Integrated Operations Management for Distributed Manufacturing

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Abstract: In traditional manufacturing operations management systems, the four pillars of ISA-95 (production, quality, maintenance, inventory) are each implemented as separate software systems. Each system independently manages its own data, operational decision-making, and resources. If the heterogeneous data from these disparate systems could be successfully integrated, manufacturing operations could be greatly improved by allowing decisions related to these systems to be made quicker, closer to the factory floor, and with a better contextualization of the connected systems. This paper describes some requirements and associated research challenges for balancing two objectives driving integrated operations management for distributed manufacturing: (1) integrating heterogeneous data and related decisions to enable better informed decision-making, and (2) making and executing operational decisions closer to data sources and control actuation. This second objective enables systems to react faster, while also reflecting the realities of distributed enterprises. The research goal is to develop and standardize model-based approaches to design, decision-support, and execution of operations management functions. The functions focused on in this paper include operational control, reliability management, and maintenance activities.

Keywords: Manufacturing, Operations Management, Model-based Enterprise, Data Analytics

1. INTRODUCTION

Production, quality, maintenance, and inventory (including storage and material handling) operations management systems are embodied in separate software systems and enterprise functions (ISA, 2010). These systems and functions own and manage their own data and decision-making to support their independent function. This structured hierarchy offers simplicity for functional team formation and other organizational considerations. However, improvements in operations management systems within the ISA-95 foundation have arguably reached saturation.

Improving smart manufacturing operations requires integrating the data and decisions made by these disparate systems, eventually (1) transitioning to integrated or coordinated systems (architecture), (2) enabling seamless information flow and decision coordination (optimization), and (3) facilitating execution across distributed smart manufacturing and their associated logistics systems (production).

Operations management encompasses many functions including data collection and synthesis, product and process definition management, and operations control functions, such as scheduling. Disparate and dissimilar information sources, heterogeneous decision-support analysis models, heterogeneous execution mechanisms make generalized, integrated operations management challenging. Humans are effective and efficient at interpreting, inferring, and “filling in the gaps” using tacit knowledge, e.g., discovering links between data and deciphering imprecise control instructions. Without the proper context, machines struggle with such tasks. As production systems become more automated, the derivation of complex insights need to be automated as well, requiring additional functional capabilities and technologies for implementation.

Standards supporting data exchange often do not provide sufficient information about system behavior to understand the effects of choices, thereby affecting stakeholders’ ability to make decisions. Data standards can be enhanced, or complemented, with logical models and models of computation (i.e., behavioral models) capturing how the system functions and is expected to behave. Figure 1 illustrates a means to consider this perspective. The expected function (F_e), expected behavior (B_e), and expected structure (S_e) of a production systems derive the realized (or actual) concepts (F, B, S). Without a formal description of each concept, causality of unexpected behavior is challenging to identify, avoid, and remedy. Consequences of unanticipated events can lead to quality loss, timely delays, and expensive change requests.

This paper is organized around a bottom-up framework that builds on common smart manufacturing standards for data exchange at the shop-floor, including the STandard for the Exchange of Product model data (STEP), MTConnect, and the Quality Information Framework (QIF) (Bernstein et al., 2018). These standards cover many aspects, or viewpoints, of a smart manufacturing system including products, processes, and resources producing data across their life-cycles – as-planned, as-fabricated, and as-inspected (Hedberg et al., 2017; Helu et al., 2018).

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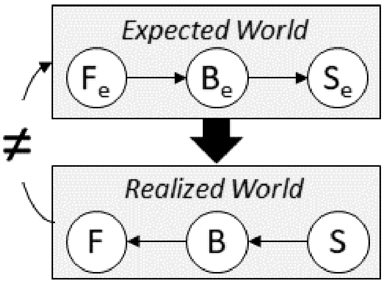

Fig. 1. An abridged diagram conveying the function-behavior-structure model (Gero, 1990).

Integrating heterogeneous (dissimilar) data enables disparate control functions and decisions to be integrated; for example, integrating production and maintenance scheduling decisions. As control functions are integrated, systems (architectures) are necessary to coordinate and orchestrate the planning and execution of these functions, balancing optimality, responsiveness, and robustness of the manufacturing operations.

