# Pathways to CP(P)S modelling & architecting

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**Abstract**
Enterprise Interoperability is getting more important in a world where enterprises are digitalizing everything. Interoperability is an extension to integration by aiming at loose coupling of systems and see integration as a continuous process. In manufacturing the trend in digitalization is aiming at Cyber-Physical Production Systems (CPPS). In this short paper, we are looking for pathways representing different stages to Interoperable Cyber-Physical (Production) Systems.

**Keywords 1**
Cyber-Physical Systems, Enterprise Modelling, Enterprise Architecture, Enterprise Interoperability, Enterprise Integration

## 1. Introduction

Enterprise Systems today are connected information systems. The term *information system* is used in a very general sense, which includes humans and artificial agents (including software), providing and consuming information. Many sensors across the enterprise are generating data that is used by human decision makers through decision support applications. Decisions trigger information and control flows in the other direction and actuators translate that information into physical action.

Smart Sensors, Virtual Sensors, Industrial Internet-of-Things (IIoT) are technology trends with respect to sensing. Business Analytics, Business Intelligence, together with cloud computing, edge computing technologies provide the infrastructure and tools for supporting decision making. Cloud Robotics and Additive Manufacturing are two examples where information systems control physical aspects (in the manufacturing enterprise).

Taking an information systems perspective we can describe the data flows between information processing systems (including human and artificial agents). This point of view excludes any physical aspect.

A Cyber-Physical Systems (CPS) point of view is needed. A CPS is a system that integrates physical, computational sub-systems that are connected through a network [1]. Here, a CPS is not a traditional embedded system or real-time system [2]. CPS integrate cyber and physical parts in every sub-system. The network is an integral part of the CPS. These two properties are the basis to have a system that is dynamically reconfigurable. High degrees of automation allow self-organization and adaptation to reach higher performance [2]. To handle complexity and scalability of large networked CPS a systems-of-systems approach is taken. In such systems, the cyber and the physical systems are physically distributed but still must be interoperable in one larger system [3].

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A Cyber-Physical Production Systems (CPPS) takes this paradigm of connected and distributed systems and puts it into a manufacturing context [4]. It allows to discuss distributed, large scale, and complex CPS from a supply chain and shop floor point of view [5].

Among other topics, interoperability in such distributed and dynamic systems is a key research challenge that needs to be addressed from a technological, semantic and organizational perspective [5], [6], [7].

## 2. Pathways

In order to map different possible routes for Enterprises (and Researchers) to a vision for *Interoperable Cyber-Physical (Production) Systems*, we use a method called pathways. This method builds on work by EFFRA (European Factories of the Future Research Association) Public Private Partnership organization. This method maps different levels towards a vision.

The following image gives an example. It was created by EFFRA, and shows the Autonomous Smart Factory Pathway. Level 1 is defined as a situation where individual office software application used. In this phase, data acquisition is manual and application specific. Level 2 is a situation where the data is automatically collected and used for planning. However, the data is used in isolation. Level 3 is about connected software. In level 4 situation optimization of plans happens before production runs (offline optimization). Level 5 is online optimization reacting to changes immediately.

On a general level, the pathways method allows different levels at the same time in subsystems. It does not define a strict one-way route. It has also to be mentioned, that while level 5 is the most advanced with respect to the given vision, it strongly depends on the situation if reaching that level does make sense. Complexity and associated costs will increase from level to level.

