Reference Architectures for Smart Manufacturing

A Critical Review

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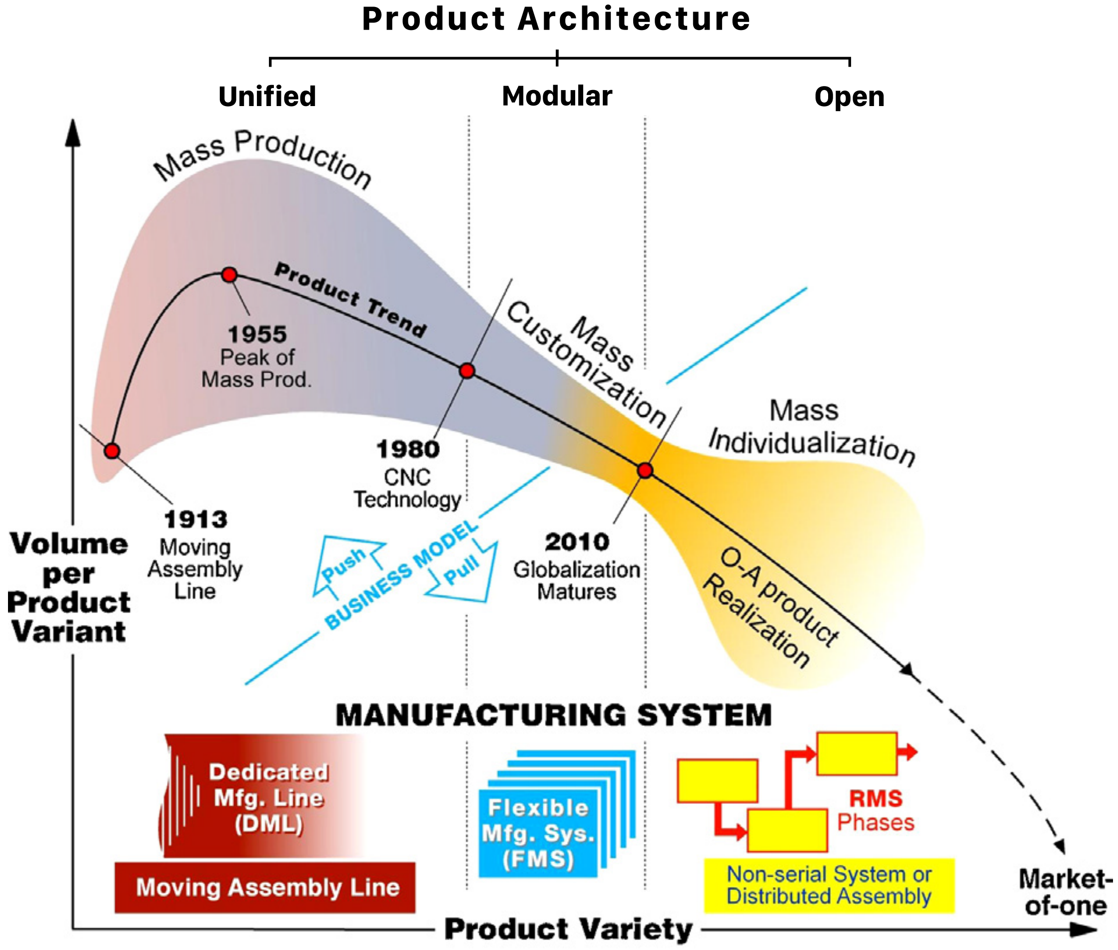
Why Smart Manufacturing?



Evolution of Manufacturing Paradigms (Koren et al., 2013)

Individualized Products (Koren et al., 2013)

OAP: "A platform that allows the integration of modules from different sources in order to adapt product functionality exactly to the user's needs"

Smart Products (Gao et al., 2011)

PSS: Life cycle services (e.g., repair, overhaul, maintenance) enabled by embedded electronics, sensors, memory, and reasoning capabilities

Mass-Personalization

	Google	amazon	UBER
Personalized	Information	Shopping	Ride
Sources	Web	Sellers	Drivers
Resources	Data	Items	Cars
Process: Matching	Data → Info	Items → Shoppers	Cars → Riders
Diversity	High	High	High
Complexity	Low	Low	Low
How?	Standard “Categorization” of Resources, Functions, & Processes		

What keeps us from applying the same idea to manufacturing?