In this sense, integrated data is the foundation to integrated control functions and architectures. Integrated data produces a complete view of the **state** of the system. Integrated decisions (functions) produce a complete view of the **actions** that can be taken to effect the system. And integrated or coordinated systems produce a complete view of the **execution** of actions.

A robust foundation for defining and integrating data, functions, and architectures enables these methods to be applied for both co-located, centralized systems, as well as those that are distributed (geographically or across enterprises) (Hedberg et al., 2018). This paper outlines some requirements (identifying potential research goals) for evolving manufacturing operations management systems to support smart manufacturing: Section 2 discusses integrating heterogeneous data, Section 3 discusses integrating heterogeneous operations management functions, and Section 4 discusses integrating heterogeneous systems.

2. DATA – INTEGRATING HETEROGENEOUS DATA

A research thrust in realizing a fully integrated facility is the integration of disparate data sources across not only the factory floor, but external to the enterprise operations. Such sources of information are highly heterogeneous and rarely designed to be linked or integrated with each other at the level required for managing, assessing, and reacting within modern manufacturing facilities. Data produced by different systems is generally created exclusively with regards to that system and loses much context and meaning when utilized outside of its original environment. However, many operations decisions require information from multiple systems and functional regimes, and as the drive for increased efficiency and automation progresses, more data will need to be accessed and be compatible with data sources foreign to its original intent.

The semantics and meta-data associated with most data are created with perspective of its native environment. The high level perspectives can generally be grouped into *Part*, *Process*, and *Resources*, but there can also be unique sub-specifications or even overlap within and between these categories (Cutting-Decelle et al., 2007). For example, vibration sensor data collected from a milling machine could be translated into health data to inform decisions on maintenance actions. These same sensor logs could, if interpreted differently while coupled with part specifications and planning, be used to develop process plans or even determine causes of deviations in individual or batch part quality. However, analyzing data outside its initial silo is difficult without the contextualization of the data with respect to other areas of operations management. From this example, it becomes clear that the needed contextualization of data goes beyond standard syntax and semantics for data exchange (i.e., interchange and interoperability). Although these needs are a part of the requirements, a need exists for a higher level linking of the uses of the data with the systems that affect or are affected by it.

Even when limiting the focus on one specific area, such as part production, many disparate elements need to be mapped accordingly to understand the state of a workpiece throughout production. A linking of the disparate data sources generated from as-planned, as-executed, and as-inspected is needed. Examples of standard files representing these data types include STEP, G-Code, MTConnect, and QIF files. Within the as-planned element, STEP and G-Code have an intuitive link since G-Code is created from a STEP (or similar) file. It may seem intuitive to link planning files, such as those relating a single product, but currently a native requirement does not exist that specifically links these sources of information. An obvious trigger for creating a link between these files would be during the creation of the file, either via internal or external meta-data. When moving onward to the subsequent information sources, methods for automating linking become less clear. 'Parent-child' relations will not be sufficient for all data files and formats since they are often created completely independently of each other, but the need for contextual linking remains.

With that perspective in mind, optimal data production and curation should conform to several requirements. Ideally, many of these requirements could be automated through the adoption of standard formats and procedures. In some cases, existing standards are not sufficient when utilized alone, but internal adjustments to the standards, or external curation services could be employed. Below is a list of high-level requirements and idealized goals for producing, storing, and contextualizing information produced in and about manufacturing facilities.

Potential Goals:

- Link data within and across the realms of *Part*, *Process*, and *Resources* to support development of a comprehensive view and assessment of the system state and condition.
- Link design information (e.g., STEP and G-Code) to capabilities and capacity.
- Capture discrete, continuous, and less traditional forms of tacit knowledge in contextually rich and semantically accessible manners.

- Recognize that different data will be used for different intermediate goals, but the ultimate goal is to optimize production and asset management.
- Provide context for possible intermediate goals and possible decisions supported from a source of data.
- Achieve closed loop feedback from design processes through production and quality assessment.

