

The reality, however, is that the pace of Smart Manufacturing adoption is highly constrained for small, medium and large manufacturers and vendors alike, and slowed because of technical and non-technical challenges that include leadership readiness, availability of skills, financial constraints, counterproductive market drivers, business risk, cybersecurity, and legacy operations. At their core, these challenges combine to make accessing data and putting them to use costly, risky, or out of reach. Not only is the adoption of Smart Manufacturing slowed, but importantly, the innovation and entrepreneurship of developing and deploying the myriad of possible smart, data-based applications are curtailed. Manufacturers struggle just to gather the right data. There are repeated scenarios of running out of resources before the data can be put to use or applications that die because they are one-off systems.

1.1 Smart Manufacturing from a business perspective

Manufacturers that have begun Smart Manufacturing explorations or initiatives tend to start with sensing and collecting data to manage operational assets or for better quality assurance. For some, the challenge is being able to sense in real time. For others, it is the effort to connect legacy equipment cost effectively, even if the sensing technology is available. For larger companies, Smart Manufacturing is encompassing managed assets in line operations and the integration of upstream and downstream effects. For small companies deploying even a single sensor application can be resource, skill, time, and risk prohibitive. Data access and interoperability in supply chain operations involving small, medium and large companies together have some early traction in some industries where tracking and traceability are important, e.g. food industry, but are generally fragmented. Supply chain optimization remains a highly complex, risky, and expensive challenge even though many of the economic benefits in Smart Manufacturing are with supply chain productivity improvements.

A major common constraint is the increasing complexity of interconnectedness with today's emerging data and information technologies. There is a huge proliferation of new software products, platforms and niche solutions for collecting data and addressing some operational problem. While IoT and the increasing numbers of automation, sensor, robot, machine, and process software platforms add local value, they are significantly increasing factory and supply chain complexity and are making data increasingly complex to access and use. New cloud platform technologies trap data and exacerbate this complexity because vendor markets still drive value from complexity and closed infrastructure, not simplicity and operational value. These data complexities increase security and operational risks, impacting the speed of implementation and scale up even further.

Not only is it a challenge to determine where to start, what product to use, what data to collect, and how to scale, it is even more challenging to derive value because the data lack context. Manufacturing data are not only "big" but also complex, creating the need for context at multiple levels. While critical pathways to economic benefit exist for predictive analytics, operational interrogation and advanced diagnostics, they are severely constrained by a lack of access to data with the right context, a skills vacuum with the modeling practices to take advantage of the data, and the complexity in scaling data use across a diversity of use cases. For smaller companies, these are insurmountable barriers. The practical reality is that the manufacturing industry overall is creating a marketplace flooded with predictive analytics and IoT solutions, leaving manufacturers across the country with application 'pilots,' questionable ROI, and no way to effectively scale up.

Lastly, it is not uncommon to hear from manufacturers that technology alone is not a barrier for them in adopting and scaling Smart Manufacturing. It is instead transforming the organization to adopt a digital culture at every level. This cultural change is a huge challenge in many industries where change impacts multiple, interconnected functions. Finding the right champions to enable this change is not easy, particularly when ROI needs to be defined in new ways. Data-driven manufacturing has created a significant need for everyone to have skills in consuming and using data, while not reducing the need for subject matter expertise to ensure that the data are right, are being used in the right context, and the right technologies are being used to solve the problem at hand. Complexity, cost, and lack of integrated workforce skills put digitalization and Smart Manufacturing out of reach for most manufacturers.

2. Smart Manufacturing and democratization

While the barriers to change loom large, the benefit drivers for change are also large. U.S. manufacturers are facing even larger cost and regulatory pressures today in a global market, driving up an already intense and relentless focus on productivity, precision and performance that now involves restructuring how and where manufacturing is done. Decades of investment in continuous improvement and productivity programs have exhausted the low-hanging fruit, with these programs plateauing in their search for diminishing returns. Fueled by new sensor, data, control, platform, and modeling technologies, including the revival of AI and machine learning, the potential with Smart Manufacturing and Industrial IoT has sparked new expectation and opportunity. Smart Manufacturing is at an early stage of transformation and it is safe to say that most manufacturers are in a mode of investigating, learning and developing their Smart Manufacturing strategy.

At issue is that much of the innovation and the research is following the same patterns seen for the past 25 years. There has been no effort to standardize any of the technologies/capabilities in the manufacturing software stack, and, unlike other industries, all efforts to consolidate capabilities (through either acquisition or organic development) have failed to create organized industry infrastructure (with any level of critical mass). Rather, the outcome of 25 years of investment in manufacturing systems has resulted in an unbelievably complex installed base of point solutions that is now getting worse. There is an incredible proliferation of innovative new IoT and analytics startups selling their solutions, each one addressing a narrow slice of a highly complex set of operational challenges. The result though is that the pace of increasing complexity is now accelerating with the downside effect of increasingly constrained innovation. Cybersecurity issues are growing so acute that most manufacturers are making impossibly difficult choices every day, weighing production continuity against the risk of a security incident. If manufacturers invest in these new point solutions, they are propagating and amplifying the very complexities they're trying to eliminate as they work to refresh and consolidate their legacy installed base of solutions. We argue that 'what got us here, will not get us there' (to Smart Manufacturing).

Democratization of "smart" business, technology, operations and smart workforce skills, extending and expanding the use of data and advanced operational modeling practices to all who can create value, is a business concept that underpins the success of Smart Manufacturing and the realization of the full economic and social benefits of digitalization. Shared digital infrastructure and application building capabilities that are structured and sourced for extended reusability are needed to enable the frictionless movement of information – data in context, among real-time operations and the people and systems that can create value for every organization. Smart Manufacturing solutions are vital for all manufacturers and all sizes of plants, and all of the supply and value chains in which they participate.

The legacy of today's manufacturing systems and transaction-based business systems make *democratization* a business transformation challenge. If democratization can approach critical mass, however, siloed, legacy business and operational systems can give way to a far more secure, dramatically simpler manufacturing IT environment, enabling productivity and performance improvements in every part of the enterprise, from sensor to supply chain. U.S. manufacturing and global markets can realign. Business and economic opportunities will shift from data isolation strategies to 'smart' data interoperability, empowering every employee and every sanctioned partner in a supply chain to become an information worker. Manufacturing operations can rebalance for data-centric automation and smart worker productivity. The longstanding cultural rift between OT and IT will break down as convergence and vendor platform infrastructure siloes shift toward the value of open interoperability. Software application markets will shift the focus to the operational value of an application, not the value of infrastructure, and the creation of de facto standards for manufacturing data infrastructure will enable the entire app development and implementation ecosystem to innovate on a scale not feasible today. Every stakeholder will be affected by and can take advantage of the democratization of information.

3. Today's complexity of interconnectedness

Fig. 1 illustrates the underpinning of technical complexity with software applications in manufacturing operations today. As shown, software products tend to be developed specifically for production and work order combinations forming nine largely isolated software product cells based on discrete, continuous and batch production types and engineer-to-order, made-to-order and made-to-stock work order modes. Software products have tended to lock down architecturally first on physical assets, processes and production/work order functions. Operational data functions are then embedded and the information technology and hardware/software requirements are developed specific to the vendor product, production types, work order types and industry. It is very difficult for software applications to be reused for other production/work order applications. It is also very difficult for embedded information and operational data technologies to be reused for other applications. It is not only difficult but counter to market drivers to integrate across vendor products.

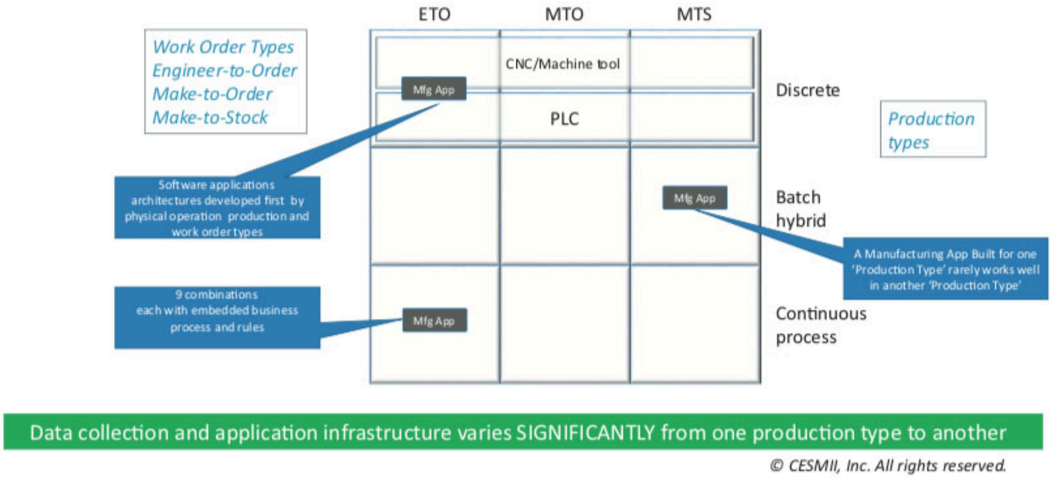

Fig. 1. Legacy software application siloes.

The result of these legacy 'silos' is a huge proliferation of independently built software applications that offer little reusability. Each comes with its own infrastructure and each requires a great deal of individual integration and maintenance.

As manufacturers push for more contextualization, information, insights, and smart applications, the ensuing complexity is revealed as shown in Fig. 2. Pictured are the data interconnections from an actual taxonomy of mission critical manufacturing systems required to produce an end-of-shift report. Each individual system (each colored box) – generally from different vendors, requires an estimated 1,000 configuration and parameter settings to connect the system to data, contextualize the data and bring the system into operation. If each of the cross-system data interconnections is automated for an enterprise Smart Manufacturing factory or supply chain application, an average of 250 person-hours per secure interconnection is required. Orchestration of the systems information and the modeling of the data to do the end-of-shift report occur in a spreadsheet limiting the ability to use the information further. Modern cloud products help the IT infrastructure requirements but do not reduce the OT configuration, connectivity, and interconnections, effectively trapping data just like on-premise siloed vendor applications.

