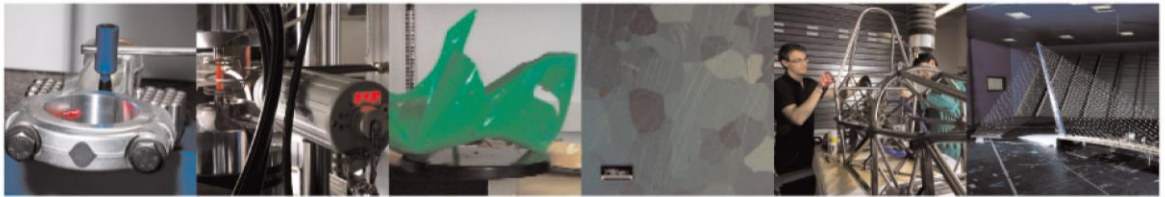




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## A digital factory platform for the design of roll shop plants

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# A digital factory platform for the design of roll shop plants

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Replying to requests for quotation in a fast and effective way is a key need for technology providers, in particular machine tool builders and system integrators. Digital factory technologies provide the opportunity of speeding up the generation of technical offers through the development of a digital twin of the system under study, thus enabling the assessment of different candidate configurations and the associated performance. In this paper we present a set of integrated digital tools to support the design of roll shop plants, i.e., plants devoted to grinding cylinders for rolling mills. These digital tools are aimed to support engineers in the design of a new system configuration through a configuration workflow, a 3D environment and performance evaluation tools. The interoperability among the software modules and the reuse of knowledge is enhanced by the use of semantic web technologies and the definition of a common data model as an ontology relying on technical standards.

Digital Factory, Virtual Factory, Discrete Event Simulation, Ontology

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## 1. Introduction

The design of production systems entails complex workflows that are more and more supported by heterogeneous methodologies and digital tools. Machine tool builders and system integrators are challenged by the need to reply to requests for quotation in a fast and effective way while concurrently working on multiple technical and commercial bids. Despite the very limited time to submit a proposal, the preliminary design phase is of fundamental importance, because a high-quality early design gives the possibility of properly calibrating the associated quotation, thus increasing the chance for the proposal to be accepted. Moreover, in case of successful bid, the preliminary design will have a significant impact on the subsequent detailed design phase.

Increasing the efficiency and effectiveness of the bid generation phase has a strong impact on company competitiveness. Indeed, some of the devised proposals do not lead to an accepted order, in spite of the relevant amount of work of the design department that is typically overloaded. Success factors to win orders include:

- speeding-up the design phase to be able to manage more bids;
- providing the customer with a set of alternative solutions to increase the chance to find a suitable proposal;
- carrying out a reliable performance evaluation for the proposed system configuration to support and justify the design choices and the associated costs;
- enriching the proposed design with 3D visual representations (static and/or dynamic) to enhance the transfer of information to the potential customer and increase the involvement during the offer selection process.

Approaches based on Digital/Virtual Factory technologies [REF], and more recently Digital Twin [1], have been proposed by both researchers and practitioners as viable solutions to improve and speed-up the design and re-configuration of manufacturing systems through the extensive use of modelling and simulation tools [2][3]. In addition, Virtual Factory can be exploited to support product design, process design, production planning and control, monitoring, etc. [REF] in a single and integrated framework. Major ICT companies (e.g. Siemens PLM, Dassault Systèmes, etc.) already provide commercial software solutions for product, process and system design, generally recognized as Product Life-cycle Management (PLM) organized in comprehensive suites. Nevertheless, the price of these very large solutions is one of the main obstacles to the adoption of these approaches, usually limited to very large companies.

Rather than pursuing a general and very large framework, we present the development of a set of digital factory tools and their integration in a platform aimed at the design of a specific class of manufacturing systems, characterized by a pre-defined architecture. Herein the attention is focused on roll shop plants, devoted to grinding cylinders for rolling mills. The proposed digital platform provides a limited set of functionalities to support the design of roll shops, namely, layout design, resource selection, discrete event simulation and 3D visualization. In particular, the digital platform has been conceived and developed to support the design department of TENOVA S.p.A., an Italian company providing complete solutions for the iron and steel industry.

This paper is organized as follows. Section 2 describes the industrial problem and the proposed approach, whereas Section 3 presents the technical solution and in particular the digital tools. Finally, the conclusions are drawn in Section 4.