New Paradigms & Architectures

Paradigms

Smart Mfg., Industry 4.0

Cyber-Physical Production Systems

Cloud Mfg., Social Mfg.

Architectures

RAMI4.0, IIRA, IBM Industry 4.0

NIST Service-Oriented Smart Mfg.

…

Common Features

Support:

1) Integrated value networks that organize and share mfg. resources over the Internet
2) Integration of resources on the IoT as adaptive, secure, and on-demand mfg. services
3) Smart and connected CPS objects that enable plug-and-produce production

Enterprise Architectures

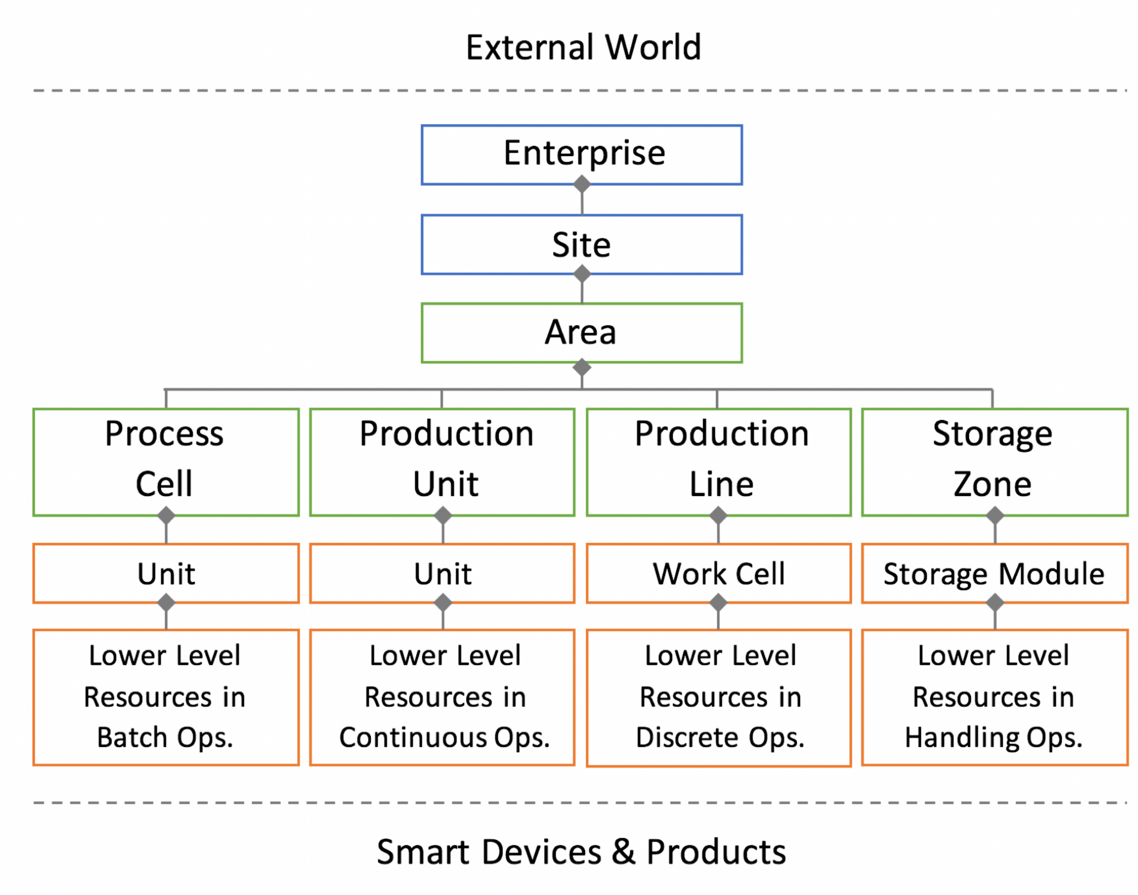
"A 'blueprint' that provides current or future descriptions of a 'domain' composed of **components**, and their **interconnections**, **actions** or **activities** those components perform, and the **rules** or **constraints** for those activities". – A. Levis

