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# Virtual Factory: an Integrated Framework for Manufacturing Systems Design and Analysis

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## Abstract

Competitive manufacturing companies have to effectively deal with the concurrent evolution of products, processes and production systems. This problem, known as *Co-evolution*, can be addressed only through the integrated use of different methodologies, provided that the digital tools implementing these methodologies can interoperate properly and effectively. This paper presents the concept of an integrated framework to support the interoperability between digital factory tools and shows how it can benefit the business processes along the whole factory life-cycle.

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## 1. Introduction and Motivation

The influence of economic, political and technological changes led to a worldwide modification of the traditional idea of manufacturing [1]. The way products are conceived, designed and built must take into consideration the availability of new material, technologies and the spread of new business models for their production and marketing. Besides this, the enterprises must cohabit with continuous rollouts of new products and high pressure on quality and costs [2].

The occurrence of such rapid changes creates a multitude of possible scenarios that companies must face in order to stay competitive. These scenarios are often unpredictable causing an increase of the complexity of the manufacturing problem that cannot be properly addressed by the existing solution approaches being not holistic and comprehensive enough.

The impact of these factors on the survival skills of the enterprises has focused the attention on specific problems and consequently driven the research priorities of the scientific community [3]. Recent advances in the literature have shown that the success of an enterprise strictly depends on its capability of jointly managing the decisions related to products, processes and production

systems, their connections and reciprocal influences together with the company strategic decisions and position in the market. Indeed, a manufacturing company must be able to deal with the *Co-evolution* of products, processes and production systems by “managing strategically and operationally the propagation of engineering changes to gain competitive advantage from the resulting market and regulatory dynamics”, as highlighted by Tolio et al. [4] (Fig. 1).

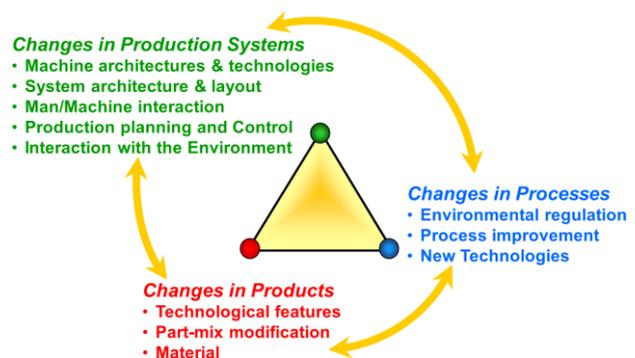


Fig. 1. The *Co-evolution* paradigm [4]

When considering the different actors playing a role in the manufacturing sector, industrial equipment users

are the ones that most often have to address the *Co-evolution* problem due to the need of combining information related to products, processes and physical resources in their plants. The strategic decisions to be taken embrace determining the system configuration that better fits the production requirement over time in relation to the changes of the market. To this aim they must be able of configuring and re-configuring their production system in terms of machines and auxiliary equipment, while adjusting the production processes, plans and schedules.

The co-evolution problem impact on the equipment producers as well, since they must be able to provide their customers with the proper equipment to meet their needs. The strategic decisions for equipment producers have to deal with the design and implementation of flexibility and re-configurability capability in their products [5].

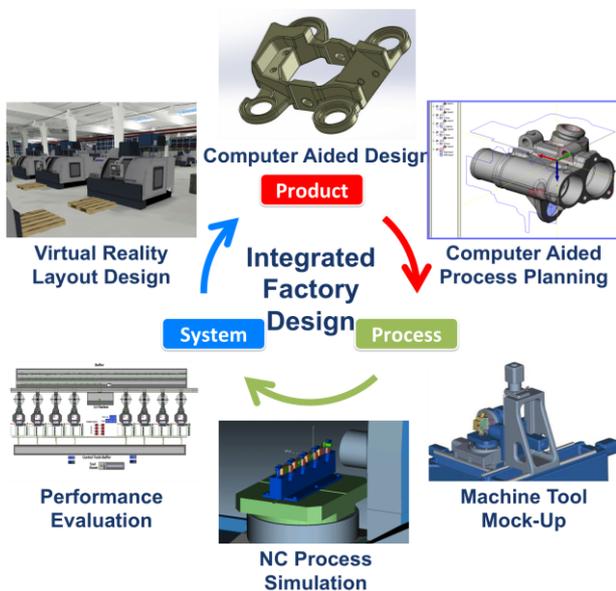


Fig. 2. A conceptual framework for the “Integrated Factory Design”

