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Virtual Factory as a Method of Foundry Design and Production Management

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Abstract

The paper outlines the methodology of virtual design of a foundry plant as a system. The most important stage in the procedure involves the development of a model defined as a set of data about the system. Model development involves two stages: defining the model's architecture and specifying the model data in the form of parameters and input-output relationships. The structure is understood as configuration of machines and transport units, representing the sub-systems and system components. As the main purpose of the simulation procedure is to find the characteristics of the system's behaviour, the merits of the iterative method involving analysis, synthesis and evaluation of results are fully explored.

Keywords: Application of information technology to the foundry industry, Automation and Robotics in Foundry, Virtual Factory Design

1. Introduction

In response to the growing pressure to search optimal organisational solutions alongside the creation of new design methods, programme libraries, databases and IT systems, necessary for design of manufacturing systems (foundry plants), current research is now aimed at development of more effective methods to support the design processes.

A most promising approach meeting the requirements of the state-of-the-art design is referred to as virtualisation, understood to be the method of simulative design of manufacturing systems, including foundry plants. The simulation procedure utilising the iterative analysis (involving analysis, synthesis, evaluation of solutions) aims to ensure some level of confidence in the final result of the project. The new paradigm of design, taking into account the virtualisation method, should define the design problems to be solved (or handled) before decisions are made regarding their implementation. That means that the final results of the projects should be forecasted and the activities aimed to attain the business goals specified.

Virtualisation of a system (a foundry) design involves four basic though interrelated groups of problems:

1. Selection of tasks suitable for virtual design; working on methods of computer-supported design graphic and heuristic methods, modelling of manufacturing or business processes, functional analysis, value analysis (evaluation of the goodness of projects).
2. IT support- principles of building databases to support foundry designs.
3. Mathematical tools to support the system models, algorithms, software.
4. Automation of routine and repetitive design tasks.

Research projects involving virtualisation of foundry design rely on theoretical backgrounds in several fields:

– theory of systems,
– decision-making theory,
– operations research,

– quantitative and general information theory,
– theory of economic, technical value, analysis of functional values,
– other theories and laws applicable in related engineering and social sciences.

Our concept aims to develop a "virtual foundry" on the basis of the virtual reality (VR), which can be viewed as a solution where the user (via GUI) interacts with the operation of the system in a three-dimensional realistic environment to provide a sense of reality. The VR is employed in various applications in design and manufacturing, such as computer-aided design, tele-robotics, assembly planning, manufacturing system visualization and simulation [7].

VR in manufacturing or a virtual factory (VF) consists in using the information technology and computer simulations to model real-world manufacturing processes that considers the factory as a whole and provides an advanced decision support capability. Easy to understand though complex three-dimensional animation models are used to represent the real manufacturing activities [2]. Machines, machine cells and material flows can be designed and evaluated on the screen before actual facilities or products are constructed. In general, three main principles of VF modelling are:

1. model the factory before building,
2. simulate before producing,
3. anticipate and solve problems before they occur.

The aim of the paper is to present the current state in this field and to provide a concept of virtual foundry design. Section 2 presents the simulation approach as the method used in management and engineering. The review of literature on the subject is given in Section 3. Section 4 outlines the concept of virtual foundry design. The conclusions are drawn in Section 5.

2. Computer simulation in design and management

The applications of computer simulation methods to the design of industrial plants date back to the 1960s, and first appeared to be very promising. In later years, however, a certain level of discouragement with the method was observed, attributable to two basic reasons. First, the modelling, design, verification and evaluation of simulation results proved to be time-consuming tasks and computer programs to be used in simulations required careful coding. The second reason was the growing difficulty associated with modelling of more intricate and sophisticated IT and manufacturing systems and limited capability of concurrent handling of several aspects of design as well as verification of results. The arrival of new concepts of business management and advances in IT methods have again spurred the interest in simulation methods used for verification of effectiveness of business processes. These solutions are user-friendly: simulation models are based on graphic objects, supported by system logic definition techniques, defining the objectives of simulations experiments and facilitating evaluation and verification of simulation results.

Computer simulations have numerous applications, the authors focus here on aspects associated with organisation of manufacturing processes, including [6]:

– defining the real production capacity,
– selection of the manufacturing technology taking into account the cost-effectiveness of particular solutions,
– design of the manufacturing structure of the plant,
– design of the IT structure,
– selection of transport facilities, storage areas and other logistic problems,
– selection and management of tools and equipment.

Modelling and simulation are tools to be used not only when solving design problems within a specified time period, but they are now widely employed in business management. Decision-makers have to be able to use methods and tools for performance analysis and for simulating the effects of the decisions being made, both in qualitative and quantitative terms. Simulation has now become the basic tool in the management-support systems, included in the Business Intelligence category. In order that simulation methods could be effective, the company's model has to be integrated with the operational database and data warehouse systems. Such models have to be developed already at the stage of design and then used in business management. These models are referred to as virtual businesses.