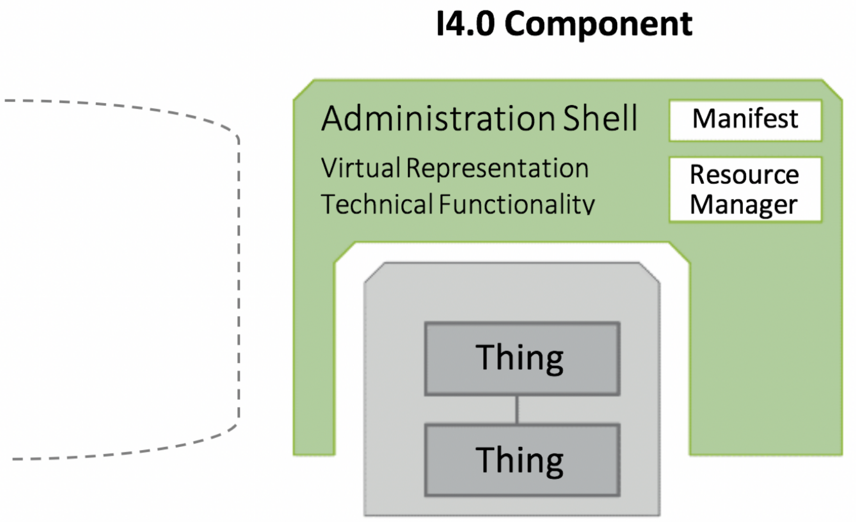
Physical Architecture	Functional Architecture	Allocated Architecture
Set of objects constituting the system and its connectivity	Set of functions to accomplish a set of system requirements	Set of rules governing interactions and independences

Our Goal: Evaluate existing and emerging architectures, identify common vernacular, educate on how they interact/overlap, and summarize strengths, weaknesses, and gaps.

Buede (2009). The Engineering Design of Systems: Models and Methods, Second Edition.