Multiple approaches and methodologies are available to address the specific engineering or decision problem in a coherent and specific way to repeatedly determine the best and most appropriate solution over time. However, addressing the *Co-evolution* entails the need of jointly using these different approaches, techniques and methods aiming at an holistic configuration of product, process and production system. By properly managing the *Co-evolution*, a company can be capable of continuously operating at a point that preserves the feasibility and profitability in spite of the dynamic context and the uncertainty of the external environment. Tackling the co-evolution problem entails the need of collaboratively designing and managing products, processes and production systems, being able of

considering the knowledge available about all of them in a multidisciplinary way [6].

Section 2 will outline the concept of an *Integrated Factory Design* framework intended as a workspace where multiple actors using different analysis and design tools from different disciplines act and interact on the same system model in a concurrent and coherent way (Fig. 2). Then Section 3 will describe how a business process related to the design of product, process and production systems may benefit from a platform guaranteeing the interoperability between software tools.

## 2. Concept for an Integrated Framework

The Digital and Virtual Factory (VF) paradigm can assist in tackling the co-evolution problem by providing software tools that implement the methodologies supporting manufacturing system design, process design, simulation, production control, visualization, etc. However, because of the complexity of the comprehensive manufacturing problem, the digital factory tools are traditionally designed to focus on specific issues and tasks, often considering their own knowledge representations and models of products, processes and production systems. Therefore, one of the main challenges in manufacturing engineering consists in the innovative integration of methodologies and tools within a common software platform.

The topic of Digital and Virtual Factory is relevant both from the industrial and research perspective. Indeed, major companies (e.g. Siemens PLM, PTC, Dassault Systèmes, SAP and Oracle) providing commercial software solutions for product, process and system design, generally recognized as Product Life-cycle Management (PLM), already offer all-comprehensive suites containing software tools that have been developed or acquired in the recent years. These tools deal with most of the factory planning, design and deployment phases, but the current approaches still do not fully meet the needs of the industry. One of the reason for this is that, despite these tools embrace the expectation of being a shared platform to capture, represent, and exchange a wide variety of data across all the phases of a product/factory life-cycle, until today they not ensure that the exchange and reuse of knowledge across the extended enterprise take place with enough easiness and effectiveness. In more concise words, the lack of interoperability. Moreover, Small and Medium Enterprises (SME) can hardly afford the expensive PLM software suites available.

This points out the need of a great step forward in the development of a Virtual Factory concept enabling the modelling the factory as a whole in terms of processes, dependencies and interrelations, data and material flows [7]. The Virtual Factory technologies should guarantee

the democratization of simulation and analysis approaches for industrial systems, by reducing the total cost of ownership of a holistic virtual representation of the factory. In particular, the following aspects need to be properly addressed:

- Handling of heterogeneous information related to the design and operational/execution phase of products, processes and resources within a coherent and updated conceptual model.
- Integration and harmonisation of knowledge and information from different tools and techniques working on various discipline and at different levels of detail.
- Decrease of the investment and operating costs that are currently associated with the commercial all-comprehensive software suites.
- Maintenance of the virtual representation of a manufacturing system so that it can be constantly synchronised with the real one.
- Extend the functionalities and usage of virtual factory tools to enable engineers and field technicians taking advantage of simulation and virtualization of processes without the need of relying on dedicated specialists.

An effective Virtual Factory platform supporting interoperability between digital factory tools must be able to address the following key technological issues:

- A common and standard Data Model for the representation of factory objects related to production systems, resources, processes and products, i.e. the Data & Knowledge.
- A shared data storage that accessible by the different digital factory tools to retrieve input data and contribute the generated output data.
- A software middleware able to access the shared data and correctly interpret/convert them according to the common data model.

Several scientific papers [8-9-10-11-12] and research projects have addressed the Virtual Factory concept. For example, the following projects can be mentioned: VFES [13], IRMA [14], DiFac [15], COPERNICO [16] and VFF (Virtual Factory Framework) [17].