Numerous solutions used for supporting the modelling and simulation of manufacturing systems are now available on the market. These solutions can be broadly categorised in three groups. The first group includes programming languages and open systems relying on graphic objects, allowing for any system to be modelled (e.g. Simprocess, Simul8, ProModel).

The second category are systems aimed at modelling of business processes, used mainly as an extension of existing tools for supporting the IT systems in the company. A good example here is a tool for creation, modelling and analysing of business models in the graphic environment Powersim Studio (manufactured by Powersim Corporation). This solution combines the modelling technique relying on dynamic description of business processes using mathematical equations and simple logic (the concept previously referred to as Industrial Dynamic) with direct connection to the data warehouse platform of the company, so the system can be used in operational analyses.

The third group includes the object systems for modelling manufacturing processes, which can be utilised both at the stage of design and manufacturing operations (e.g. Simulaiton Solutions, QUEST, i2 Factory Planner or eM-Plant). Similar to business processes modelling tools, these solutions now allow full integration with the operative management-supporting IT systems. These applications enable us to optimise the material flow, the company's resources and logistics on all levels of the organisational structure, starting from the global model, through the company's divisions, right through to individual process lines. Modelling of manufacturing processes using standard libraries and specialised components allows for creating structural hierarchical models of industrial plants, factory floors, manufacturing lines and processes. The applications are equipped with dedicated libraries of objects for business process modelling. When the libraries are expanded and new components added, we are able to model any type of systems.

The adequacy of existing solutions was evaluated in [5], in terms of their usability in design of industrial plants, particularly the foundry plants. The third category of tools seem to be most promising, their main advantage being the ease with which we are able to construct models on any level of complexity. Moreover, they can be easily integrated with database systems, so we are able to fully exploit the advantages of the SQL language as the tool for supporting the company's IT system model. However, those solutions preclude the modelling of IT systems, they just allow for using the existing systems. Further, the possibilities of representing the decision-making processes are fairly limited. In practice, creation of optional solutions of decision-making modules requires their coding in the language similar to Visual Basic, which restricts the group users to IT staff. Paradoxically, their universal character becomes the key drawback of those solutions. When designing foundry plants, we have to handle a group of repetitive tasks, which should be easy to model, without requiring us each time to develop new unique models.

3. The examples of virtual foundry design

In spite of the large number of theoretical works on virtual reality, there are only a few studies available dealing with virtual foundries.

Ravi and Datta [8] proposed a virtual foundry as a web-based casting engineering integrated with Holonic Manufacturing System (HMS). A *holon* is defined as an autonomous and cooperative building block of a process for transforming, transporting, storing, and validating information and objects. The virtual foundry is a replica of a real factory, with separate departments for part design, tooling design, methoding, casting trial, and planning functions. The virtual foundry consists of five major sections with the following functions (Figure 1):

1. **Part section**; functions for sending and viewing a part model, selecting an alloy, calculating geometric properties, selecting the casting process and checking part manufacturability.
2. **Tooling section**; functions for selecting the casting orientation and mould parting, pattern design (applying draft and other allowances), and core design (print or supports, and allowances).
3. **Methoding section**; functions for deciding the location, shape and dimensions of feeder(s) and gating elements, as well as number of cavities in the mould and their layout.
4. **Casting section**; the most important section, where simulation of mould filling and casting solidification are carried out to predict related defects.
5. **Planning section**; casting process planning (steps, parameters and checks in mould-making, core-making, melting, pouring and fettling operations), material requirements planning, and casting cost estimation.

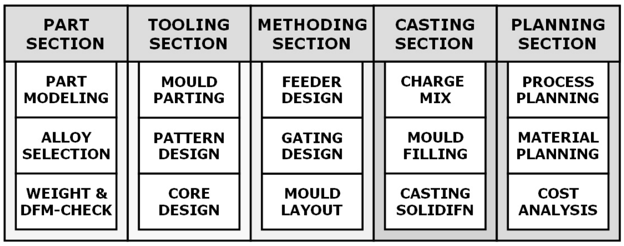

Fig. 1. Major subsystems of virtual foundry. Source: [8]

The operation of the virtual foundry comprises two phases:
1. initial creation of a virtual foundry,
2. using a particular virtual foundry to develop new castings.

It is apparent that the proposed virtual foundry is product-oriented. Moreover, the project is still in concept phase and it is not developed.

Schenk at al. [9] tested the approach combining simulation and virtual reality into truly interactive and immersive environments. In a pilot project conducted with Rautenbach Guss Wernigerode GmbH (a foundry factory) the simulator eM-Plant was used. The application areas include the virtual-interactive planning and design of new factories, the support for operating a factory, the worker qualification. In the design phase the processes of the planned factory can be tested and optimized within the VR environment. In the operation phase of the factory life-cycle the VR world can act as the virtual representation of the real factory. In case of emergencies (e.g. machine failure) the factory operator can plan and test different plans of action and select the best option.