Physical Objects



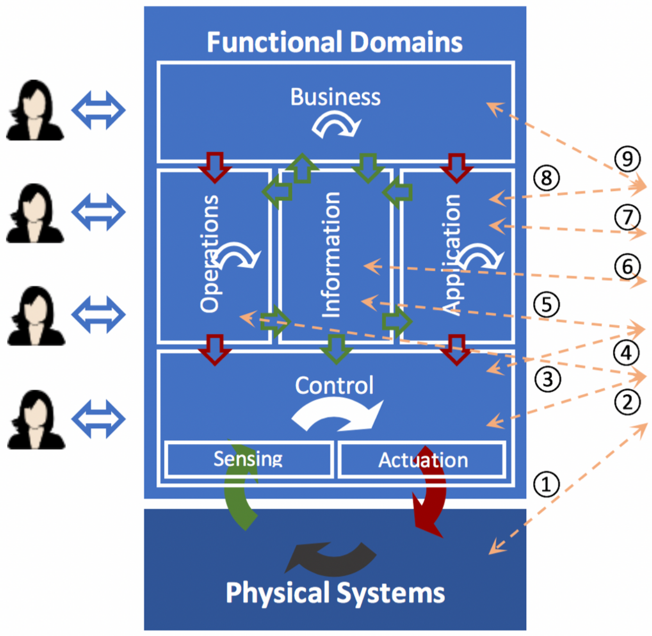


ISA-95 Equipment Hierarchy

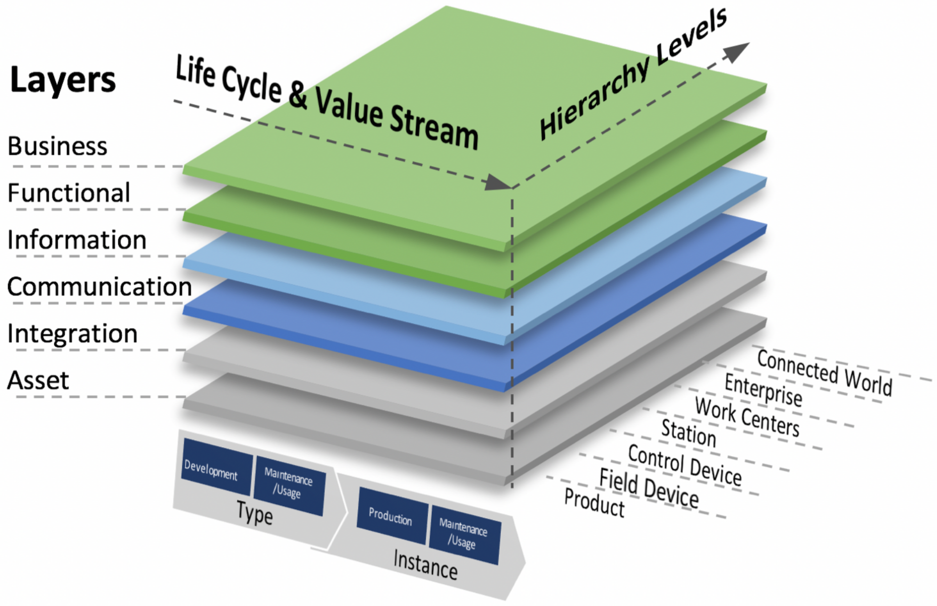
Industry 4.0 Component (RAMI4.0)

Emerging Models/Architectures

① Hardware; Software; Human Resources; Ideas; Concepts
② Sensing; Actuation; Virtualization; Modeling; Execution
③ Communication; Interfacing
④ Provisioning; Deployment; Asset Mgmt.; Monitoring; Diagnostics; Prognostics
⑤ Data Collection
⑥ Semantics; Syntaxes; Persistence; Storage; Quality Processing; Analytics; Distribution
⑦ Engines; Activity Flows; Workflows; API & UI; Service Modeling
⑧ Specification of Rules & Models
⑨ Service Orchestration; ERP; CRM; Life Cycle Mgmt.; Billing; HRM; Planning; Scheduling