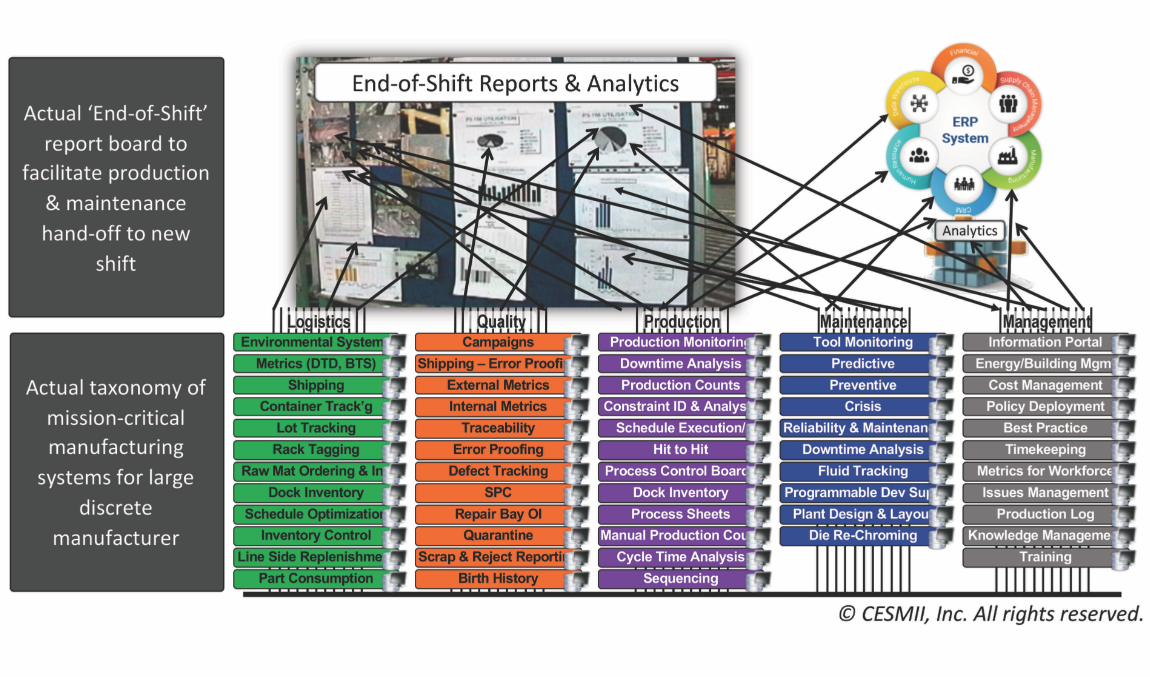

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Fig. 2. The complexity of legacy siloes for digitalization.

4. Reducing the heavy lift of data modeling and contextualization

Considerable time, effort and expense are invested in the design, development and deployment of an individual operational data/modeling system. Each application developed produces data models for contextualized data and model configuration, knowhow that are not readily reused because of lock-in with physical operation modeling and with vendor, type, mode and objective, as shown in Fig. 1. Consider the potential for building a data/model system and being able to leverage the knowhow with templates for a next similar application. As an example, we use the smart performance application for a Steam Methane Reformer (SMR) (see Ref. [1]).

The SMR has a large cubical shaped structure with elevation and side dimensions approaching 50 ft. and a combustion chamber insulated with refractory walls. The top-fired furnace has 336 reformer tubes (7 rows each with 48 tubes) and 96 burners and 8 flue gas tunnels. The burners are arranged in 12 rows of 8 burners. Fuel can be adjusted with throttle valves located on each burner. Each of the reformer tubes are 40 ft. in length. Careful management of the temperature spatially throughout the furnace is required because a persistent temperature of greater than 20 C above the maximum tube wall temperature reduces the life expectancy of reformer tubes by half [2]. There are significant variations in local furnace temperatures due to variations in fuel and air flows to each burner as well as non-ideal flue gas flow patterns inside the furnace.

The *Performance* objective is to measure and control for a much more even spatial temperature distribution at all times avoiding hot or cold spots so the overall furnace temperature can be increased to increase energy efficiency and therefore hydrogen productivity of the SMR. A total of eight infrared (IR) cameras and 70 thermocouples were installed to measure the tube wall temperatures and spatial temperature distribution throughout the furnace in real time. The harsh, high temperature furnace environment and the vibrations of the furnace produce noisy, and at times corrupted, IR camera data. Thermocouple data were short lived and rapidly became missing information. Real-time IR camera image data were mapped into spatially located temperature data points and stored in an on-premise (edge) historian. Additional data, such as fuel and production flows, were drawn from the control systems.

As shown in Fig. 3, there are multiple ways to reuse the engineering knowhow of having developed and implemented the smart application. Mapping the IR camera image data to temperature data, spatially located throughout the furnace, required considerable development to ensure spatial coverage, address overlapping camera data, and cross-verify the spatial temperature measurements from IR images with point values of thermocouple data. When the proprietary operating data are separated out, what is left is a *data model* for an IR camera temperature sensor system for a geometrically square SMR furnace. We call this an *SM Profile* for the sensor system as a device (see upper left-hand box). To actually use the operational temperature data, the data needed to be further contextualized and configured for the subsequent model transformations. Again, significant effort went into determining that an axial temperature plane 15 ft from the top of the SMR furnace, corresponding to the length of the burner flame, was the best location for estimating where tube temperatures would be highest at any point in time. Also, axial plane temperatures collected at one-minute intervals and averaged over one-hour time horizons produced sufficient accuracy and precision. Corrupted IR camera data could be crossvalidated and replaced with readings from overlapping camera images. As previously mentioned, when the operating data are removed what is left is a *contextualized data configuration* and *data template* for using the real-time spatial temperature data in SMR furnace models (see upper middle box).

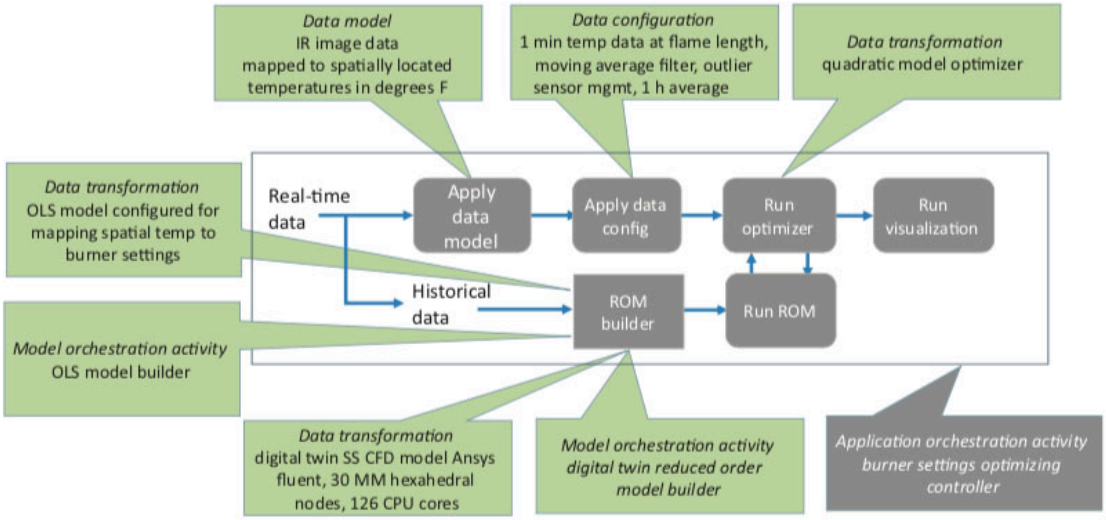

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Fig. 3. Example of knowhow reusability in a smart application.

As shown, real-time operating data are continuously going into a store of historical data that are available to build and update a reduced order model (ROM) that maps spatially distributed furnace temperatures to spatially distributed fuel settings for the 96 burners. The ROM can run fast enough to be used in operation. A Run Optimizer is used as a *Data Transformation* model configured to iterate with the ROM to determine optimum burner settings and the size of changes. These are output as a Run Visualization for operator action. The configuration of the Run Optimizer as an optimizing controller and how it interacts with the ROM is reusable engineering knowhow in the form of configurations and workflows about how to configure and use the models.

Two different modeling approaches were applied. One was to build an ordinary least squares (OLS) model directly from historical data (see Ref. [3]). Once the OLS Data Transformation model was worked out, there remains a reusable ROM configuration and a machine learning strategy and routine using furnace temperature and burner setting data. We call this a *Model Orchestration Activity*. These are illustrated in the boxes on the left of the graphic. The other modeling approach was to develop a Digital Twin of the furnace and use the temperature predictions to build the ROM by iterating between the Digital Twin temperatures and the ROM predicted temperatures until convergence. The Digital Twin strategy is illustrated with the lower green boxes where there is the Digital Twin Data Transformation model itself and a *Model Orchestration Activity* using the Digital Twin to build the ROM. The Digital Twin model is a Computational Fluid Dynamics – CFD model (see Refs. [4, 5]), of the furnace developed as an Ansys Fluent model constructed with a computational mesh of 30 million nodes that runs on 128 parallelized CPU cores. A single calculation could take up to 72 h of CPU time to converge. Just using the Digital Twin involved another workflow to automate changing conditions and converging the computation. The Data Transformation model configuration templates and the *Model Orchestration Activities* are associated with an SMR furnace SM Profile.

Finally, there is an overall optimizing-control application for leveling and raising the temperature distribution in the furnace with the ROM-Optimizer shown in the lined box that brings all of the components together. When all of the data models, data configurations, data transformations and model orchestration activities are orchestrated together they form an *Application Orchestration Activity* for the SMR furnace.

This SMR example brings out how data modeling, data configurations, model configurations, and model and application orchestration activities can be captured as reusable templates and workflows that are associated with devices and processes. The example also brings out that when appropriately structured these templates can build from each other through multiple efforts to extend capability and/or applicability under different physical situations. We address this kind of data and modeling application capability with *Data Centricity*.

5. The data-centric view of smart manufacturing

See publications by Davis et al. [6, 7] for a history of Smart Manufacturing and the national discussions that influenced its definition. More recently, there have been additional characterizations (see Ref. [8]). For this chapter, we use the data-centric characterization of Smart Manufacturing developed within CESMII, The Smart Manufacturing Innovation Institute. As emphasized on the left of Fig. 4, Smart Manufacturing builds first on the concept of “Right Information.” *Right Information* is defined as contextualized, interpreted data in the *Right Form*, at the *Right Time* and in the *Right Place*, ready for consumption. *Data and Information (i.e. actionable data)* are used to *set up* for various manufacturing execution and operational actions through *data transformations* and *model orchestration* activities. Shown in the blue box are common data transformation and model orchestration objectives encompassing exploration (*model*, *analyze*), reaction (*monitor*, *diagnose*, *control*) and pro action (*predict*, *optimize*, *self-interrogate*).

As shown in the middle of Fig. 4, the *Right Technology*, the *Right People*, and the *Right Automation* are application *orchestrations* to enable smart decisions and actions and to achieve business and operational objectives. *Execution* is used to mean any level of manufacturing process operation (individual asset to supply chain) that is run to a specified set of demand instructions, i.e. a recipe. *Human-centered operations* are any aspects of manufacturing execution run or changed using human decision making. *Automation* is any execution run or changed using algorithmic decision making. *Operational Technologies* (OT) are the digital control, automation, visualization execution and business systems and the “OT Data” that reflect physical operation and interface with the physical manufacturing facilities. Included in OT are the instantiated data models and configurations, data transformations, model orchestrations and application orchestrations that are designed, sustained and used in operation. *Information Technologies* (IT) are the data networking, streaming, storage, computation, management, security and communications that are conjoined with OT.

