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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 dedicated to grinding cylinders for rolling mills. These digital tools are aimed to engineers and provide a configuration workflow, a 3D environment and performance evaluation tools. The interoperability among the software modules and the reuse of knowledge is enhanced by 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

1. Introduction

The design of production systems, like most engineering projects, involve various stakeholders and entails complex workflows that are more and more supported by heterogeneous methodologies and digital tools. Contractors 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 [1]. Despite the 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 [2].

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 bids 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 [3], and more recently Digital Twin [4], have been proposed by both researchers and practitioners as viable solutions to improve and speed-up the design and re-configuration of manufacturing systems and supply chains through the extensive use of modelling and simulation tools [5][6][7]. In addition, Virtual Factory can be exploited to support product design, process planning, production planning and control, monitoring, etc. [8][9] in a single and integrated framework. Major ICT companies already offer commercial software packages providing a subset of these functionalities, typically identified as Product Life-cycle Management (PLM) suites. Nevertheless, the price of these very large solutions is one of the main obstacles to the adoption of these approaches, usually limited to 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 set of functionalities for the design of roll shops, i.e. layout design, resource selection, discrete event simulation and 3D visualization. In particular, the digital platform was 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.

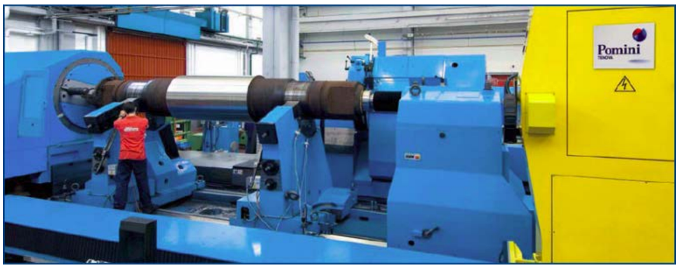

Fig. 1 A roll grinding machine (courtesy of TENOVA S.p.A.)

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 proposal;
- 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.

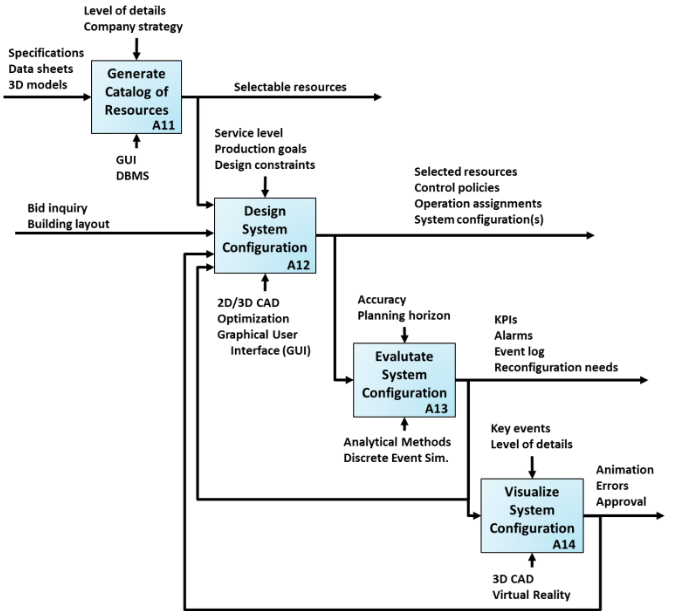

Fig. 2 IDEF0 diagram representing the reference workflow of production system design.

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 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. Re-design loops may be necessary after *activities A13* or *A14* because specific reconfiguration needs or 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.

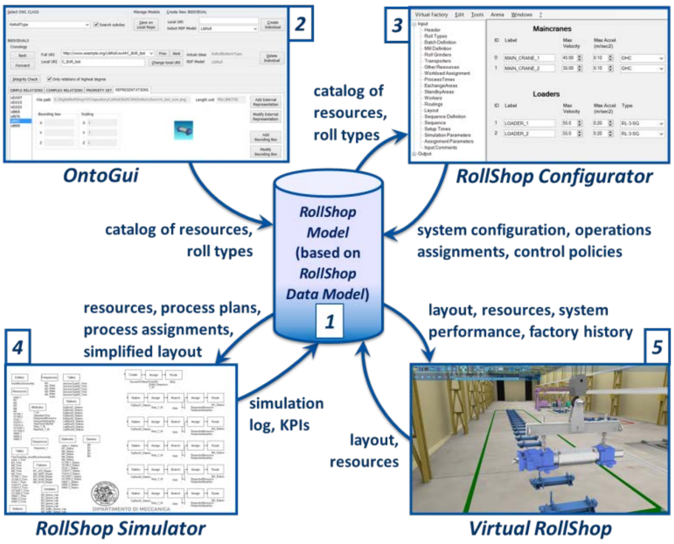

Fig. 3. Model-based integration of tools in the *Digital RollShop* platform

OntoGui (*component 2*) 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 shows the results of the performance evaluation (*activity A13*). *RollShop Simulator* (*component 4*) runs 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 their dynamics (*activity A14*). The next sub-sections will give details about the 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 [10]. The data

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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 [11]. In particular a novel ontology module named *rollshop* was developed as an extension of the *dmanufacturing* ontology presented in [11] that in turn inherits several ontology modules like ifcOWL and SOSA/SSN [12]. 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 [11]. 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	http://www.ontoeng.com/dmanufacturing#
expr	https://w3id.org/express#
ex	http://www.ontoeng.com/expression#
factory	http://www.ontoeng.com/factory#
fsm	http://www.learninglab.de/~dolog/fsm/fsm.owl#
ifc	http://www.buildingsmart-tech.org/ifcOWL/IFC4_ADD1#
ifcext	http://www.ontoeng.com/IFC4_ADD1_extension#
list	https://w3id.org/list#
osph	http://www.ontoeng.com/osph#
rs	http://www.ontoeng.com/rollshop
sosa	http://www.w3.org/ns/sosa/
ssn	http://www.w3.org/ns/ssn/
statistics	http://www.ontoeng.com/statistics#

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

Class IRI	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 [13]. *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

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environments, in particular factories [14]. 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 provides 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).