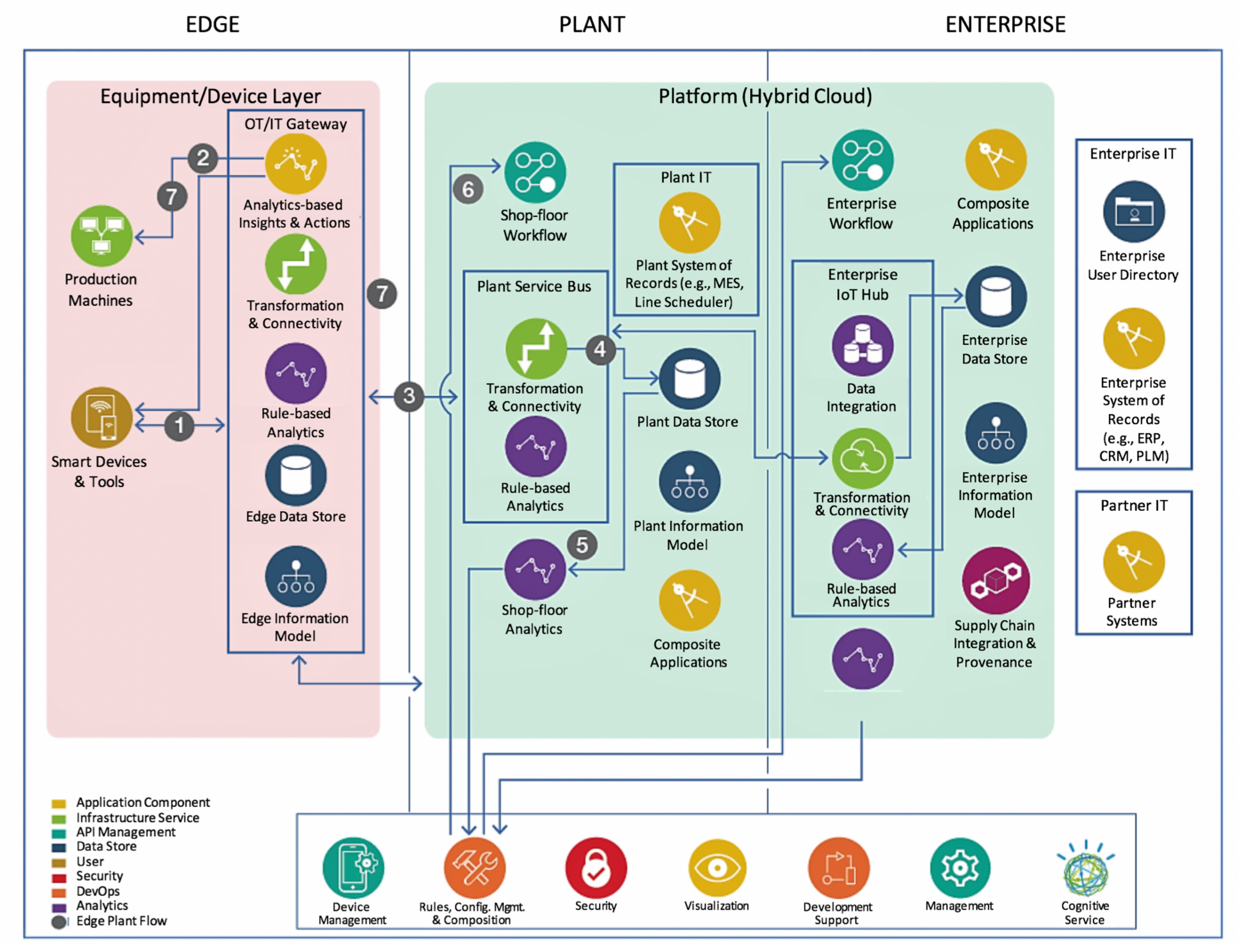


IIRA (Functional Viewpoint)