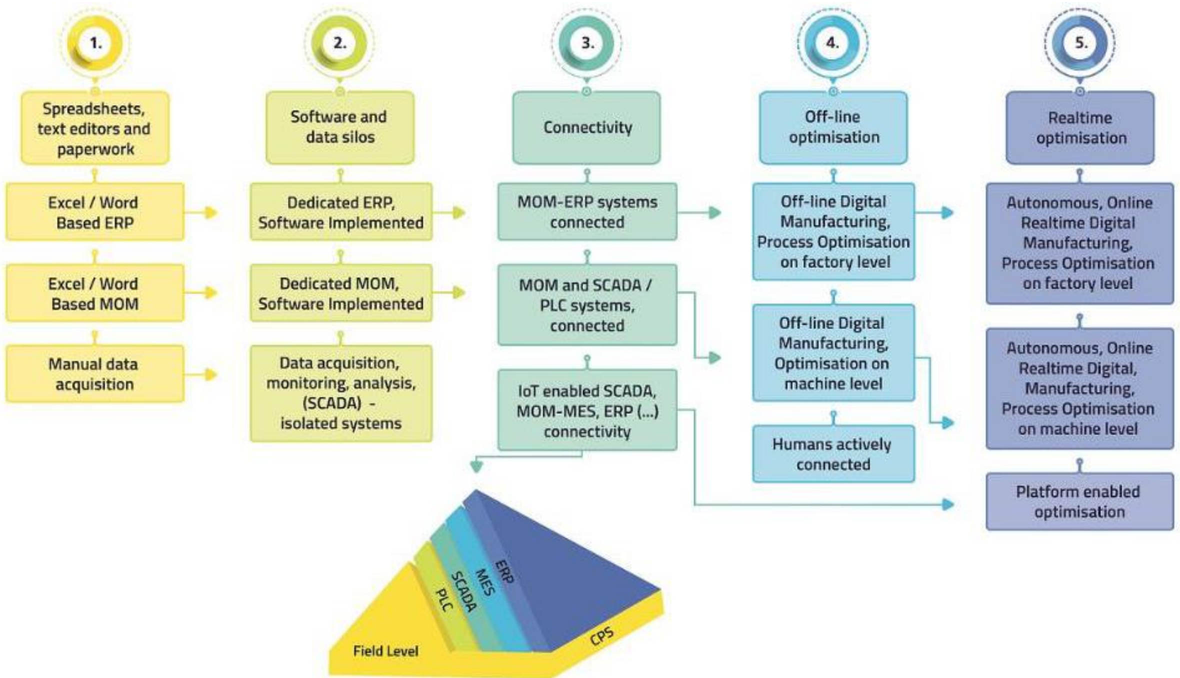


**Figure 1**: EFFRA Autonomous Smart Factory Pathways (www.effra.eu)

As can be seen the pathways follow a simple schema. We will use that schema to discuss interoperability of cyber-physical (production) systems.

## 3. Interoperability of Cyber-Physical Systems

For the analysis of pathways to CPS modelling and architecting, we first take a look at three levels of analysis taken from enterprise interoperability (EI) [5]. EI uses a systemic perspective [8]. It addresses the enterprise as a system-of-systems [9]. Organizations are physical systems and EI discusses interoperability between information systems, data models and physical systems.

The used, simplified framework, discusses enterprise interoperability on three levels. The *technology level* includes data structures, programming interfaces, technological standards that allow to have multiple technical systems interact. The *semantic level*, discusses tools and approaches that allow systems and humans to understand the meaning of data/information. The third level is the *organizational level*, where interoperability issues arise if different organizations have, for example, different processes or rules with respect to information access (security, privacy, etc.).

From level I to level IV the pathway moves from an isolated system over simple exchange of data/information/knowledge flows to a level where high dynamics and self-organization among human and artificial agents is possible. The different levels give the different stages a name but are not normative. Level V supports self-organization of systems, which are connected and exchange information with an agreed semantics of the exchange.

**Table 1**

Pathways for Interoperability of Cyber-Physical Systems

| Aspect | Level I | Level II | Level III | Level IV | Level V |
|---|---|---|---|---|---|
| Technology | Closed Systems | System specific API[2]s | Open APIs | Standards | Infra-structure for Self-Organization of systems-of-systems |
| Semantics | Data Silos | Semantic Description | Onto-logical Data Structures | Open Data Sets | Advanced Reasoning and Planning of Agents |
| Organizational | Isolated Group of People | Hierarchies | Process Management | Agile Teams | Enterprise as Complex Adaptive System |

## 4. Cyber-Physical (Production) Systems Modelling & Architecting

Based on the above point of view, we propose these pathways for Modelling and Architecting of Cyber-Physical (Production) Systems. It addresses the different needs of systems that range from isolated systems to dynamic systems-of-systems (SoS) capable of self-organization.

**Table 2**

Pathways for Cyber-Physical (Production) Systems Modelling & Architecting

| Aspect | Level I | Level II | Level III | Level IV | Level V |
|---|---|---|---|---|---|
| System | Isolated System | Adaptive System | Connected Systems | System-of-system | Cyber- Physical SoS |
| Model | Static Model of a system | Dynamic Model / Simulation | Heterogeneous models | Distributed Systems modelling | Agent-based modelling and negotiation |
| Interoperability Environment | Compatible | Tight Integration | Standard Interfaces | Loose Integration | Federated Interoperability |

The systems aspect describes the relationship of the system to other systems. As such it includes an abstract view on the complexity. The model aspect takes a look on the model in general with respect to dynamics. Interoperability is seen on a continuum. Compatible is a level, where multiple systems are not working together, but simply do not disturb each other. Tight integration is often the result of one-

[2] Application Programming Interface

off modelling and implementation efforts, where the systems are coupled in a way that makes them strongly dependent on each other. Standard interfaces provide an initial way to a loose coupling were individual systems can be exchanged with other systems. Loose Integration refers to a situation where exchange of systems is the norm not the exception. Federation means that interoperability and interfaces are communicated / negotiated at runtime rather at design time. Level IV and V need a supportive environment and general standardized system services that allow to maintain a loose coupling over time.

## 5. Conclusions and perspectives

We have used the pathways method to sketch different levels of interoperability in Cyber-Physical Systems. The sketched pathways are used as initial input in order to start a scientific discussion on how to enable loose integration (aka. Interoperability) of such systems.

We hope the discussion will bring forward technologies and methods that make cyber-systems, physical-systems and cyber-physical systems interoperable. Organizational aspects and production technologies and physical production process need to be included not only information systems and software systems perspectives.

## 6. Acknowledgements

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