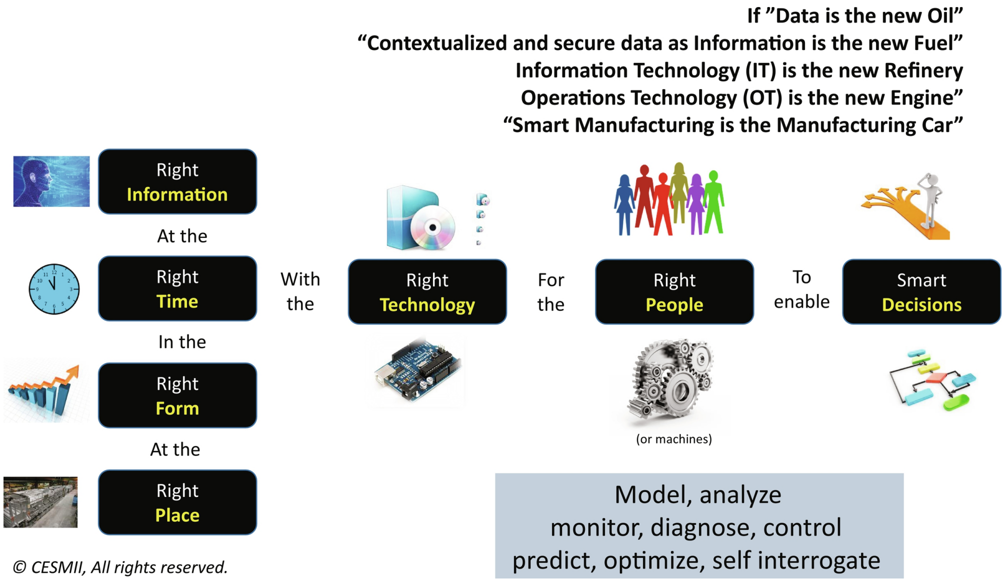

Fig. 4. The data-centric characteristics of smart manufacturing.

In this data-centric view, IT refers to data that are generated, stored, communicated without operational context, while OT data are contextualized, analyzed, transformed and used in operational context to actuate physical operations. *OT/IT convergence* foundationally implies OT Data at all times, i.e. data have operational context at all times and all places, but are used and enabled by IT capabilities. Data transformations in the form of algorithms, machine learned models, simulations, digital twins, etc. are synonymous with data in that they are constructed or validated with data and are used to produce/transform data for operational use.

Orchestration is used at two levels. First it is used to describe how data transformation models are orchestrated with data models and configurations instantiated with OT data to meet an individual data transformation objective. Orchestration is also used at an application level to describe how multiple data transformations, time, and human centered and automated execution come together into an economic, sustainable, safe manufacturing enterprise application. *Time* is a distinguishing attribute for Smart Manufacturing in that the value of a *Right Action* is highly dependent on whether it is ‘*at the right time’* or ‘*in time*.’ At a fundamental level Smart Manufacturing requires *time* to be a primary variable such that the overall orchestration, transformation, and execution are all responsive to time.

6. The building blocks of smart manufacturing

Fig. 5 illustrates the generalized data-centric building block functions and processes that make up Smart Manufacturing. As shown, there is a process comprising physical assets, for example a machine, a process operation, or an enterprise, and the associated physical sensors and the physical and human means for actuation. Moving clockwise, there are physical assets and people that sense, infer, generate and stream digitized data of many types, some of which are acted upon at device level forms of the data, e.g. safety functions, interlocks. The two shaded ovals indicate cyberphysical interfaces. For example, a sensor is a physical device that generates and stores digitalized data. We use the light-colored ovals to indicate a cyber activity. The dark storage icons indicate levels of reusable data banks of contextualized data in appropriate storage and database management systems.

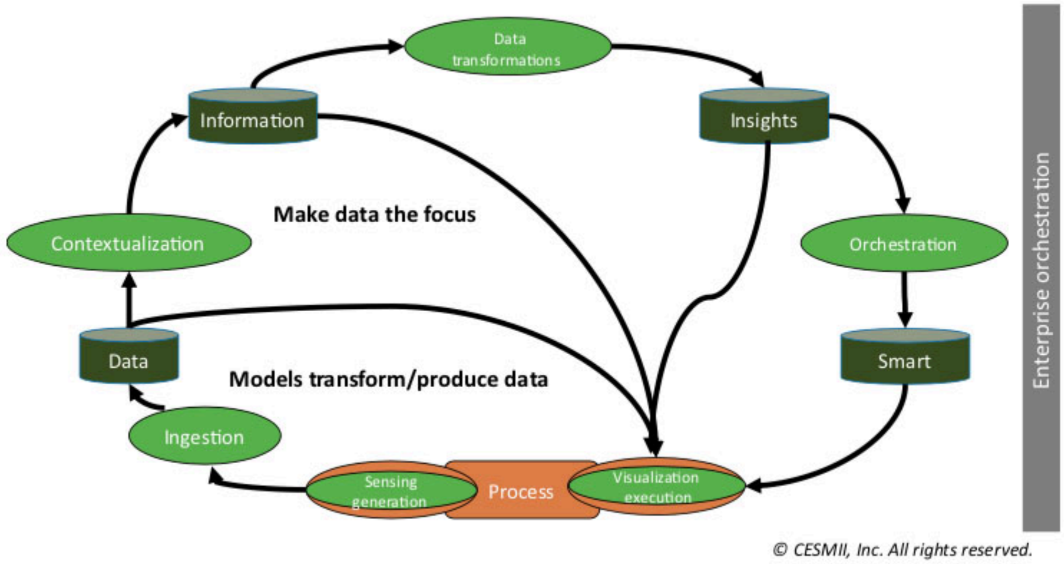

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Fig. 5. The data-centric building blocks of smart manufacturing.

For operating data to be used for higher level modeling functions, such as integrated alarms and visualizations, data are modeled, aggregated, contextualized and interpreted to form *information – data for purpose*. These contextualized data are now consumable after appropriate data transformation with model orchestrated activities such as analytics, monitoring, diagnosis, etc. which provide higher level operational insights. At the highest level of operational execution, data, information and additionally-transformed data are further contextualized and orchestrated together for optimization, prediction, and automated and operator-involved actions that drive high-level operational and business objectives. Smart Manufacturing comprises not only the component cyber and physical technologies that produce and use data but also the necessary instantiation, integration, orchestration and execution of any or all four levels of data-driven action throughout a manufacturing enterprise. From a business perspective, Smart Manufacturing allows manufacturers and their supply chain partnerships to transform their operations from being reactive (responding to what happened) to being proactive (predicting when things will happen and influencing future outcomes).

Fig. 5 brings out *data* as the focus of attention, acting on the physical process. There are the cyber functions in the ovals producing progressively greater levels of contextualized, transformed and orchestrated data repositories. The lines are data connections, interfaces, communications, and security to provision and operationalize the data, which we call *core capabilities*. The storage icons are the database management systems from which the data are provisioned. The vertical bar to the right is the *Application Orchestration* required to make all elements work together and act as an overall application in time. From a data-centric perspective, we view the contextualized OT data as key assets. There is an overall mindset change in that data are key assets and models that act to transform and produce data into useful forms that drive the process.

With reference to Fig. 5, data generation, ingestion, data contextualization, data transformation and orchestration are recognized as a repeatable *Data Lifecycle* pattern, which is shown in Fig. 6. Data centricity is the key principle that makes it possible to structurally leverage this repeatability. As shown on the left of Fig 6, physical operations, facilities, humans-in-the-loop and sensor assets generate data. There needs to be a cyber physical interface and the physical OT side framework for validating and contextualizing data. Similarly, on the right-hand side, data, after they have been ingested, contextualized, transformed, and orchestrated, are provisioned for physical execution and/or visualization and human-centered actualization, again requiring a cyber physical interface.

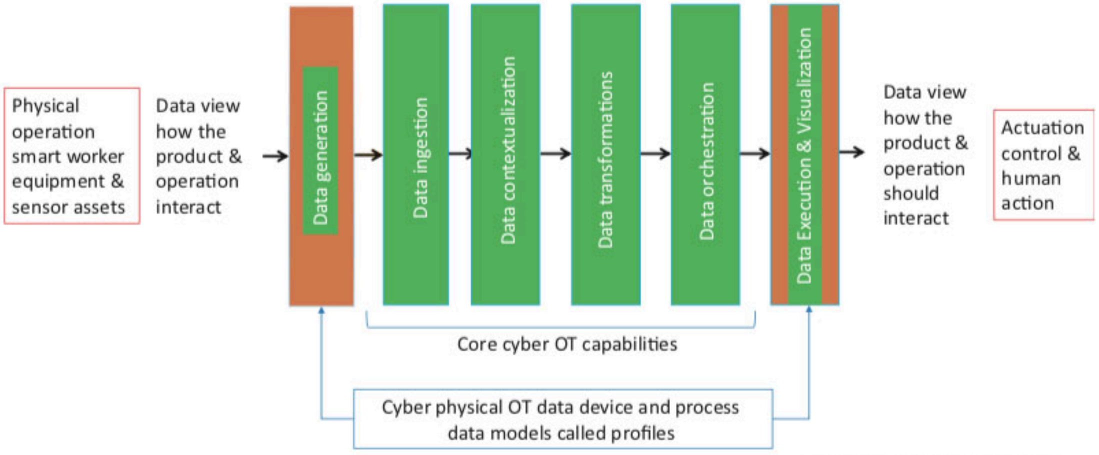

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Fig. 6. End-to-end cyber OT data lifecycle model.

This Data Lifecycle view makes it possible to establish Core cyber OT capabilities that are reusable and/or sharable for cyber-side data operations (see Refs. [9, 10]). When separated from physical model types and modes, these cyber capabilities make up reusable OT/IT infrastructure that does not need to be reconstructed for each physical application even though the physical operation and modeling type may be quite different. This separation of cyber and physical data modeling is key to managing a much smaller set of core cyber data capabilities and the utility of infrastructure that does not need to be built for every application.

The cyber physical endpoints in the two color bars are addressed with SM Profiles™ that are templatized operational data contextualization models, data configurations and data transformations for physical assets. SM Profiles contain the interfaces and are architected for interfacing physical- and cyber-side data generation and first level contextualizations and physical-side visualization, actuation and execution. Leveraging cyber and physical in this manner supports vendor agnostic software interoperability since the cyber infrastructure can be common for modeling products and interoperable with sensor and execution systems through the SM Profiles that are structured to integrate with core cyber OT capabilities.

7. Operational data models, SM Profiles, and the SM Innovation Platform

Taking the SMR example in Fig. 3 into more technical detail and, as an introduction to the more detailed treatment to follow, data centricity offers the technical foundations for OT/IT–converged, "core" cyber-side data services as specifications for a Smart Manufacturing (SM) Innovation Platform, which operates as a *wireframe*. The term 'wireframe' importantly connotes *open* platform services with the necessary digital interface specifications and services that vendor, experimental, open and community source software products and platforms can "slot" into [the wireframe]. Users can more easily access and operationalize application products over a full range of on-premise, edge, cloud and hybrid data network structures. These wireframe specifications need to be instantiated as a *de facto standard* for deploying 'smart', real-time data-centric manufacturing operational applications that draw benefit from shared infrastructure. We use the term "de facto standard" to mean there needs to be an agreed position taken on how these core cyber-side capabilities are structured and integrated and how data models and data modeling functions are structured, selected, composed, and orchestrated in the SM Innovation Platform [wireframe] to form data-driven applications that address operational objectives. The wireframe services themselves are *closed* in order to manage the de facto standard, the cybersecurity and trusted business data exchange processes.