### 2.1. Data Model

The problem of developing a comprehensive data model for the manufacturing domain has been extensively addressed in the literature and the research community has also tried to standardize the related information. For instance, the Standard for the Exchange of Product Model Data (STEP) [18] supports the exchange of information aiming at creating an interlingua for exchanging manufacturing product data. The derived standard STEP-NC [19] further extends STEP by focusing on manufacturing operations. The

Process Specification Language (PSL) [20] standard proposes a general ontology to represent manufacturing processes to exchange process information and knowledge. The Industry Foundation classes (IFC) standard by buildingSMART [21], partially based on STEP, represents an open specification for Architectural Engineering Construction (AEC) industry domains and its data structures can be further specialized for other industrial domains, such as the manufacturing domain. ANSI/ISA-95 [22] is an international standard for developing an automated interface between enterprise and control systems. This standard has been developed for applications in all industries and in all sorts of processes, ranging from batch processes to continuous and repetitive processes. ISA-95 aims at providing both a consistent terminology and information models as well consistent operations models. However, most of the existing technical standards are focused on particular areas of the factory domain. Therefore it can be often necessary to integrate various contributions to cover all the required knowledge domains, as already highlighted by Colledani et al. [23-24] and Valente et al. [25].

In the literature, a different class of data models has been proposed that exploits Semantic Web technologies [26], being ontologies [27] a possible way to generate a more flexible data model integrating different knowledge domains. Indeed, the Semantic Web technologies offer the possibility to represent formal semantics, efficiently model and manage distributed data, ease the interoperability of different applications, and exploit generic tools that can infer from and reason about an ontology. Moreover, ontologies allow integrating fragmented data models into a unique model without losing the notation and style of the individual ones [28]. Various ontologies have been developed to support the virtual enterprise (e.g. CIMOSA [29], FDM [30], MOSES [31] and MISSION [32]) and then extended focusing on the operational scope. Lin et al. [33] designed a Manufacturing System Engineering (MSE) ontology to provide a common understanding of manufacturing-related terms and to enhance the semantic and reuse of knowledge resources within global extended manufacturing teams. Léger et al. [34] presented a Manufacturing's Semantics Ontology (MASON) that is built upon three main concepts: entities, operations and resources. Similarly, Martin and D'Acunto [35] developed an ontology decomposed into product, process and resource areas. ADACOR (A Collaborative Production Automation and Control Architecture) could be classified as general-purpose manufacturing ontology [36].

Terkaj et al. [37] proposed a Virtual Factory Data Model (VFDM) to formalize and integrate the concepts of building, product, process and production resource handled by the digital tools supporting the factory life-

cycle phases. Instead of creating a brand new data model, the development of the VFDM aimed at exploiting as much as possible the already existing technical standards for manufacturing (e.g. IFC, STEP-NC, ISA-95), thus trying to favour the interoperability between software tools. The VFDM was implemented as an ontology, by translating the existing standards into a common language and developing the required extensions.

### 2.2. Integration of Tools and Interoperability

The integration of a digital factory tool into a platform supporting the interoperability requires the development of a specific middleware that takes care of I/O data conversion and transfer from the internal data structures of the digital factory tool to the shared data storage, and vice-versa. A proper middleware may be developed only if:

- The digital factory tool offers a way to access and modify (if needed) its internal data structures, e.g. via an application programming interface (API).
- It is possible to map the classes and properties of the common data model to the internal data structure of the digital factory tool.

If such requirements are met, then a digital factory tool can be integrated into a Virtual Factory platform by developing a proper middleware according to the language required by the API. Then, it is necessary to populate the shared repository with data and knowledge required as input by the newly integrated digital factory tool. Such population can be accomplished by means of Graphical User Interface (GUI) tools, by transferring data from existing databases or legacy systems, or by integrating further digital tools within the Virtual Factory platform.

The adoption of an efficient and effective solution for data storage is fundamental for the success of a Virtual Factory platform. The data storage should provide also remote access and guarantee data consistency via versioning and locking systems. It is possible to adopt solutions based on traditional relational databases (e.g. MySQL, PostgreSQL, etc.) or more recent developments like NoSQL database (e.g. MongoDB [38]), object database and mixed solutions (e.g. Virtuoso Universal Server [39]) that can be exploited also by digital factory tools adopting Semantic Web technologies.

### 3. Application Cases

This section presents two application cases showing how an integrated factory platform may lead to increase the effectiveness and the efficiency of the business processes related to the design of products, processes and production systems. At first, the case of joint

product and process design will be addressed, while considering also the capability of the production system (Sect.3.1); then the problem of designing a production system while taking into consideration both its physical characteristics and its performance will be presented (Sect.3.2).