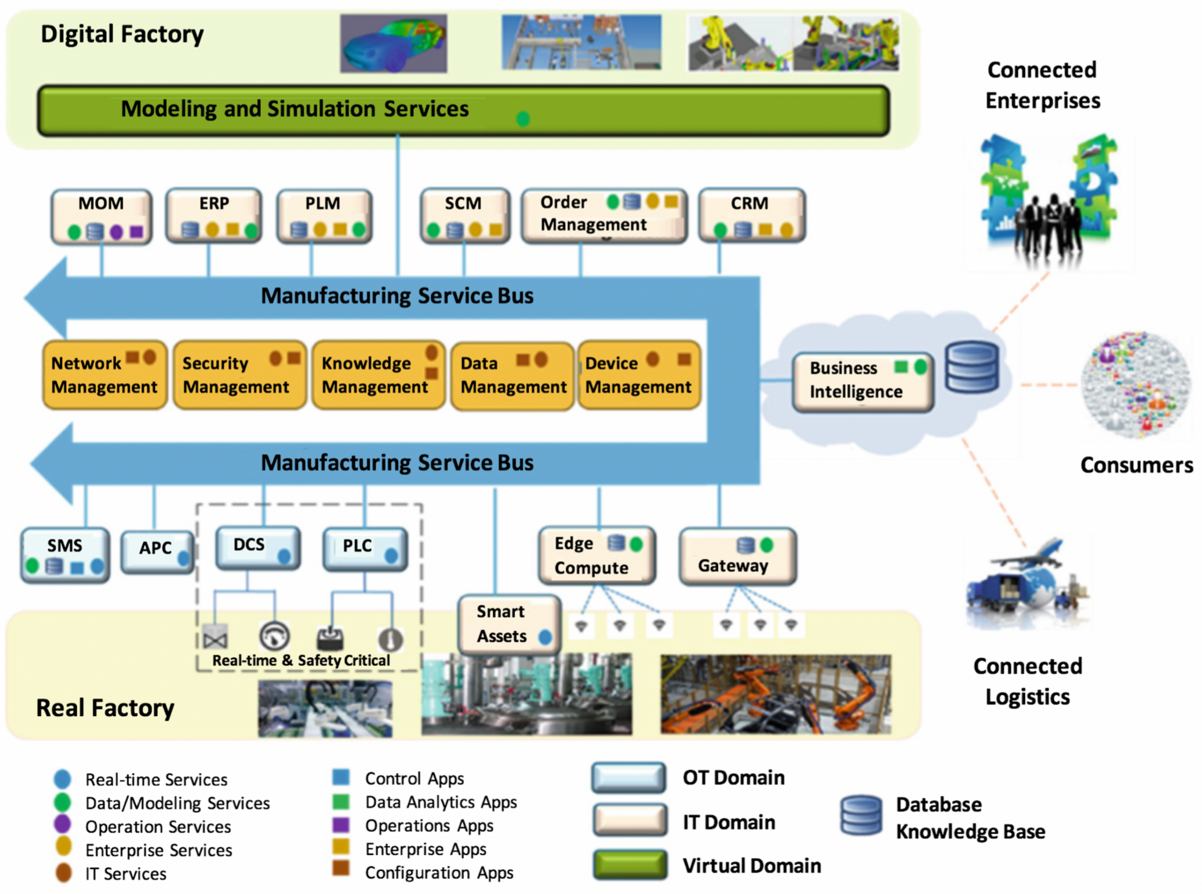
RAMI4.0

Emerging Models/Architectures



IBM Industry 4.0 Architecture

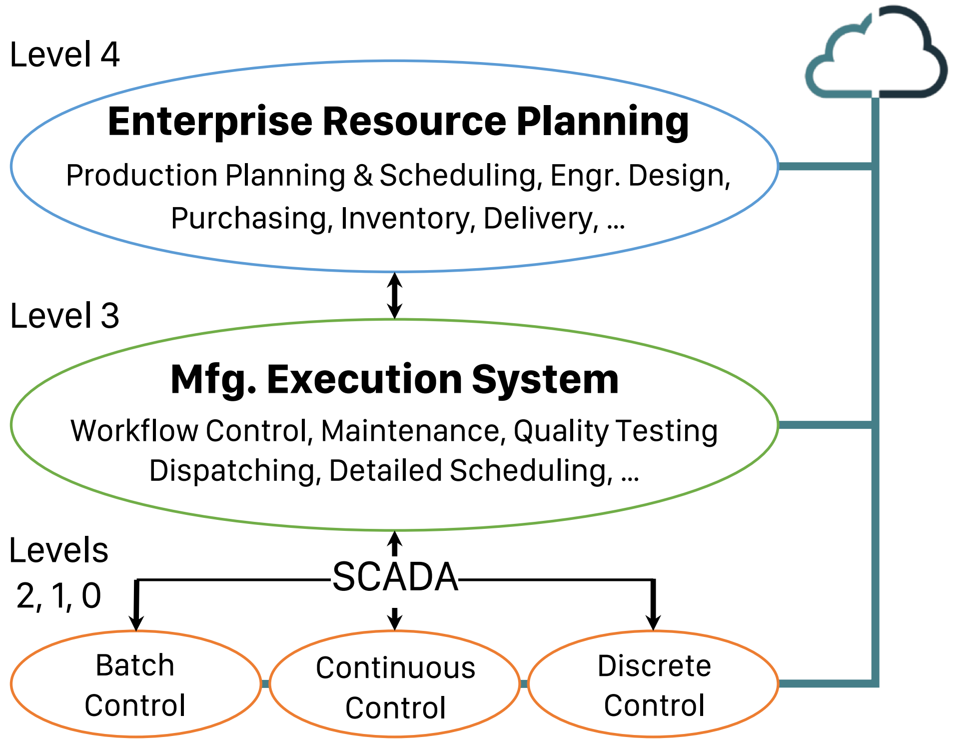
Emerging Models/Architectures



NIST Service-Oriented Manufacturing Architecture

Conceptual Research

Scope Definition ➔ Review ➔ Hypothesis & Propositions ➔ Interviews ➔ Analyses



ISA-95 Functional Hierarchy

Service-Oriented Architecture will be the Next Generation Enterprise Architecture

Questions

- What are the characteristics of a reference architecture for smart manufacturing?
- How can businesses upgrade their current architectures (e.g., ISA-95) to accommodate these characteristics?