3. FUNCTIONS – INTEGRATING HETEROGENEOUS OPERATIONAL CONTROL DECISIONS

In ISA-95, operational control focuses on scheduling production, maintenance, quality, and inventory (including material handling) activities. Integrating these decisions may yield significant benefits to manufacturing operations. For example, maintenance decisions affect the capacity and capability of production resources. Coordinating downtime on particular resources with production requirements and prioritizing maintenance on critical resources to minimize disruptions can have a significant impact on the throughput of the manufacturing system (Chang et al., 2007; Hoffman et al., 2018). Integrating quality and production decisions, such as scheduling rework, ensures that orders are completed on-time, or minimize tardiness. Quality and maintenance decisions can be integrated to produce a better understanding of current capability of resources, ensuring the right capabilities are available when necessary. Finally, inventory and material handling functions impact the availability of parts and raw materials to both production and maintenance systems.

While mathematical abstractions support scheduling across heterogeneous domains, translating dissimilar data from these domains into those models and then translating the output into executable actions is challenging and highly dependent on the system configuration, specifically the degree and kind of automation. As with data, standard syntax and semantics is necessary but often insufficient to supporting interoperability – contextualization of decisions (state, actions, and execution) are necessary.

Scheduling resources across heterogeneous domains to execute operational control decisions requires standard definitions of resource capacity and availability. Such capability would enable a consistent definition of scheduling, e.g., a matching of provided and required capabilities not exceeding capacity or availability constraints. Since many scheduling methods focus on assigning resources to a part's process plan, integrated operational control require methods for augmenting these process plans with all the auxiliary / "logistics" steps. This would support developing uniform methods for tracking, planning, and executing each step required to produce a part, including move, store, test, and rework processing steps in an integrated fashion.

Consistent and standard abstractions for modeling the state and behavior of the system and formulating control decisions also supports the goal of reusable, plug-and-play decision support. Each decision requires decision support and analysis models that help the system or operator select the best control action to take to effect the system. Operational control definitions enable standard interfaces and interoperable decision models. Ideally, these analysis models and tools could be applied uniformly across the heterogeneous domains or to integrated decision problems spanning multiple domains. For example, standard abstractions for describing resource behavior and specifying the work required to complete a part moves us closer to standard scheduling models, enabling research on supporting algorithms to be tested and implemented.

Scheduling, however, is not a monolithic activity. Dynamic operational control is composed of several smaller atomic functions that impact the flow of resources and work around the factory floor (Sprock et al., 2019). Control functions are defined by two corresponding components: the decision function and the actuator function. What decisions need to be made (when/where in the system)? How are the decisions made? And, how are the selected actions executed? Integrating traditionally independent, domain-driven control functions requires extending the integrated and contextualized view of the system state (provided by the above section) to include a common model for defining the decision functions and actions that can be taken to affect the system.

Integrating heterogeneous decisions has several research goals focused on developing standard functional definitions for operational control activities, supporting integrating decisions across heterogeneous domains.

Potential Goals:

- Link control decisions across production, quality, maintenance, and inventory (and material handling) concerns.
- Develop standard definitions of capability enabling matching capabilities to produce a part with capabilities provided by resources available to the system.
- Develop standard definitions of resource availability and capacity and models of resource behavior.
- Construct methods for augmenting process plans with auxiliary "logistics" steps, such as move, store, test, and rework steps.
- Define control functions with a consistent (standard) definition that supports the interfaces and decision support interoperability.
- Deploy interoperable (plug-and-play) decision support analysis methods that leverage these standard definitions and models.
- Integrate data and support decision-making by linking enterprise planning, operational, and shop floor execution functions.

4. ARCHITECTURE – INTEGRATING HETEROGENEOUS SYSTEMS

Integrating heterogeneous production, quality, maintenance, and inventory (and material handling) systems requires that the systems supporting the decision making and execution are no longer isolated, but rather coordinating and cooperating, beyond simply sharing information. Standard functional descriptions of operational control functions (and interoperable decision support) enables these functions to be configured into architectures suitable to the requirements. Selecting an appropriate architecture guides the trade-offs between the agility and responsiveness of purely distributed systems and the optimal-