The SM Innovation Platform is purpose-built code that makes it possible to construct sets of core cyber OT data services from software products produced by others. Corresponding to Figs. 5 and 6, the SM Innovation Platform's core services include secure wireframe capabilities for slotting in software products for data ingestion, data contextualization/configuration, and the workflow orchestration of selectable, composable and fillable *SM Profiles,* once instantiated and bound with data. The SM Innovation Platform also builds in core data store and management products for provisioning data transformations and core trusted services for securely exchanging selected business data with a wide range of exchange formats. *SM Profiles* are OT data model templates and device/process model configurations constructed, merged or inherited to expose structured data to the wireframe. "Filling in" operational-specific information into data contextualization templates and model configuration schema for proven manufacturing applications populates an SM Profile instance for ready interoperability with and execution in core data services.

As illustrated with the SMR example in Section 4*,* SM Profiles are physical asset data models that have been developed once. When the proprietary operational data are removed, what remains is a data model template and model configuration that can be scaled for broader industry use when data and/or physical assets are used similarly. When multiple *SM Profiles* are instantiated and augmented with intermediate data transformations, they form *Model Orchestration Activity Profiles*™ that may also have scalable or reuse value as an orchestrated data transformation in application. When all elements are orchestrated together they form an *SM Application Orchestration Activity Profile*™.

While these shared core data services radically reduce the cost and time of setting up infrastructure for ingestion, contextualization and consumption of data, *SM Profiles, SM Model Orchestration Profiles, and SM Application Orchestration Activity Profiles* are the frontline application OT data templates and model configurations that define the contextualized data for sensors, devices, machines, and process assets. They are reusable and searchable "building blocks" that are manufacturer-independent and vendor-agnostic. Furthermore, they are defined for practical use at that level of device or process decomposition that offers value in the reusability of the template. For example, a sensor and the data models for the data generated are likely useful but data models for individual components and circuitry of the sensor are probably not useful.

Fig. 7 brings out the concepts of the SM Innovation Platform and SM Profiles together and how they change and impact today's manufacturing infrastructure. The left-hand LEGACY view depicts typical single legacy applications in which all OT and IT technologies are vertically developed and implemented to the operational application. The results are monolithic technology stacks designed uniquely for each product. In the TODAY graphic the manufacturing market has seen value in common connectivity standards with some emerging headway. OPC or Open Process Communications standards are illustrated as an example. Another example is Industrie 4.0, which has standardized on physical hardware connections (see Ref. [11]). Also shown are examples of how providers of data management capabilities tend to play in TODAY's infrastructure, making it difficult to impossible to use and reuse data across applications. The TOMORROW view illustrates that there is continuing progress at the data connectivity layer with OPC Unified Architecture (OPC UA), Message Queuing Telemetry Transport (MQTT), etc. Importantly, the TOMORROW graphic shows how the SM Innovation Platform makes it possible for vendor products to interoperate and for contextualized data to be shared and reused within a common infrastructure stack.

The SM Innovation Platform captures four primary leverage points of a common infrastructure stack for greater interconnected simplicity: (1) access to expanding data ingestion protocols that can be specified and aligned for different SM Profile data models or when a single profile may have adapters for multiple protocols; (2) a platform "wireframe" for slotting in various software capability services and products into an interoperable technology stack of core OT Data contextualization services; (3) the ability to build application data model templates and model configurations by separating out proprietary operating data (*Profile Builder*™); and (4) the ability to use workflows to integrate a wide diversity of vendor application products as Profile products used within profile interface structures and data contextualization configurations to form operational application systems.

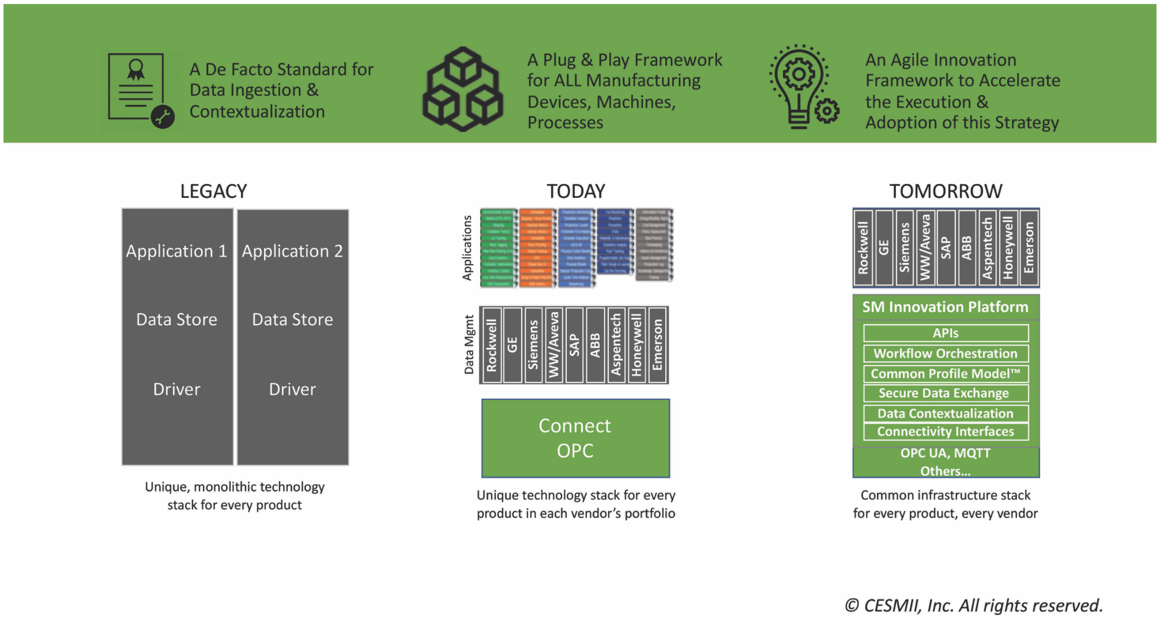

Fig. 7. The SM Innovation Platform as new baseline OT infrastructure for ALL vendors and App developers to build on and create value.

7.1 SM Profiles

In a data-centric view, the use of materials and energy, the processing and transformation of materials, the formation of parts, and the assembly and packaging of units and products in manufacturing operational steps and stages are described by the flow and transformation of data. However, data centricity alone is insufficient to address contextualized OT data requirements and needs to be enhanced with decision-centric modeling to drive contextualization, model transformations and orchestration. For example, data contextualized and used for abnormal situation monitoring is very different than that same data used for diagnosis. In our earlier SMR example, the use and orchestration of data in the simple OLS model leads to an extended derivative profile when used with the optimizer. Data centricity *together* with decision centricity (see Data and Decision Centricity Approaches–adapted from INFORMS Analytics Body of Knowledge, edited by Cochran, [12]) produces different sub-profiles that enrich a common base profile.

As another example, new sensor and modeling systems offer new kinds of data and features about how operations and the properties of the product generated by those operations come together, but these are contextualized within a framework of expected decisions or function. A physics-based process model can produce data and shed light on dominant process features acquired with a data-driven model. Similarly, a data-driven model can be used to improve the physics of a first-principles model. The two kinds of models can be used together operationally to the benefit of the manufacturing objectives. This synergy around purpose is brought out with the SMR example. Data and decision centricity are also aligned to significant opportunity with autonomous manufacturing assets within an entire value chain enterprise. This is the concept that, as a product moves through the steps and stages of production, the product and the operations that make it, can communicate to establish and control what is needed locally to ensure the product at the end of the value chain. This is the basis for all of the "self's"—self interrogation, self-awareness, self-organization and self-repair.

As brought out in Fig. 6, SM Profiles are the device, system and/or process centric and application-oriented operational data models that interface physical- and cyber-side data generation and cyber-side data transformations and physical-side actuation and execution in context. Profiles include the configurations for data contextualization and transform models for different objectives, e.g. prediction, health, associated with the device. Importantly, an SM Profile contains the data connectivity, contextualization and model transformation forms for an '*atomic*' cyber physical system (CPS). With respect to the cyber-side perspective, an SM Profile is a building block CPS device and operational domain that defines the data, information and time environment for the data *cyberspace* associated with the device or process based on the NIST Cyber Physical System workgroup report (see Ref. [13]).

An SM Profile cyberspace is typically defined by a vendor product for a system but could be defined by a firewall, or an on-premise edge structure. A single sensor that stores digital data, a sensor system that is networked to its own historian, a machine that collects and stores data, a single actuator supported by a digital data system and a controlled operation or set of control operations are all examples of SM Profile device and operation cyberspaces. A tightly coupled control system on a device or process forms a single SM Profile cyberspace because the data and models are so integrated, and individual tasks are indistinguishable. A system that *contains* the sensor, actuator and set of control operations may have a Profile that exposes aggregate data for that system, or it may have a *compound* Profile that depends on the Profiles for each of the constituent parts.

Leveraging cyber data and physical operations with structured SM Profiles supports vendor agnostic software interoperability since the cyber infrastructure can be common for modeling products. Repeatedly-used connections and interfaces with sensors and human and machine execution systems are captured in the SM Profiles which are architected to use core capabilities of data ingestion, contextualization, management, and workflow-based orchestration tools certified by CESMII.

7.2 An SM Profile machine example

We illustrate an SM Profile with a simple machine example for an Extrusion Cylinder (see Fig. 8). The Extrusion Cylinder is one device component of an Extrusion Press, which is comprised of a Cylinder, Pump, Die and Servo-Valve. It has been determined there are actionable advantages to considering each device function and operation in its own cyberspace and time view and then orchestrating the data and models of each as a system-of-systems to manage the overall function of the Extrusion Cylinder in the Extrusion Press. The actionable advantage has to do with managing and optimizing the precision of the product quality as a direct result of the cylinder operation.