#### 3.1. Process Requirements and Machine Tool Capability

The design of a product and its manufacturing process relies more and more on computer-aided design (CAD) and computer-aided manufacturing (CAM) software tools. The importance of the integration between these two design phases has been vastly addressed in the scientific literature and many major companies provide software packages to reach this aim.

However, the link between the product design phase (CAD/CAM) and the process planning is still weak, due to the difficulty of matching the characteristics of the manufacturing process with the capability of the equipment and, in general, with the production system design and management. This is also the reason for the scarce availability of software tools supporting the generation of process plans (or Computer Aided Process Planning, CAPP).

Referring to Numerically Controlled (NC) production resources, the link between the CAD, CAM and the NC-related issues aims at supporting the integration of product and process information with kinematic and functional information of the production resources devoted to the execution of the machining process.

The integration of different tools in this area aims at jointly considering the design of a machining process and its verification through NC simulation software able to detect collisions and verify the tool-paths (Fig 3).

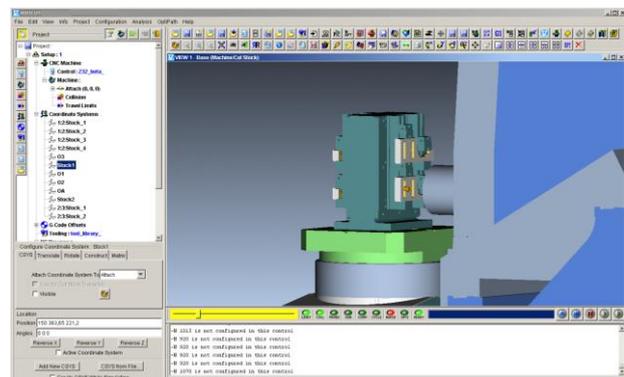


Fig. 3. NC simulation software (VERICUT [40]).

This assessment of the requirement of the process and the verification phase offers the option of modelling customised machine tools and component solutions thus supporting the design of new concept and architecture of machine tools and auxiliary devices to match the product

and process evolution. In addition, it also provides the capability of assessing different aspects of the process execution like the energy consumption and the dynamic compliance of the machine tools in relations with the operations to be executed.

These last aspects have been addressed, for instance, in the European research project “DEMAT-Dematerialised Manufacturing Systems: A new way to design, build, use and sell European Machine Tools” [41], aiming at exploiting the concept of *dematerialization* for machine tools and systems whose design principles answer to energy savings [42] and cutting edge performance requirements across their lifecycles [43] (Fig 4).



Fig. 4. A prototypal “dematerialised” machine tool

### 3.2. Layout Design and Performance Evaluation

The design of a manufacturing system is a complex task strictly related to manufacturing strategy decisions having an impact on a long time horizon (usually more than two years) and involving a major commitment of financial resources. The complexity of these decisions and their importance from the point of view of the profitability of capital investments emphasizes the need to have formal and structured approaches to evaluate the performance of a manufacturing system.

Usual performance indicators in a manufacturing context can be the production volumes, the quality of the output, the incurred cost, etc. In addition, more detailed performance indicators may be calculated, e.g. the utilization of production resources, the average flow time of products, the average level of the work in progress. Different models can be used to address specific types of analysis and levels of detail while modelling a manufacturing system to evaluate its performance.

The design phase can benefit from the availability of virtual representation of the manufacturing system that is continuously updated during both the design and operational/execution phase, thus allowing the use of different performance evaluation approaches (e.g.,

analytical methods and simulation) and guaranteeing an overall coherence of the obtained results.



Fig. 5. Layout design of a manufacturing system grounding on the Virtual Factory Framework.

The development of a framework for the interoperability between software tools supporting factory processes has been carried out within the European project “Virtual Factory Framework”. This framework has been successfully applied to provide an integrated framework for the design of the layout of a manufacturing system and to provide the capability of assessing the associated performance using multiple evaluation approaches [44].

## 4. Conclusions

This paper addresses the concept of an *Integrated Factory Design* framework providing the capability of using different and heterogeneous analysis and design tools on the same manufacturing system model in a concurrent and coherent way. This framework is highlighted as a prerequisite condition to tackle the co-evolution problem, i.e., the integrated management of product, process and production system and their evolution over the time.

The main related technological problems have been highlighted and compared to the available solutions and the not yet fulfilled needs, outlining emerging research challenges that need to be addressed.

Application cases have been provided to show the benefits of an integrated factory platform related to effectiveness and the efficiency of the design of products, processes and production systems.

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