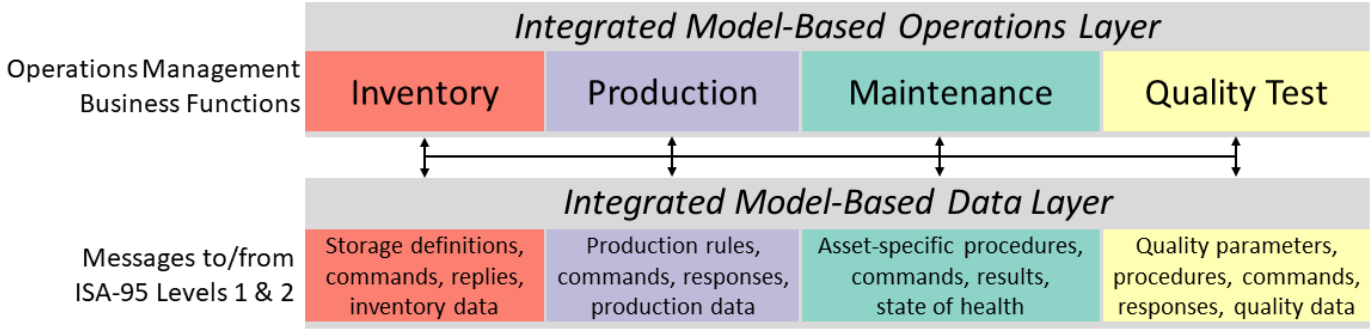

Fig. 2. Future state of integrated smart manufacturing operations management data and functions.

ity and robustness of centralized decision-making (Dilts et al., 1991). Self-similar architectures build upon the control function definitions in Section 3, treating resources uniformly and matching provided and required capabilities (Sprock, 2018). They provide a way to transition from one architecture to another, e.g., from a traditional hierarchical control architecture to one that is more, but not completely, decentralized, such as mediator architectures (Maturana and Norrie, 1996).

Methods and standards for specifying and integrating data, functions, and systems for smart manufacturing also require support for verification and validation the resulting system. While one aspect testing and validation relies on reference data sets and standard interfaces, system models and virtual (simulation) test-beds that support experimentation of operational control architectures and decision support methods, e.g., the work from Schluse et al. (2017). Simulation-based systems engineering requires experimentation on the virtual test-bed, including its decision-making and execution, as well as testing and deploying interoperable decision-support analysis models. These research goals would complement the many traditional hardware-driven, physical test-beds that are essential to testing and integrating process and device level research required for smart manufacturing.

Potential Goals:

- Leverage linked data and coordinated control functions into deployable, integrated manufacturing operations management architectures.
- Develop self-similar architectures that enable operations management functions to be composed into architectures that satisfy the defined requirements – such as distributed enterprises.
- Construct virtual simulation test-bed enabling experimentatation, testing, and validation of model-driven smart manufacturing operations management concepts, including decision support and control architectures.

5. OUTLOOK AND CONCLUSION

The reality is that most organizations are distributed: functionally within a facility, across multiple locations within an enterprise, or geographically within a supply chain. As a result, it remains challenging to coordinate disparate data across such a diverse distribution network. Figure 2 presents a different approach to the siloed operational verticals presented in ISA-95. Across the four fundamental operations management business functions: inventory, production, maintenance, and quality testing, there is significant potential for merging the vertical data sources within a unified layer. It is expected that messages already passed within these verticals would present opportunities when accessed from other perspectives, e.g., leveraging inventory capacity data to plan maintenance schedules. If realized, such a framework would improve the efficiency of decision-making, help identify non-obvious, complex relationships across domains, and facilitate a deeper awareness from the perspective of *Part*, *Process*, and *Resources*.

To help realize this vision, a set of proposed requirements are shared below:

- Developing contextual and semantic links in a manner that is relatable regardless of data or file type. Native and/or externally curated meta-data may be necessary to achieve data mapping.
- Creating links should be created as close as possible to the time of creation or capture of the data.
- Capturing formalized basic minimum sets of information. This should include the capability to be expanded with custom case specific or tacit knowledge pertinent to all stakeholders.
- Characterizing links based on direction with respect to process flow (where applicable).
- Creating searchable information links such that information relevant bidirectionally is easily accessible.
- Assuring that storage and access of data are independent to support modular model development.
- Accommodating alternations in storage and location of linked files, similar to a standard handle system.

The ability to integrate data, functions, and systems (the standards, methods, and technologies) is an essential to supporting distributed manufacturing. Allowing systems to interact seamlessly, sharing and linking data and coordinating decisions, enables organizations to select and deploy the configuration that best satisfies their requirements. This paper describes requirements and challenges in realizing this goal. Future work will use these requirements to link different data sources for specific decisions across different pillars in ISA 95.

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