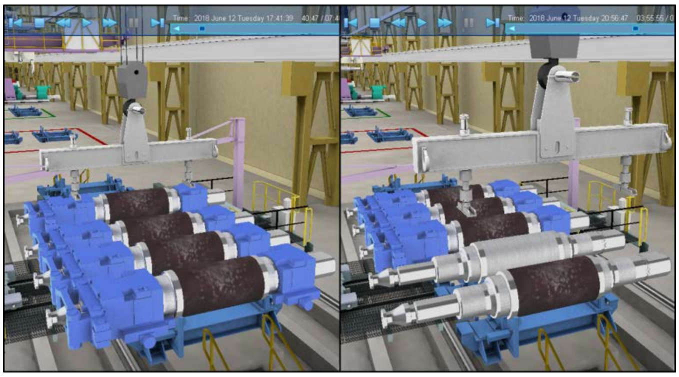

Fig. 6. Two screenshots of *Virtual RollShop* showing different states of the rolls: work with chocks (left), worn without chocks, resurfaced without chocks, and worn with chocks (right).

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 [15]. 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 easier 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.

4. Conclusions

The proposed *Digital RollShop* platform was developed in cooperation with TENOVA S.p.A. 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 synchronization with a real roll shop to enable its monitoring and the implementation of simulation-based decision support tools [15].

References

[1] Philbin SP (2008) Bid management: A systems engineering approach. The Journal of High Technology Management Research, 19(2):114-127.
[2] Smartt CD, Ferreira S (2012) A systems engineering perspective on proposal management. IEEE Systems Journal, 6(4):667-674.
[3] Kádár B, Terkaj W, Sacco M (2013) Semantic Virtual Factory supporting interoperable modelling and evaluation of production systems. CIRP Annals Manufacturing Technology, 62(1):443-446.
[4] Grieves M, Vickers J (2017) Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In: Kahlen FJ, Flumerfelt S, Alves A (eds) Transdisciplinary Perspectives on Complex Systems. Springer, Cham
[5] Jain S, Shao G, Shin S-J (2017) Manufacturing data analytics using a virtual factory representation. International Journal of Production Research 55(18):5450-5464
[6] Belkadi F, Colledani M, Urgo M, Bernard A, Colombo G, Borzi G,Ascheri A (2018) Modular design of production systems tailored to regional market requirements: A Frugal Innovation perspective. IFAC, 51(11):96-101
[7] Cigolini R, Pero M, Rossi T (2011) An object-oriented simulation meta-model to analyse supply chain performance. International Journal of Production Research, 49(19):5917-5941
[8] Büscher C, Meisen T, Schilberg D, Jeschke S (2016) VPI-FP: an integrative information system for factory planning. International Journal of Production Research, 54(8):2215-2226
[9] Lechevalier D, Shin SJ, Rachuri S, Foufou S, Lee YT, Bouras A (2017) Simulating a virtual machining model in an agent-based model for advanced analytics. Journal of Intelligent Manufacturing, in press
[10] Ekaputra FJ, Sabou M, Serral E, Kiesling E, Biffl S (2017) Ontology-Based Data Integration in Multi-Disciplinary Engineering Environments: A Review. Open Journal of Information Systems (OJIS), 4(1):1-26.
[11] Urgo M, Terkaj W, Giannini F, Pellegrinelli S, Borgo S (2019) Exploiting modular pallet flexibility for Product and Process co-evolution through zero-point clamping systems. In: Tolio T, Copani G, Terkaj W (eds) Factories of the Future - The Italian Flagship Initiative. Springer
[12] Janowicz K, Haller A, Cox SJD, Phuoc DL, Lefrançois M (2019) SOSA: A lightweight ontology for sensors, observations, samples, and actuators. Journal of Web Semantics, in press
[13] Terkaj W (2017) OntoGui: a Graphical User Interface for Rapid Instantiation of OWL Ontologies. Proceedings of the Workshop Data Meets Applied Ontologies, Joint Ontology Workshops 2017, CEUR Workshop Proceedings, vol. 2050
[14] Terkaj W, Viganò GP (2017) Semantic GIOVE-VF: an Ontology-based Virtual Factory Tool. Proceedings of the Workshop Data Meets Applied Ontologies, Joint Ontology Workshops 2017, CEUR Workshop Proceedings, vol. 2050
[15] Terkaj W, Tolio T, Urgo M (2015) A virtual factory approach for in situ simulation to support production and maintenance planning. CIRP Annals Manufacturing Technology, 64(1):451-454

W. Terkaj, P. Gaboardi, C. Trevisan, T. Tolio, M. Urgo (2019) A digital factory platform for the design of roll shop plant
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