## 2. Industrial case and proposed solution

Roll shop plants are manufacturing systems dedicated to the grinding of cylinders employed in rolling mills. In the iron and steel industry, milling is the main process to obtain sheets of different thickness. Milling plants consist of a set of milling steps where two or more cylinders are used to progressively reduce the thickness of the metal sheet. Due to the contact with the processed material, the surface of cylinders is damaged during the rolling process. Therefore, exhausted cylinders are transferred to the roll shop area to be grinded. In case of hot strip mills, cylinders (weighting between 10 and 100 tons) must be frequently grinded (between two hours and 30 minutes according to the position in the mill). The typical reconditioning process entails a cooling phase (only for hot rolling processes) and the removal of bearings to facilitate grinding operations. Hence, cylinders are transferred to the machines that execute the grinding process. Different classes of cylinders (i.e. working, intermediate and backup rolls) are usually assigned to different machines, since their dimensions are significantly different. Grinding machines (Fig. 1) processing backup rolls have a higher power and are usually more versatile, being able to process a wider range of different types of cylinders if properly set up. Handling and transportation of cylinders is operated through overhead and semi-gantry cranes.

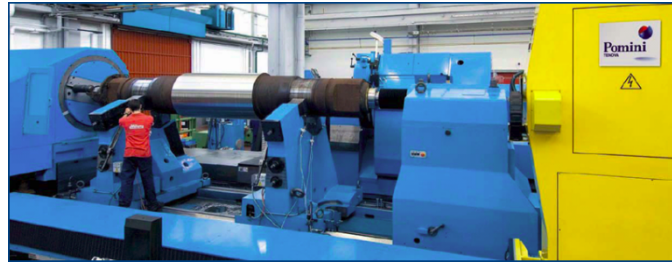


Fig. 1 A roll grinding machine (courtesy of TENOVA S.p.A.)

Herein, the main objective is to develop a digital platform to support the design of roll shop plants and the negotiation with potential customers during the bidding process while providing the following key functionalities:

- evaluation of the roll shop performance considering the system dynamics and the actual capacity of production resources to quantitatively and accurately validate the technical offer;
- fast generation of a 3D representation of the roll shop that can help to optimize the roll shop layout and visualize the dynamic behavior of the system.

The workflow of activities related to the design of a roll shop plant resembles that of a generic production system as represented in Fig. 2 using the IDEF0 formalism.

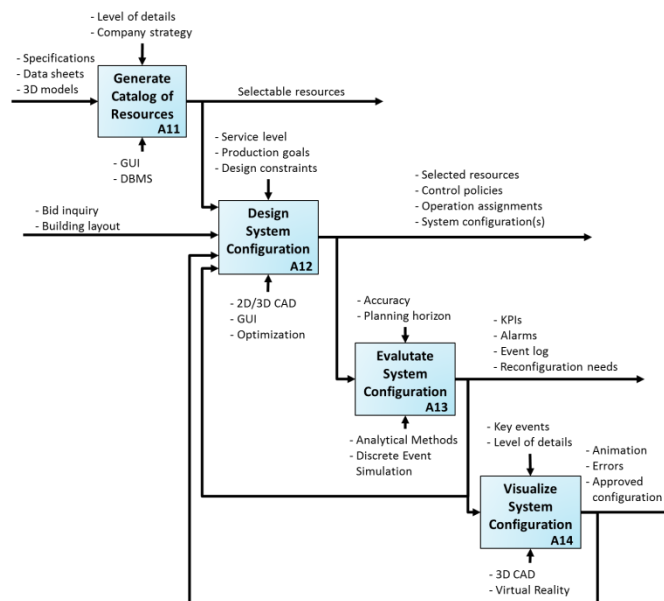


Fig. 2 IDEF0 diagram representing the reference workflow of production system design.

The *Generate Resource Catalog* activity (A11 in Fig. 2) deals with the formalization of a catalog of production resources that can be included in a roll shop plant. This activity must be carried out whenever there is an update in the specifications of the resources because of research and development or new market needs.

The *Design System Configuration* activity (A12 in Fig. 2) takes as input the resource catalog and the information provided by a potential customer in the bid inquiry, e.g. building layout, rolls to be employed, but also production goals and constraints. The output is the roll shop configuration consisting of system layout, selected production resources, process plans and control policies.

The *Evaluate System Configuration* activity (A13 in Fig. 2) aims at estimating the performance of the roll shop configuration. Various methodologies can be employed to evaluate the performance of a roll shop depending on the required accuracy and level of details. The output will typically include key performance indicators (KPIs) that can be compared with the production goals and constraints.