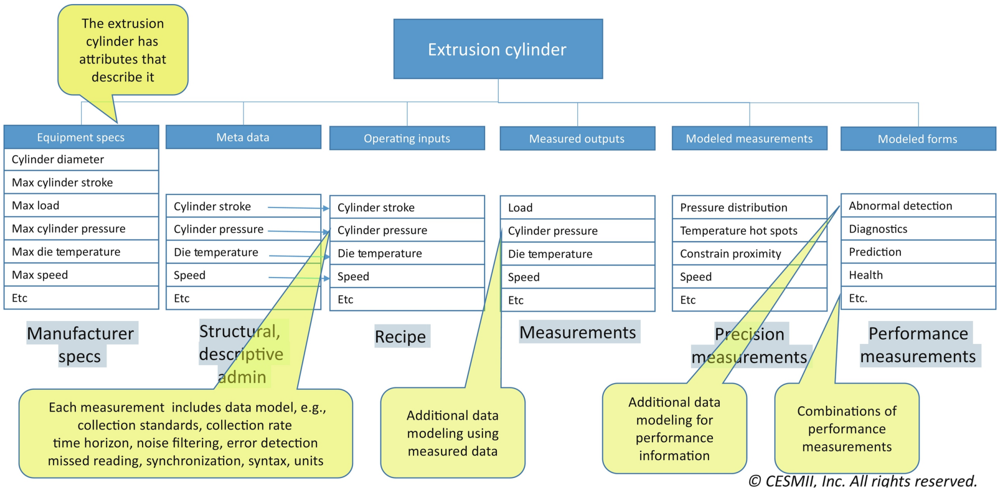

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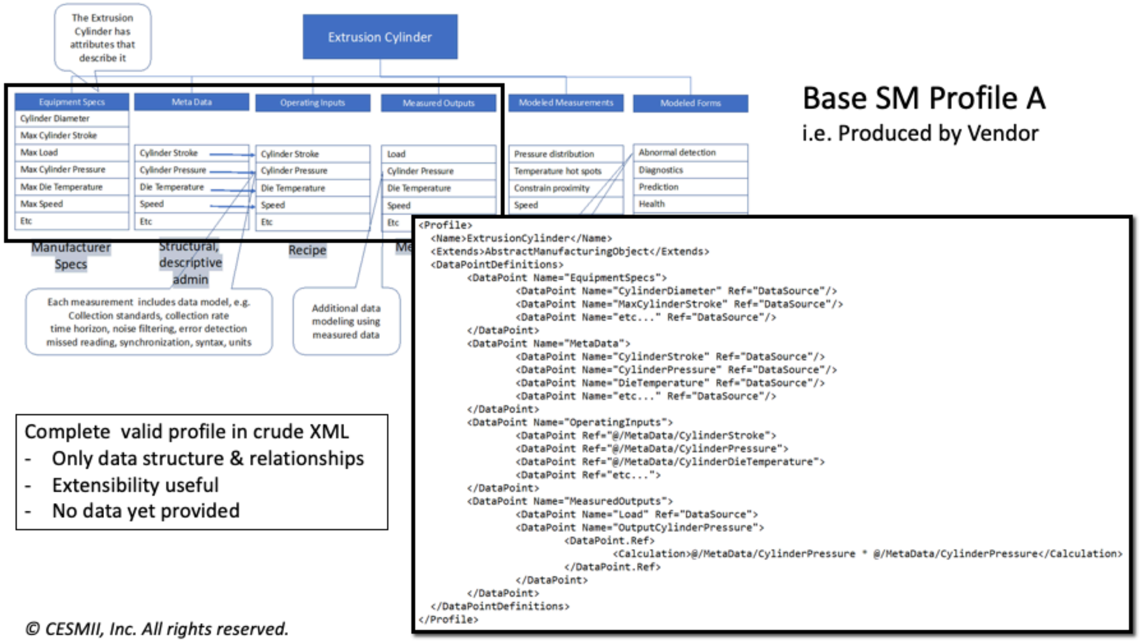
Fig. 8. An example SM Profile with data expectations for an extrusion cylinder.

As shown in Fig. 8 there are equipment specifications, operating inputs, measured outputs, modeled measurements, data transformation and model orchestration activities in a defined schema that can be associated with this particular device and its associated cyberspace time. Importantly, the SM Profile embeds the standards-based physio-cyber mechanisms for converting a measurement of interest into digitally communicable data or converting digital data into an actuation and a standards-based way to determine conversion time and rate of data so that the operational function of the device can be predicted and communicated. The SM Profile is able to reference time from an appropriate source and it defines the time horizon that establishes the smallest periodicity for raw data collection and the smallest window in time that data are to be modeled. Reusability addresses structuring and/or building standardized capability so that the clock information is explicit and the Profile can do timing calculations within the cyberspace. All data produced is used or ingested into data stores where each data point carries associated information on time and a set of standards-based structural, descriptive and administrative operational meta data. Reusability addresses digitization of measurements into communicable data, time and meta data in a standards-based format.

While Fig. 8 provides a static view of a profile, the importance and value of the SM Profile approach is illustrated much more strongly when used in a process of developing an SM Profile for an operational application. Consider Fig. 9A-C in sequence. Fig. 9A shows Base SM Profile A that has, for example, been produced by the vendor of the extrusion press as a deliverable with the device. Shown as a rough XML example are specific data points and names, data points as operating inputs, and data points as measured outputs. In other words, the vendor provides data names and contextualized data useful in the operation of the device. Now consider Fig. 9B where, for example, an integrator has worked out how to populate the data using CIP (Common Industrial Protocol). By using the Base Profile A and extending it with the CIP Profile B for the device there is now a usable combined profile produced by the vendor and the integrator.

In Fig. 9C there is a Model Orchestration Activity Profile that calls and executes a data transformation with needed data identified and gathered.



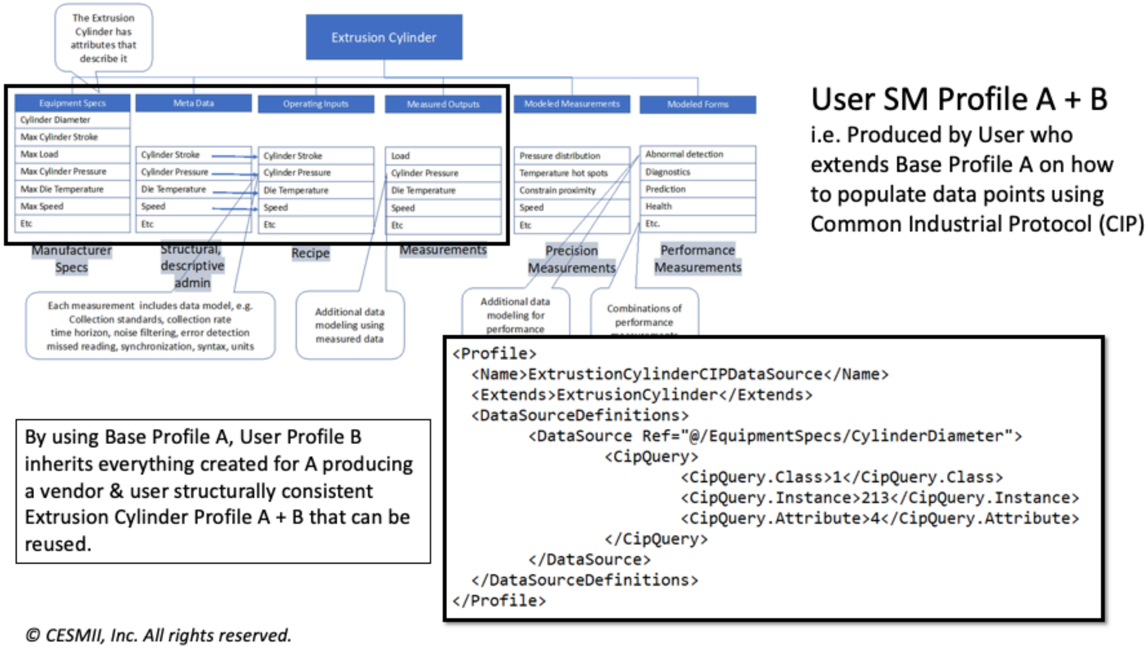
Base SM Profile A

i.e. Produced by Vendor

```
<Profile>
  <Name>ExtrusionCylinder</Name>
  <Extends>AbstractManufacturingObject</Extends>
  <DataPointDefinitions>
        <DataPoint Name="EquipmentSpecs">
                <DataPoint Name="CylinderDiameter" Ref="DataSource"/>
                <DataPoint Name="MaxCylinderStroke" Ref="DataSource"/>
                <DataPoint Name="etc..." Ref="DataSource"/>
        </DataPoint>
        <DataPoint Name="MetaData">
                <DataPoint Name="CylinderStroke" Ref="DataSource"/>
                <DataPoint Name="CylinderPressure" Ref="DataSource"/>
                <DataPoint Name="DieTemperature" Ref="DataSource"/>
                <DataPoint Name="etc..." Ref="DataSource"/>
        </DataPoint>
        <DataPoint Name="OperatingInputs">
                <DataPoint Ref="@/MetaData/CylinderStroke">
                <DataPoint Ref="@/MetaData/CylinderPressure">
                <DataPoint Ref="@/MetaData/CylinderDieTemperature">
                <DataPoint Ref="etc...">
        </DataPoint>
        <DataPoint Name="MeasuredOutputs">
                <DataPoint Name="Load" Ref="DataSource">
                <DataPoint Name="OutputCylinderPressure">
                        <DataPoint.Ref>
                                <Calculation>@/MetaData/CylinderPressure * @/MetaData/CylinderPressure</Calculation>
                        </DataPoint.Ref>
                </DataPoint>
        </DataPoint>
  </DataPointDefinitions>
</Profile>
```

Complete valid profile in crude XML
- Only data structure & relationships
- Extensibility useful
- No data yet provided

Figure 9A. A Base SM Profile.



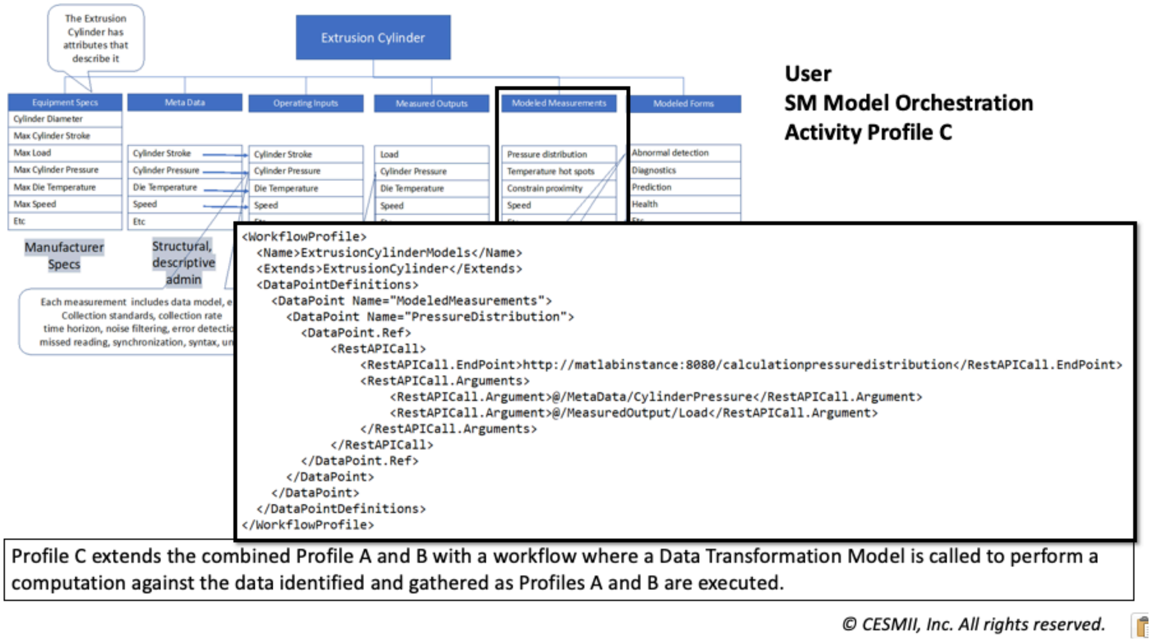
User SM Profile A + B

i.e. Produced by User who extends Base Profile A on how to populate data points using Common Industrial Protocol (CIP)

```
<Profile>
  <Name>ExtrustionCylinderCIPDataSource</Name>
  <Extends>ExtrusionCylinder</Extends>
  <DataSourceDefinitions>
        <DataSource Ref="@/EquipmentSpecs/CylinderDiameter">
                <CipQuery>
                        <CipQuery.Class>1</CipQuery.Class>
                        <CipQuery.Instance>213</CipQuery.Instance>
                        <CipQuery.Attribute>4</CipQuery.Attribute>
                </CipQuery>
        </DataSource>
  </DataSourceDefinitions>
</Profile>
```

By using Base Profile A, User Profile B inherits everything created for A producing a vendor & user structurally consistent Extrusion Cylinder Profile A + B that can be reused.