Experts

#	Profile	Related Experience
1	R&D leader at a conglomerate research facility	System integration experience for advanced manufacturing in a major industrial corporation
2	Executive architect at a technology company	Contributing member of standards organizations’ Industry 4.0 documentation; Industry 4.0 leader in a major industrial corporation
3	System integration specialist at a government research facility	Multiple research publications about Industry 4.0 and advanced manufacturing; Previous advanced manufacturing experience
4	Advanced manufacturing consultant	Contributing member and leader of multiple standards organizations’ Industry 4.0 documentation; Previous advanced manufacturing experience
5	Product strategy leader at manufacturing services company	Contributing member and leader of standards organization's Industry 4.0 documentation; Previous advanced manufacturing experience
6	System integration specialist at a government research facility	Multiple research publications about Industry 4.0 and advanced manufacturing
7	Advanced manufacturing consultant	Contributing member and leader of multiple standards organizations’ Industry 4.0 documentation

Proposition 1

The next generation enterprise architecture will be a service-oriented architecture (SOA) model adapted for manufacturing adoption.

- Yes – Need to differentiate mfg. SOA from software SOA
- Currently more applicable to Levels 4 and 3 than to Levels 2, 1, and 0
- Integration of shop-floor with CPS services for plug-and-produce production
- Service representation, composition, discovery, and registration
- Standard taxonomy of mfg. processes as services is fundamental
- Need to focus on micro-services
- Interoperable and asynchronous communication is key
- Need for more publish/subscribe types of API and services

Proposition 2

In a manufacturing SOA, the various capabilities of IoT objects (a.k.a., I4.0 component; e.g., machine, sensor, software, idea, concept) will be standardized and published as services (i.e., everything-as-a-service).

- Yes – Is it possible to describe everything as a service?
- Ontology and taxonomy of shop-floor services based on Level 2 function models
- Similar to IEC 61360: Common Data Dictionary for automation devices
- Sufficient for service discovery, matching, optimization, orchestration, and execution?
- Standardization of components is a prerequisite
- Complexity of the service is proportional to the “smartness” of the IoT object
- The common language for standardization and publishing of services?

Proposition 3

A service-oriented architecture will offer many benefits over the traditional, hierarchical models (such as ISA-95) including better interoperability and reusability (though standardization), loose-coupling and lower complexity (through separation of concerns; service as "black-box" to user), as well as higher scalability of operations.

- Yes – But ISA-95 does not demand any implementation
- ISA-95 is a useful guide for executing operations, processes, and business workflows, and synthesizing them as reusable services via the definition of the objects needed to communicate between tasks
- Architectural decision for information filtering, aggregation, and sharing (broker?)
- Economics of acquisition, implementation, and integration
- Interoperability and reusability in addition to reducing up-front costs

Proposition 4

Service-orientation will enable end-to-end and real-time value network coordination and enhance local autonomy and self-reconfigurability in the operative level.

- Yes – Lack of methods for creating and orchestrating on-the-fly value networks
- Building certain governance functions into an SOA is key
- Autonomy "enhanced" by SOA but "enabled" by plug-and-produce work
- All devices must have standardized names, descriptions, and functionalities to be dynamically orchestrated with other devices
- SOA demands shop-floor devices to be more autonomous, self-/environment-aware, capable of reasoning, planning, self-diagnosis, and self-maintenance
- Optimize the IEC NC-65E's interacting lifecycles: order-to-cash value network, product design-manufacture-maintenance cycles, and supply networks

Proposition 5

ISA-95 is currently too rigid, hierarchical, and monolithic to accommodate the afore-mentioned changes. ISA-95 may need to be modified, or completely replaced with a new architecture, in order to reflect a service-oriented approach.

- No – ISA-95 does not reflect an architecture
- Functional models provide the building-blocks for developing the micro-services
- One proposal: Transform the functional blocks into three dimensions of product life cycle, smart factory, and business management
- ISA-95 does not properly support the idea of horizontal integration
- ISA-95 does not support flexible/adaptive manufacturing
- Integration of ISA-95 into a cloud-based architecture and connection of business processes to those services will be challenging

Proposition 6

The largest barriers to adopting SOA in manufacturing are security concerns, implementation costs, lack of standards, inadequate infrastructure, privacy concerns, immature technology, interoperability concerns, and most importantly, lack of knowledge.