Finally, the digital version of the roll shop can be visualized (*activity A14* in Fig. 2) taking as input the results of the previous activities. This activity can be carried out to run an internal check of the designed roll shop plant or to better communicate a proposal to a potential customer. It must be noted that, after completing *activities A13* or *A14*, it may be necessary to start a re-design loop if these activities highlight specific reconfiguration needs or because of changes in customer requirements.

### 3. Digital Roll Shop platform

A Digital Factory approach was adopted to support the design of a roll shop (cf. Fig. 2) by integrating different digital tools as shown in Fig. 3. The basis for the implementation of this approach is a formal representation of the information involved in the design process through a common and shared *RollShop Model* that instantiate a reference *Data Model* (*component 1* in Fig. 3). The resulting digital platform is characterized by a *star network* configuration and each digital tool may support more than one roll shop design activity.

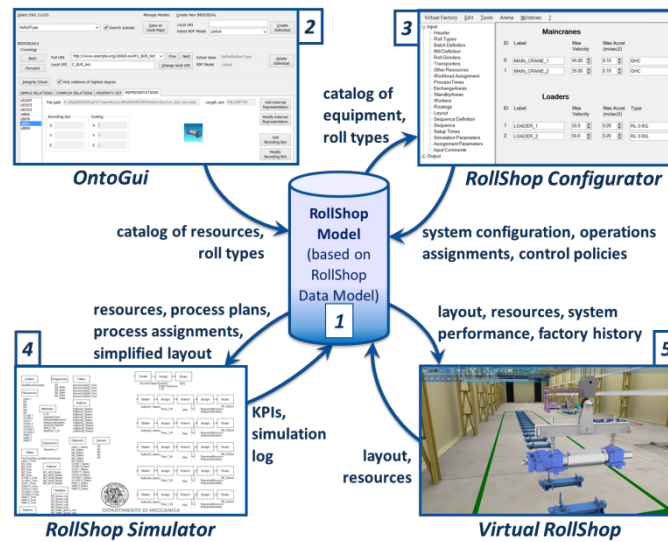


Fig. 3. Model-based integration of tools in the *Digital RollShop platform*

*OntoGui* (component 2 in Fig. 3) supports the generation of the resource catalog (activity A11 in Fig. 2). *RollShop Configurator* (component 3) leads the user through the configuration of a roll shop plant (activity A12) and show the results of the performance evaluation (activity A13). *RollShop Simulator* (component 4) enables the performance evaluation of roll shop configurations (activity A13) via discrete event simulation, while generating also a log of events that is used to visualize the system dynamics (activity A14). *Virtual RollShop* (component 5) is a 3D virtual reality environment supporting both the design of roll shop configurations (activity A12) and the visualization of system configurations and dynamics (activity A14). The next sub-sections will give details about the methods and tools composing the proposed digital factory platform.

### 3.1 RollShop Data Model

Semantic Web technologies have been exploited to facilitate the interoperability among the different digital tools [4]. The data model for the roll shop domain was developed as a modular ontology in OWL 2 language to formalize the information that is relevant to the design of a roll shop plant while reusing and extending previous works [5]. In particular a novel ontology module named *rollshop* was developed as an extension of the *dmanufacturing* ontology presented in [5] that in turn inherits several ontology modules like *ifcOWL* [6] and *SOSA/SSN* [7]. The overall data model consists of the modules listed in Table 1, i.e. the novel module named *rollshop* (prefix *rs*) and a subset of the modules included in [5]. The *rollshop* module defines classes representing hardware and software elements that are used to design a roll shop plant. Table 2 reports examples of such classes, their definition and the link with their super-classes defined in other ontology modules.

Table 1 List of ontology modules with prefix names

Prefix name	Prefix IRI of ontology module
dm	<a href="http://www.ontoeng.com/dmanufacturing#">http://www.ontoeng.com/dmanufacturing#</a>
expr	<a href="https://w3id.org/express#">https://w3id.org/express#</a>
ex	<a href="http://www.ontoeng.com/expression#">http://www.ontoeng.com/expression#</a>
factory	<a href="http://www.ontoeng.com/factory#">http://www.ontoeng.com/factory#</a>
fsm	<a href="http://www.learninglab.de/~dolog/fsm/fsm.owl#">http://www.learninglab.de/~dolog/fsm/fsm.owl#</a>
ifc	<a href="http://www.buildingsmart-tech.org/ifcOWL/IFC4_ADD1#">http://www.buildingsmart-tech.org/ifcOWL/IFC4_ADD1#</a>
ifcext	<a href="http://www.ontoeng.com/IFC4_ADD1_extension#">http://www.ontoeng.com/IFC4_ADD1_extension#</a>
list	<a href="https://w3id.org/list#">https://w3id.org/list#</a>
osph	<a href="http://www.ontoeng.com/osph#">http://www.ontoeng.com/osph#</a>
rs	<a href="http://www.ontoeng.com/rollshop">http://www.ontoeng.com/rollshop</a>
sosa	<a href="http://www.w3.org/ns/sosa/">http://www.w3.org/ns/sosa/</a>
ssn	<a href="http://www.w3.org/ns/ssn/">http://www.w3.org/ns/ssn/</a>
statistics	<a href="http://www.ontoeng.com/statistics#">http://www.ontoeng.com/statistics#</a>