Figure 9B. A user profile inheriting properties from a base profile.



```
<WorkflowProfile>
  <Name>ExtrusionCylinderModels</Name>
  <Extends>ExtrusionCylinder</Extends>
  <DataPointDefinitions>
    <DataPoint Name="ModeledMeasurements">
      <DataPoint Name="PressureDistribution">
        <DataPoint.Ref>
            <RestAPICall>
                <RestAPICall.EndPoint>http://matlabinstance:8080/calculationpressuredistribution</RestAPICall.EndPoint>
                <RestAPICall.Arguments>
                    <RestAPICall.Argument>@/MetaData/CylinderPressure</RestAPICall.Argument>
                    <RestAPICall.Argument>@/MeasuredOutput/Load</RestAPICall.Argument>
                </RestAPICall.Arguments>
            </RestAPICall>
        </DataPoint.Ref>
      </DataPoint>
    </DataPoint>
  </DataPointDefinitions>
</WorkflowProfile>
```

Profile C extends the combined Profile A and B with a workflow where a Data Transformation Model is called to perform a computation against the data identified and gathered as Profiles A and B are executed.

Figure 9c. Executing SM Profiles with a model orchestration activity profile.

8. Overarching R&D considerations

8.1 Discretized modeling

With reference to both this extrusion cylinder example and the earlier SMR example, when proprietary operating data and modeling information are removed from the data model what is left is a contextualized data model template or SM Profile for the device. Similarly, when the proprietary data and operating information are removed from a model transformation what is left are the model type, the configuration and a model orchestration activity workflow.

Importantly, emphasizing the data lifecycle pattern architecturally, i.e. data generation, contextualization, transformation, orchestration and execution in a discretized manner, we are able to capture data model templates, model configurations for devices and workflows for the different model transformations and their respective objectives, i.e. control, as explicit elements of SM Profiles.

As discussed in the SMR example, there is template-based reusability for an SM Profile for an IR camera data model used similarly to measure temperatures spatially. There is reusability for a workflow-based SM Model Orchestration Activity Profile for orchestrating a ROM builder using a high fidelity Digital Twin. There is reusability with an SMR profile containing the CFD model configuration, mesh and convergence strategy for a similar furnace, a profile containing the configuration and training strategy for a similar OLS MATLAB model, and a workflow-based model orchestration activity profile for orchestrating an operational optimizer and control ROM. Importantly, each profile defines the contextualized data, model configurations, data connectivity protocols for the device, process or data transformation in a declarative template which is reusable as a starting point template for similar physical and cyber applications (don't need to build an application from scratch). These can all roll up into an SM Profile for an SMR furnace as a device.

Discretized workflow orchestration is used in a foundational role as a form of data modeling that uses workflow at an activity level as a fundamental construct. A workflow construct makes it possible to distinguish and work with individual data contextualization models and data modeling transformations as individual steps, in orchestrated combinations and with different approaches for different application objectives. Each step is an activity that can be associated with a distinguishable cyberspace such that time can be managed with orchestration and system-of-systems properties. Discretized modeling vs. tightly coupled modeling or blackbox machine-learned models has orchestration and execution advantages, for example when data need to be exchanged by business agreement, there are smart workers in-the-loop, there are cross architecture, cross vendor, security management and mitigation opportunities. Discretized modeling also has domain knowledge advantages in that sequencing, branching, conditional and causal logic are explicit and make it possible to include tightly coupled models in an interpretable operational context. Data executed in workflow activities provide execution data patterns for further operational optimization as well as operational behaviors useful for security. Discretized modeling also has advantages of reusability, composability, orchestrated management and DevOps (Development Operations) application development approaches. Key research areas include leveraging hybrid model approaches and predicting properties of these workflows for operational timeliness, viability, stability, and resilience.

8.2 SM Innovation Platform and a de facto standard

There is a need to operationalize a *de facto standard* for the manufacturing industry to drive advantageous properties for the SM Innovation Platform so that the infrastructure can be consistently shared. From a CESMII perspective, this requires a new form of *open access* but hyper-scaled digital infrastructure at national and global scales that can only be provided by the vendor community. However, a shared, de facto standard needs to be managed for industry by industry through trusted governance. The SM Innovation Platform therefore provides the operational vehicle in which a de facto standard can be governed and managed as a *wireframe* specification that can be scaled by the vendor community. The platform wireframe defines the particular construction of digital services that can be instantiated into an openly accessible platform. All stakeholders, e.g. manufacturers, providers, integrators and innovators, can use it to individual and collective advantage through business agreement. *Democratization* as a business objective is baked into the wireframe specification through properties and operating definition for accessibility to certified profiles that can be instantiated as apps and secure core data services built with converged OT/IT properties for shared infrastructure.

More broadly, a de facto standard can be designed and manipulated to drive the desired properties of a stack architecture to address democratizing and accelerating the adoption of Smart Manufacturing while addressing cybersecurity protection and mitigation strategies with interconnectedness. As shown in Fig. 10, CESMII has converged on a set of industry-defined business and operational properties. These are properties that small, medium and large manufacturers and their supply chains need individually and together to pursue productivity, precision and performance opportunities faster, more easily and more cost effectively. In addition to application accessibility, the wireframe properties address technology and business practices that reduce complexity, lower cost, expand application extensibility and make it possible to change market drivers with lowered risk. These are digitally-enabled business and operational properties that in turn define the IT required for interconnectivity cybersecurity and comprehensive management of business, operational, information and implementation agreements involving data. Agreement and adoption of a de facto standards-based wireframe is driven first and foremost as a business decision about individual value that is achieved as a collective and not the standard itself.

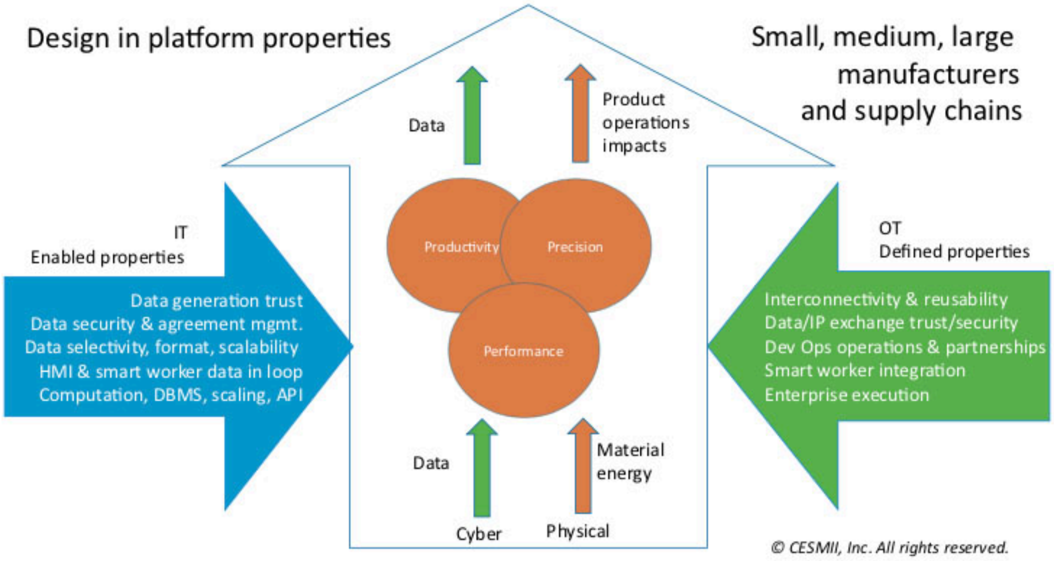


Fig. 10. OT/IT converged properties for business and technology democratization access and extensibility.

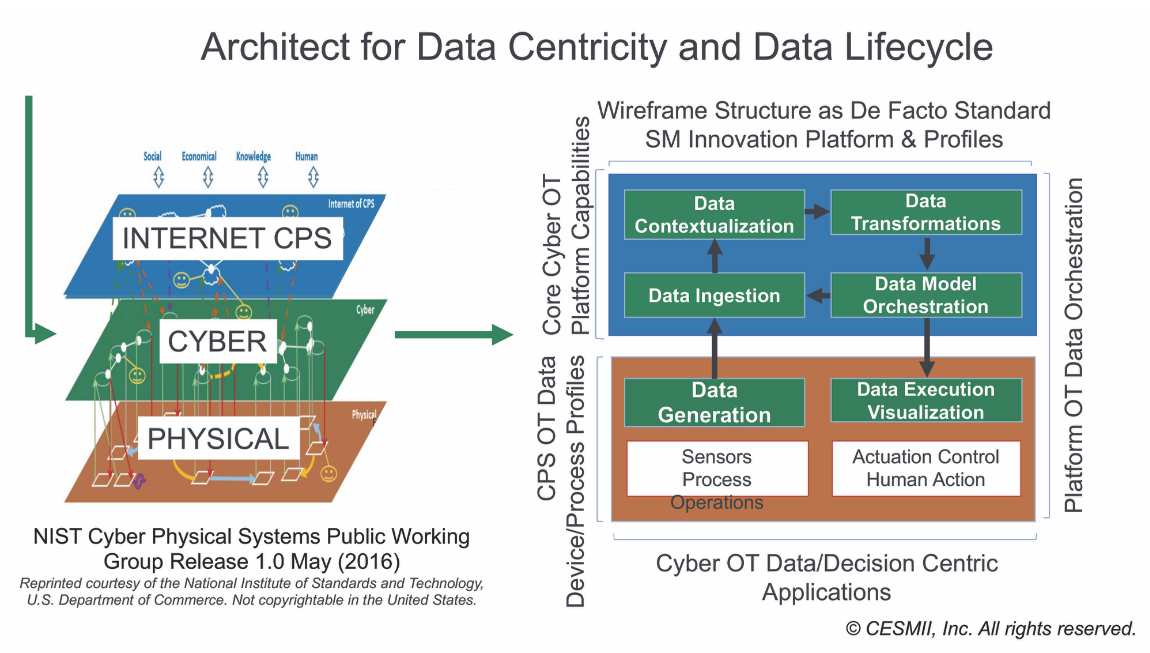
In the right- and left-hand arrows, Fig. 10 lists these cyber-side OT/IT converged properties that have been advocated by industry and are baked into the SM Innovation Platform's wireframe service design. Fig. 10 illustrates the data-centric view as a cyber flow of data that is distinct from the physical material and energy flows. This distinction is technically and operationally important since we now wish to build cyber-side operational data infrastructure that can interoperate with the physical-side structure in a dominate manner instead of a subordinate manner. While the physical-side and cyber-side flows and their respective operational data and material transformations are necessarily tightly aligned, cyber data operations and physical manufacturing operations are free to realign differently to address new demands for productivity, precision, and performance. Just as there are important properties and expectations with physical manufacturing structures and the use of physical assets, there are properties and expectations for cyber infrastructure and the use of data assets.