- Standards are key in defining how mfg. services can be integrated and described
- High-level application eng. expertise a barrier to plug-and-produce production
- Cultural issues; human-machine symbiosis
- Transition of myriad enterprise-wide applications to cloud services is a barrier
- Many existing mfg. systems not even componentized/modularized
- Inconsistent pace of transformation—OEMs vs. SMEs
- Lack of education and mentoring for younger professionals

Open-Ended Question

How do we get from point A (where we are, e.g., ISA-95) to point B (where we are going, e.g., SOA)?

- A first step: company's assessment of where it currently stands as a baseline
- Benefits of the transition must be quantified from a business perspective
- Determine what technology is needed for the IT solutions
- Develop multi-generational plans broken down into steps and projects
- Consistency across vendors, suppliers, manufacturing, and standards org.
- Embracing open standards such as OPC-UA or W3C
- Standards and guidance for "good" modules, interfaces, and data exchanges
- An ecosystem of middleware/middlemen between legacy and new systems

Open-Ended Question (Cont.)

How do we get from point A (where we are, e.g., ISA-95) to point B (where we are going, e.g., SOA)?

- Support from existing collaboration platforms such as the cloud at Level 4 (ERP)
- Software vendors will then move in a similar direction to modularize Level 3 (MES)
- Service-orientation can finally be taken to Level 2 (shop-floor), starting from functions that are NOT real-time critical or safety critical
- Education and training for developing skillsets in IT and information modeling
- Study the cultural and social changes that this evolution will bring

R&D Challenges

(Very Compact) Summary

	E1	E2	E3	E4	E5	E6	E7
Integration of shop floor, business processes, and cloud services for plug-and-produce work (P1)			✓	✓	✓	✓	
Fully-integrated industry—inter-enterprise, cloud-based publication and sharing of services (P1)						✓	
Service representation, composition, discovery, registration, and matching (P1)			✓				
Service definition—shift of focus from macro to micro services in manufacturing SOA (P1)							✓
Representation of complex capabilities such as cognitive systems or analytics as services (P1)		✓					
Standardized taxonomy of manufacturing processes as services (P1/P2)		✓	✓			✓	
Asynchronous and interoperable communication mechanisms and publish/subscribe API (P1)	✓			✓	✓	✓	
Need for 'smarter' objects to execute more complex services (P2)							✓
Standardized description of objects as prerequisite for standardization of services (P2/P4)			✓			✓	
Common language (e.g., OPC-UA) for standardizing object and services (P2)	✓		✓		✓	✓	
Mechanisms for orchestration, filtering, aggregation, and sharing of cloud services (P3/P4)		✓			✓	✓	
New models for the economics of acquisition, implementation, and integration (P3)						✓	
New models for automated, on-the-fly creation and governance of value networks (P4)				✓		✓	
Horizontal integration of product life-cycles through micro-services (P4)		✓					
Need for autonomous, self-/environment-aware, intelligent devices for service-orientation (P4)			✓				
Concurrent optimization of order-to-cash and design-manufacture-maintenance cycles (P4)							✓
Lack of horizontal integration and reconfigurable manufacturing capabilities in ISA-95 (P5)		✓					
Integration of ISA-95 into a cloud-based architecture (P5)						✓	
Transition from myriad enterprise-wide applications to consistent cloud-based services (P6)		✓					
Lack of modularity of legacy manufacturing systems hindering 'composability' (P6)		✓					

Concluding Remarks

On the Shop-Floor

Integration to micro-services

Taxonomy of services is key

Open standards (e.g., OPC-UA)

Higher-level, less critical services first

ISA-95 a great transition guide

Throughout Value Network

Interoperable & asynchronous communication

Common languages for services

Interactions & governance

Consistent transition

Future Research Directions

(1) Modeling and composition of micro-services

(2) Optimizing the topology of interactions

Concluding Remarks

An extended manuscript of this research is under review:

Moghaddam, Cadavid, Kenley, Deshmukh (2018). Reference Architectures for Smart Manufacturing: A Critical Review. **Journal of Manufacturing Systems**. Under review.