**Table 2** Excerpt of classes defined in the *rollshop* ontology module

Class URI	Class Definition
rs:CoolingDownArea	Area where rolls are places to cool down. Subclass of ifc:IfcSpatialZone
rs:StandByPlace	Stand-by place where the rolls can be stored. Subclass of dm:BufferElement, ifc:IfcElement
rs:Roll	Roll that is employed in the roll milling plant. Rolls can be of different type, e.g. work roll, backup roll. Subclass of ifc:IfcElement
rs:OverheadCrane	Overhead crane to move rolls along the roll shop. Subclass of ifc:IfcTransportElement
rs:AutomaticLoader	Semi-gantry crane to move rolls along the roll shop. Subclass of ifc:IfcTransportElement
rs:RollGrinder	Roll grinder. Subclass of ifc:IfcElement, factory:MachineTool
rs:RollStateChocking	State of the roll regarding the presence of bearing chocks (i.e. chocked or dechocked). Subclass of fsm:Simple
rs:RollStateSurface	State of the roll regarding the surface (i.e. worn or resurfaced). Subclass of fsm:Simple
rs:RollLength	Length of a roll. Subclass of ssn:Property
rs:RollGrindingTask	Comprehensive grinding process. Subclass of ifc:IfcTask, factory:ManufacturingTask

The classes of the *rollshop* module can be grouped as follows:

- a partition scheme for the layout (e.g. rs:CoolingDownArea);
- hardware elements representing rolls (i.e. rs:Roll), transporters (e.g. rs:OverheadCrane, rs:AutomaticLoader), machines (e.g. rs:RollGrinder), buffers where rolls can be placed (e.g. rs:StandByPlace);
- manufacturing operations (e.g. rs:RollGrindingTask);
- state of objects to represent dynamic behaviors (e.g. rs:RollStateChocking, rs:RollStateSurface);
- properties specifying the characteristics of elements (e.g. rs:RollLength).

### 3.2 *OntoGui*

*OntoGui* is a general-purpose graphical user interface supporting the direct instantiation of OWL ontologies, i.e. A-box ontology modules consisting of OWL individuals [8]. *OntoGui* was employed to generate the catalog of resources (*activity A11* in Fig. 2) while referring to the common *data model*. As for the data model, modularity was exploited also to instantiate the catalog as a set of libraries: *LibDechocker* for dechocking machines, *LibGrinder* for roll grinders, *LibRoll* for roll types, *LibStorage* for stand-by places, *LibTexturing* for texturing machines, *LibTransporter* for transporters.

Each type of resource defined in the libraries is characterized in terms of class, properties, size, and 3D model (see Fig. 4). Resource catalogs can be reused for every roll shop project and can be updated whenever new specifications are introduced.



**Fig. 4.** Examples of rolls (first row) and stand-by places (second row).

### 3.3 *RollShop Configurator*

The *RollShop Configurator* is a graphical user interface developed in C# language to support engineers in the design of roll shop plants (*activity A12* in Fig. 2) by providing a standardized configuration workflow starting from the definition of the roll types and subsequently asking the user to provide the needed information (e.g. processing times) and take configuration decisions (e.g. routings, layout). The elements composing a roll shop configuration are selected according to production resources available in the resource catalogs described before. The workflow in the *RollShop Configurator* has been designed taking into consideration the know-how as well as the design practices in the reference company, thus aiming at guaranteeing a complete and standardized design process for all the technical quotations. Beside this, the *RollShop Configurator* provides also a set of reports assessing the performance of the roll shop plant in terms of KPIs (e.g. lead time and flow time for each class of cylinders, saturation of the machines, etc.) that are obtained from another digital tool, the *RollShop Simulator*.

### 3.4 *RollShop Simulator*

The *RollShop Simulator* is a reconfigurable Discrete Event Simulator (DES) based on the commercial simulation package Arena by Rockwell Automation.