8.3 Technical foundations and instantiation of the SM Innovation Platform

As developed in this paper, Data Centricity is the key foundation making it possible to orchestrate data in ways that do not need to directly align with function, structure or behavior of the physical operations. The explicit distinction of physical-side cyberspaces from physical asset operations makes it possible to structurally leverage a repeatable, far less diverse cyber-side lifecycle pattern of data. Data are transformed and applied separately from the physical-side manufacturing operation even though there can be a great diversity in the function of the physical operation. The data lifecycle pattern makes it easier to configure cyber infrastructure that is reusable and/or sharable based on common cyber-side patterns of data generation, ingestion, contextualization, transformation, workflow-based orchestration and physical-side interfaces [8].

Fig. 11 shows how the CPS-layered view published by the NIST CPS workgroup (see Ref. [13]) is used to map and enable Core Cyber OT Services with SM Profiles and Orchestration. The arrow on the left indicates the driving emphasis on cyber, not physical or IT (Internet). With reference to Fig. 6, the Data Generation, Data Execution and Visualization endpoints that interface with the physical layer are shown on the right of Fig. 11 as cyber-data modeling interface capabilities that are overlaid on the physical-layer. The Data Device/Process SM Profiles contain the data model templates for interfacing cyber-layer with the physical layer. The four Core Cyber OT Data Platform Capabilities, corresponding to the data lifecycle, emphasize cyber layer modeling overlaid on the IT/Internet layer that enables them. As shown on the right-hand side of the figure, the SM Innovation Platform captures all of these capabilities as Core Cyber OT Platform Capabilities (left-hand top). CPS OT Data Device/Process Profiles (left-hand bottom) are combined with data and modeling functions, implemented using the Core Cyber OT Platform Capabilities. These are orchestrated broadly (right) to build Cyber OT Data/Decision Centric applications (bottom). The De Facto Standard (top) specifies how these services come together in a wireframe set of services.

To encourage broad use and access to platform properties by manufacturers, the CESMII SM Innovation Platform is developed as an *open, collaborative and integrated*[a] platform as properties of the wireframe de facto standard. This platform design position is key to enabling manufacturers to solve problems using operational technology (OT) tools and applications developed by technology providers and subject matter experts in CESMII's ecosystem [8]. This is illustrated in Figure 12.



NIST Cyber Physical Systems Public Working Group Release 1.0 May (2016)

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Fig. 11. Cyber physical system foundation of the SM Innovation platform structure.

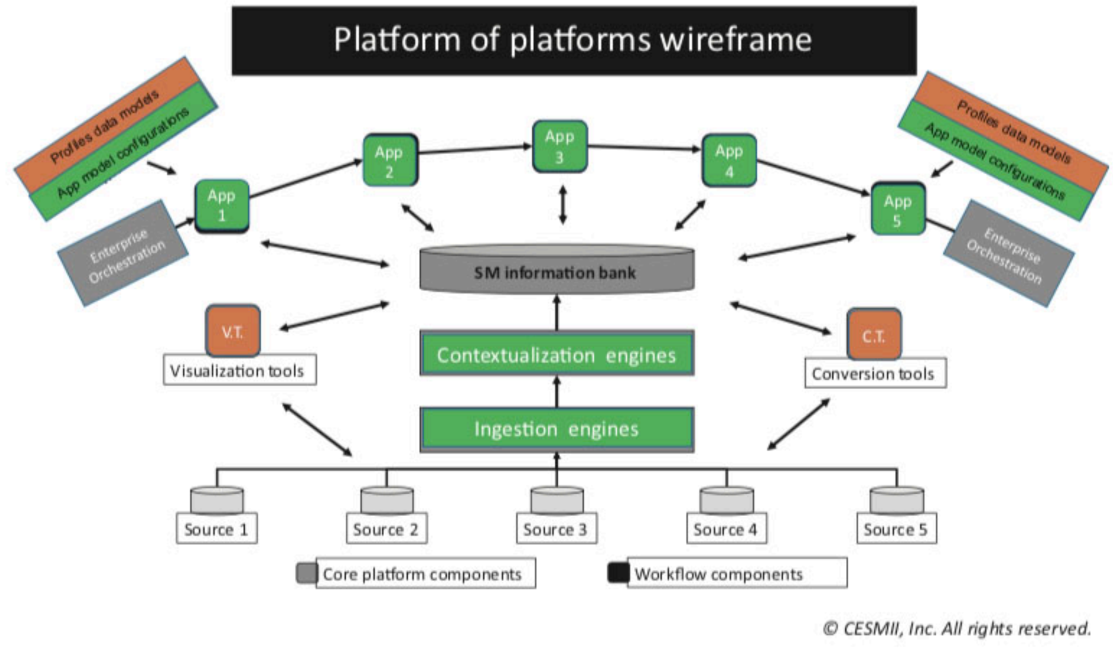

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Fig. 12. Functional Illustration of the SM Innovation Platform wireframe.

As shown, data can be ingested in different forms from multiple sources. Different data stores for different types of data are available, ingestion and contextualization engines and tools are managed as platform core capabilities and not just individual vendor production functions. Apps in the form of “filled in” SM Profile data models and common data model transformations, and conversion and visualization tools that are selectable from a marketplace are managed through an enterprise orchestration workflow construct that is vendor agnostic and also provides secure business data exchange tools. As an overall platform-of-platforms wireframe service for integrating commercial and other available platform services, the SM Innovation Platform makes it possible to more readily integrate and orchestrate vendor products for overall objectives but also for one vendor product to use the service of another vendor product.

The de facto *standard* further describes how the suite of services integrates and how the overall properties become outcomes of the structure. As stated, *Open Access* is also defined by the de facto standard, specifying the access and ability to integrate with the wireframe core services and with application profiles, additional data transformation services and tools in a marketplace as a user, provider or integrator. The wireframe services themselves are *closed* in order to manage the de facto standard, the security and and trusted business data exchange processes. A particularly important closed OT/IT converged service is with the data stores. Rather than data stores for every product and the multiple copies of data that result and need to be interfaced, fewer data stores and fewer copies of data with greater selectivity of data through the business exchange services reduces complexity and security vulnerabilities, and enhances application interoperability, security management and mitigation.

The SM Innovation Platform has been designed and operationalized for manufacturing cyberspace services as a Platform-as-a-Service (PaaS) set of wireframe services for Smart Manufacturing data-centric applications using the NIST 800-145 definition (see Ref. [14]) as illustrated in Fig. 13. It is functionally distinguished as PaaS infrastructure designed to support the prescribed set of integrated wireframe OT services. In order to scale, the SM Innovation Platform de facto standard is built on top of commercial hyperscale Infrastructure-as-a-Service (IaaS) platforms and virtual machines so that cloud and edge capabilities/features, such as service-oriented architecture, portability, scalability, programmability, costing, security, etc., interoperate with other commercial and open source IaaSs, PaaSs and SaaSs (Software-as-a-Service) based on a set of cloud and edge architecture and integration IT standards. As shown in the Enabler area, the SM Innovation Platform, when instantiated (filled-in) with service products, provides the services for the development, deployment, orchestration, and operation of data workflow environments based on SM Profiles so these can co-exist seamlessly and readily shift between design and operational roles, creating a DevOps environment. Ultimately, the SM Innovation Platform is instantiated with vendor products for core services and for the apps. The SM Innovation Platform lays the foundation for multiple partners to create and disseminate innovative, cost effective solutions for small, medium and large manufacturers alike.

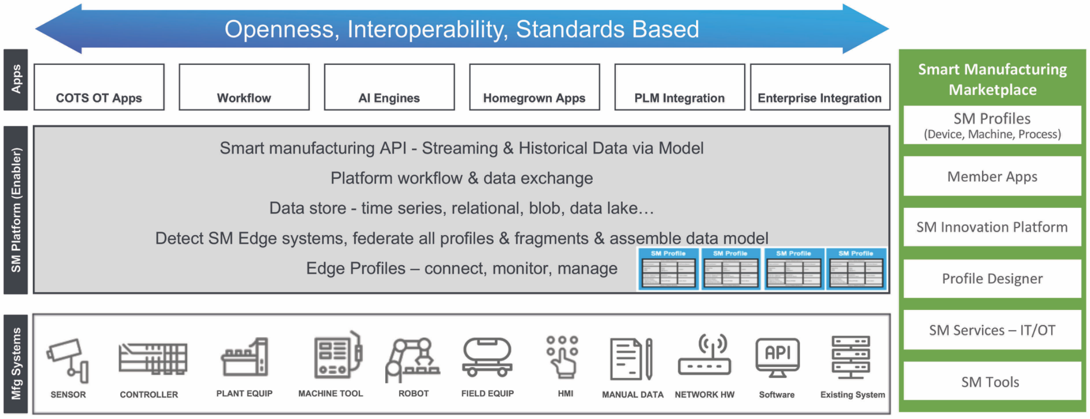

Fig. 13. The SM Innovation Platform as a wireframe of OT/IT and API services operating in edge-cloud structures.

The SM Innovation Platform uses cloud orchestration services at the infrastructure layer and extends declarative templates to describe how to construct data workflow environments and resources as reusable SM Profiles [15]. A common profile template provides the de facto standard for interoperability. An important artifact of this platform-of-platforms approach in Fig. 12 is that the SM Innovation Platform is not just bringing OT and IT services together but is building OT and IT systems-of-systems cyber spaces with emergent behaviors and characteristics that do not need to be fully prescriptive. Behaviors and characteristics can change as systems within systems dynamically change as a result of changing operational and business conditions or decisions. This is an open research area where the ability to orchestrate systems-of-systems across cyber products, operations, companies, and cyber spaces with different time constants requires predicting and managing the resilience, stability, and controllability properties of an end-to-end enterprise systems-of-systems implementation.

As illustrated earlier with the SMR use case, the SM Innovation Platform is set up for manufacturers to access a marketplace and select SM Profiles that match or are reasonably close to the needs of new applications of interest, i.e. furnace similar to the SMR furnace. These profiles can be used on premise with edge capability that reflects the de facto standard, directly through the SM Innovation Platform or as a hybrid of both to form an edge-cloud structure. An SM Profile will have defined the contextualized data requirements and may itself associate with application environments, i.e. MATLAB and particular MATLAB toolboxes configured for an application. Profiles in the marketplace can contain device, model orchestration, or application orchestrations as extended profiles or as separate device and model orchestration activity profiles that can be orchestrated differently in new applications. Applications like the SMR, therefore, stimulate multiple profiles depending on the reusable value of constituent profiles and the nature of the models.

When an SM Profile is in the marketplace at any level, a user can select, instantiate their own version of that Profile, and either use it as is or extend it for another application, creating another unique profile. CESMII's roadmap includes developing a Profile Designer to facilitate the creation of a large library of SM Profiles. It also includes a number of cross-industry and platform projects to build a portfolio of SM Profiles in the marketplace, while simultaneously continuing to build core capabilities so the profiles can be bound to the data and application environments and executed as workflow orchestrations. This approach is designed to stimulate multi-level profile building to drive application profiles into the marketplace for evaluation and expansion, and monetization when used in production. It also makes it possible to do R&D on applications and profile structures at the same time. The core capabilities that underpin the marketplace are maintained in a ready-to-execute state.

9. Conclusion

With a lens on industry-wide cyberinfrastructure for more rapid adoption and scaling of Smart Manufacturing, our CESMII conclusion is the need for an open, standards-based (de facto standard) manufacturing data and application platform that facilitates ubiquitous access and orchestration of multi-source data and multi-vendor modeling solutions. This is paramount to access and integration for all manufacturers and a refocusing of attention on the operational value of the application and not on its infrastructure. The market corollary is that the current need for vendors to develop and sustain their own proprietary platforms needs to give way to shared core capabilities and the use of the de facto standard (the wireframe). This enables multiple vendor products to be integrated securely for interoperability and it drives economic value for manufacturers and providers alike.

A key objective for cyberinfrastructure, therefore, is striving for a new democratized pattern of development, innovation and value creation at scale with an open platform that focuses on horizontal interoperability, leverages contemporary technologies, and enables crowdsourcing of vital domain expertise. Again, the potential stems from spurring an industry-wide reach to the productivity, precision and performance benefits of Smart Manufacturing while substantially reducing the cost of implementation. While it is a heavy lift to change innovation practices and economic drivers established over years, there are new economic drivers, global forces and new technologies to re-consider taking on a platform-supported approach in a new way. For the manufacturing industry there needs to be a line of sight to dramatically increasing the velocity of solution acquisition, development and deployment that is just not possible with today's verticalized, transaction-based structures. There is both the need and the opportunity to substantially free up the new economic potential to be a pull on expansion and democratization of Smart Manufacturing.

It is with these broad industry goals and aspirations that this paper describes a data- and decision-centric approach to shared Smart Manufacturing cyberinfrastructure based on a layered physical, cyber, and Internet analysis by the NIST CPS workgroup.

The data-centric view leverages the reusability of a repeatable operational data lifecycle between data generation and physical actuation by separating cyber and physical layers and emphasizing the cyber-side data orchestration. An inherent general challenge with operational data and modeling is developing actionable insights from the right set of data and taking into account the uncertainty in both the data and model. In applying data and decision centricity together, decision centricity defines data contextualization based on meaningful application objectives.

Shared cyberinfrastructure called the SM Innovation Platform is described as a set of wireframe services that make it possible for different vendor products to slot in as Core OT Data Services. A de facto standard drives a set of properties for the integrated services that include interconnected cybersecurity, secure data exchange, execution resilience, smart worker in the loop, vendor agnosticism, hyperscaling, a DevOps approach to application design, and deployment and design from previously applied data contextualization templates and model configurations for similar applications. SM Profiles provide the device/process data contextualization data model templates and data model transformation configurations. The SM Innovation Platform also provides an R&D scaling capacity to study groups of cross-industry applications. There is R&D on the SM Innovation Platform and R&D through it since it provides the scaling to expand and accelerate the necessary research and the vehicle to test, evaluate and assimilate the continued development at scale. Significant R&D questions on SM Profiles and the SM Innovation Platform remain as illustrated in Fig. 12. Profiles and the platform need to align further technical, architecture, business and interface developments together. We have started with the simplest SM Profiles and the simplest of core services in the SM Innovation Platform. What is unique is the integration that underpins the wireframe services developed with the data- and decision-centric view.

The CESMII SM Innovation Platform distinguishes itself from the vast majority of IIoT (Industrial Internet of Things) platforms that are being proliferated in the market today:

- *Span:* The SM Innovation Platform spans operational endpoint data sources to on-premise, edge data aggregration and computation to human-in-the-loop to cloud, and back to human-in-the-loop and/or execution/actuation endpoints. Span is also across vendor products, process operations and manufacturers in a supply chain. Data centricity and a new operational data lifecycle concept provide the technical foundations for enterprise business execution properties and cross boundary smart manufacturing systems to be comprehensively evolved and managed as converged OT and IT functions.

- *OT/IT integration with OT data centricity:* Nearly all IIoT platforms available today have the flavor of “connect your device to my cloud platform and our product will monitor and manage your data.” This is still an IT service that remains function–and physical asset-centered, not data-centered. Contextualization and data preparation before data becomes useful is not reusable and it is still heavily dependent on subject matter experts. OT data centricity focuses on creating data models, physics-based models, predictive tools, and workflow-based solutions as OT apps based on reusable data models. Hyperscale cloud platform partners provide a ready, standards-based IT infrastructure that makes it possible to plug in OT core capabilities and profile- and model-based OT apps into an OT marketplace that can reside, operate and scale using the IT tools in their IIoT services platforms.

- *Vendor agnostic collaborative innovation:* Most existing IIoT platforms tend to lock down manufacturers into using single vendor technologies for acquiring data, contextualizing it and consuming it for analytics on a specific cloud-based platform. While some of these platforms do provide flexibility in using different vendors for various data functions, the integration is typically a one-off solution. The SM Innovation Platform is designed for integrating content and technologies in a vendor agnostic framework. As a cloud platform for integrating platforms, the SM Innovation Platform provides the means for applications to interoperate through configuration and integration standards that are based on an industry-managed de facto standard for the wireframe services and embodied in the SM Profile specification. Profile-based applications in the SM Innovation Platform marketplace will be “certified” to interoperate.

- *Data ingestion:* Making data ingestion a core capability ensures that the platform can connect to and acquire data from multiple source endpoints including sensors and systems on the manufacturing floor as well as data from sources beyond the boundary of the factory. Data ingestion involves the ability to select from many connectivity protocols and encompasses the ability to transmit, stream and store data in databases or historians for extended and broader use. Conversely, the connectivity to the data sources is needed to transmit results back to the manufacturing floor control and execution systems or as visualizations for human-in-the-loop actions.

- *Data models and contextualization:* The heavy lift with operational data systems is contextualization. For ingested data to be consumed by the applications, the data need to be connected, integrated, aggregated, normalized, and interpreted across the various data streams at multiple levels to provide the necessary context for the multiple applications that need to use the information. This requires subject matter expertise, and is typically manifested in a data model configured in a traditional Relational Database Management System (DBMS). The SM Profile is the key construct that makes it possible to develop a contextualized data model once, expand it and extend it rather than building a new profile every time. Reusability and extendibility for a manufacturer to grow its base of contextualized data is a critical pathway capability.

- *Information management complexity:* Information management deals with the storage and retrieval of contextualized data and information so that far fewer data stores are used by far more software applications. Reducing the complexity of interconnectedness requires the reduction of data stores and data flows between them. This can be accomplished either through an "information bank" in the form of a database, or an information map that allows data to be accessed from its original source without duplication in additional databases. The information management system in the SM Innovation Platform allows multi-vendor applications to access and consume data in a consistent/standard manner providing architectural guidance to explicitly reduce databases and data interconnections and manage data exchanges. This is a critical pathway capability to reduce the complexity and address the cybersecurity challenges of interconnectedness.

- *Workflow as a modeling construct:* Workflow orchestration of data as a platform core capability provides the systematic means of automating analyses and data transformations, exchanging information, and managing diverse datasets and applications that can achieve operational 'span.' When developed as a fundamental discretized modeling construct, workflow provides an alternative or extended means of modeling the flow of data transformations for a process operation so that transformations and operational impacts can be interpreted and time can be managed explicitly compared to tightly-coupled modeling approaches. Workflow also allows the orchestration of the data to be reproduced and methods repeated and adapted as activity profiles. In the context of the SM Innovation Platform, a workflow utilizes other building blocks of the platform to create the capability to solve a problem in a systematic manner. As an operational utility, workflow provides the application orchestration with humans in the loop.

- *Application marketplace:* The SM marketplace is distinguished from other platforms as a marketplace and full functioning operational utility. It is a convenient location for end users to access Smart Manufacturing profile-based applications for use in edge or cloud applications. The marketplace is also a convenient location for application developers to integrate their products based on the profile specification to be used as reusable components in the SM Innovation Platform. As an operating utility with core capabilities, a profile-based application can be selected, data can be connected, ingested, bound and executed independently as an orchestration workflow. The marketplace also integrates trusted business data exchange and secure management of data partnerships and provides the interfaces and tools for using applications all together based on business agreements.

- *Scalability, extensibility and interoperability through SM Profiles:* Traditional IIoT platforms are built to solve specific problems. Every time a new problem needs to be solved, the manufacturer typically starts afresh by building new connections to the data sources, re-creating data models for contextualization, and re-configuring data connectivity to applications. This results in replication of effort and a multitude of point solutions. Instead SM Profiles (data models) for factory assets and SM Model Activity Profiles that allow seamless integration between data ingestion, data contextualization and data consumption emphasize reusability and extendability. Profiles include data necessary for a variety of applications to interoperate and create solutions for productivity, performance and precision. Scaling occurs as a result of reusing contextualized data models and not having to generate and connect data models for every device, every time. The focus shifts to orchestration and value.

Broadly, the Smart Manufacturing cyberinfrastructure described in this paper is premised on a need to build capability and capacity for small, medium and large manufacturers to engage aggressively in respective Smart Manufacturing explorations, a critical outcome for this cyberinfrastructure democratized innovation. Needed R&D on new value-driven uses of data and on scaling the potential of the platform can become force multipliers when done at scale throughout the manufacturing eco-system. When application innovation is on a consistent infrastructure, it can proceed faster through the TRLs (Technology Readiness Levels) to production use; integrated system solutions can be developed and studied more easily building on the work of others; and the non-proprietary knowhow can be extended at scale. Larger manufacturing organizations are able to build on secure, sanctioned and scalable platforms that all future vendors can leverage for model-based access to the plant floor and for application interoperability. Small and medium manufacturers can afford Smart Manufacturing solutions for the first time, and not require significant engineering or IT domain expertise on staff. The lofty goal is for manufacturers, vendors, integrators and researchers throughout all stakeholder institutions to work toward empowered employees – with secure access to real-time data – to innovate, improve and create sanctioned solutions and drive economic growth based on value instead of 'shadow IT' solutions.

Exploration and adoption of Smart Manufacturing is recognized as a process, a data and digitalization journey (not a single project), that derives staged benefit and builds readiness for collaborative supply chain interoperability, where a significant portion of the untapped Smart Manufacturing potential resides. However, this journey needs to avoid the compartmentalized patterns of vertical innovation and change that have been used for the past twenty-five years. Smart Manufacturing fundamentally is about the substantially untapped opportunity of "horizontal" integration that is amplified with new technologies that drive greater precision and performance. We have stressed the point that if Smart Manufacturing is left on its current trajectory, the dilemma of interconnected complexity will dramatically impede the anticipated value creation and U.S. manufacturing competitiveness in the global market.

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Footnotes

[a] https://www.thecge.net/archived-papers/the-rise-of-the-platform-enterprise-a-global-survey/.