The *RollShop Simulator* aims at providing design engineers with the capability of evaluating the performance of a system configuration using a dynamic model without the need of being expert in DES (*activity A13* in Fig. 2). The simulator grounds on a skeleton DES model

containing all the possible range of characteristics and options that are relevant in a roll shop plant. Moreover, the simulator can be dynamically adjusted to model a specific configuration by switching on/off these options. As anticipated, the *RollShop Simulator* provides as output a set of KPIs, e.g. the service levels guaranteed by the roll shop to the rolling mill(s), statistics related to the machines, the transporters, utilization of the buffers. Finally, the simulator generates as output the log of events taking place during the simulation run(s).

### 3.5 Virtual RollShop

The *Virtual RollShop* was developed as an enhancement of GIOVE Virtual Factory (GIOVE-VF), a 3D virtual reality collaborative tool supporting the design, visualization and exploration of 3D environments, in particular factories [9]. One of the main advantages of GIOVE-VF, compared to other commercial off-the-shelf solutions, is the capability to be easily customized and integrated with other software tools through its semantic web interface. GIOVE-VF was conceived as a tool to be mainly used by SMEs, being also free and simple to use and install.

The *Virtual RollShop* supports the modification of a roll shop design (activity A12 in Fig. 2) when used concurrently with the *RollShop Configurator* to:

- check the detailed roll shop layout and change the placement of equipment by means of a 3D manipulator widget or a 2D user interface (see Fig. 5). The positioning of items can be supported by the import of an existing 2D layout (as a DXF drawing) into the 3D scene.
- add and place new pieces of equipment (e.g. roll grinders, texturing machines, cleaning cabin) by accessing the resource catalogs. The catalogs can be easily upgraded as new elements are offered by the company (activity A11 in Fig. 2).



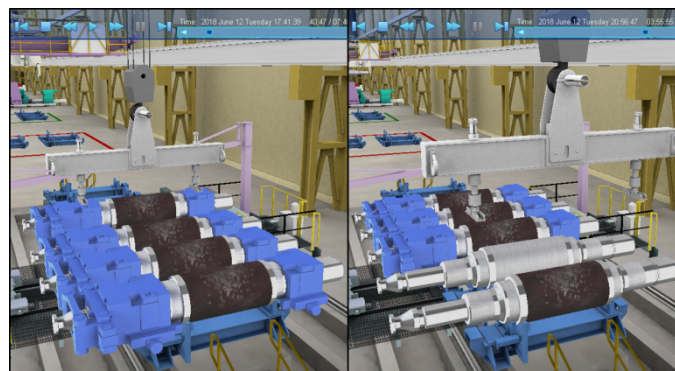
**Fig. 5.** Example of roll shop reconfiguration: addition of a roll grinder. The icons of the resource catalog can be noticed at the bottom of the screenshot. The user interface in top-right corner provide details about the selected object.

The *Virtual RollShop* can be also used to visualize the dynamic behavior of the plant (activity A14 in Fig. 2), i.e.:

- movements of the transporters and their components (e.g. tongs and chains);
- movements of rolls within the plant;
- progress of the processing in terms of changes of the roll state linked to a change in its 3D representation (Fig. 6).

The 3D animation is generated by automatically transforming the output of the *RollShop Simulator* into a sequence of events affecting the rolls and the equipment, tracking their evolution in time in terms of placement, state, and dynamic properties [10]. This transformation is facilitated by the underlying common data model and also provides a categorization and simplification of the very large log of the simulation into something that is more easy to understand by a human. The *Virtual RollShop* embeds video player controls (on the top of Fig. 6) to navigate through the different relevant events in the animation. This may be useful to:

- validate the simulation model, e.g. by checking if the modelling hypotheses are correctly implemented;
- check the soundness of the system configuration grounding on its visual behavior and performance;
- be exploited for marketing purposes as an enriched presentation of the roll shop plant design to the customer.



**Fig. 6.** Two screenshots of *Virtual RollShop* showing different states of the rolls: work with chocks (left), worn without chocks, resurfaced without chocks, and worn with chocks (right).

## 4. Conclusions

The proposed *Digital RollShop* platform was developed in cooperation with TENOVA Pomini to support the design of roll shop plants, specifically for the process of offer generation. Benefits coming from the use of this platform are twofold. Firstly, the design process can be enriched (i.e. number of alternative designs, simulation, 3D visualization) and sped up to match the requirements of the customers. Secondly, the adopted ontology-based approach enables the implementation of a comprehensive but concise and extensible design platform. Possible future developments are the exploitation of the digital model during the use phase of the plant, through a synchronization with a real roll shop to support its monitoring and the implementation of simulation-based decision tools [10].

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