Creighton and Nahavandi [3] proposed a discrete event simulation for system design of a melt facility. The model allows greater insight into dependencies between controllable parameters and noise factors in the production environment and provides methods to minimize the impact of those dynamic or stochastic factors to be identified. The understanding of the system performance is possible by analysis and simulation of key production and organization factors. The simulation model can be used to evaluate production capacity, schedule production tasks and detect bottlenecks limiting the system performance.

Bal and Hashemipour [1] put forward a VR-based concept for enhancing the design and implementation process of holonic control systems in manufacturing practice. The virtual factory, containing buffers, machines and material handling systems, integrates VR-based modeling into an agent platform in order to realize the holonic manufacturing control within a discrete event simulation environment (see Figure 2). A case study of a medium size die-casting factory is described to demonstrate the effectiveness of the proposed method. Although the goal of the proposed virtual foundry is to test the various control systems, this approach can be useful in handling more general design problems.

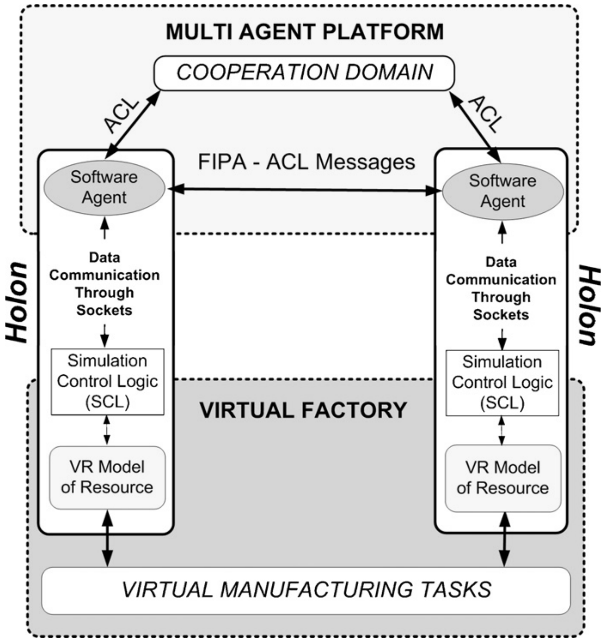

Fig. 2. The architecture of virtual holonic factory. Source: [1]

The VFF-MTP (Virtual Factory Framework - Manufacturing Technology Platform) project, financed under the 7FP, has been started in 2011. This IMS (Intelligent Manufacturing Systems R&D program) project objective is to define the next generation Virtual Factory Framework [10]. VFF-MTP consists of four clusters:

1. Development of a reference model for planning of factory from different sectors, development of the VF manager core for managing the interaction of the different modules and synchronising the exchange of data and development of the knowledge repository and good practice.
2. Analysis and applicability of standard and neutral file formats to achieve real-time connection between digital factory tools and real factory.
3. Knowledge based control for reactive and proactive management of manufacturing system.
4. Investigation of virtual models for the multi-site multi-nation factory for the production of customer driven products.

Expected results in the VFF project are collaborative customer-driven VF tools for cost-effective and rapid creation, management and use of complex knowledge-based factories.

In summary, the literature review leads us to the following assumption:

- there is no uniform methodology for the foundry design using virtualization approach,
- the proposed solutions are incomplete, mostly focused on products design and not taking into account a foundry as a system.

4. Methodology of virtual foundry design

The distinctive feature of the design process is that it involves the transition from the abstract to the concrete (a material system). The transition is gradual, through putting the concept in concrete terms (specification or providing details) in design solutions that have to satisfy certain requirements [11]. This approach involves the iterative method of subsequent approximations, as shown in Figure 3. As a rule, the starting point in the procedure is synthesis (conceptual, solution). The result of synthesis should be then analysed and the evaluated. In the evaluation procedure the results of analysis of solutions obtained through synthesis are confronted with the set of requirements underlying the design task. When the results fail to meet the requirements, the synthesis and subsequent operations will be repeated, forming an iterative loop. The iterative procedure is over when the results begin to coincide with the requirements or, in negative terms, when no further data can be provided in favour of the given solution.

In the virtual design, this process is extended and the basic iterative loop at each stage has a different sequence (see Figure 4). This configuration of the process prevents the premature declaration that the problem has been solved while in fact only an apparent solution has been found.

The methodology outlined here is applied to the manufacturing system in a foundry plant. From the standpoint of the general theory of systems, a system is an interrelated set of structures and material, energetic and information processes. The structure is understood as configuration or arrangement of its components (machines, plants, transport facilities), which are defined as sub-systems and elements of sub-systems.

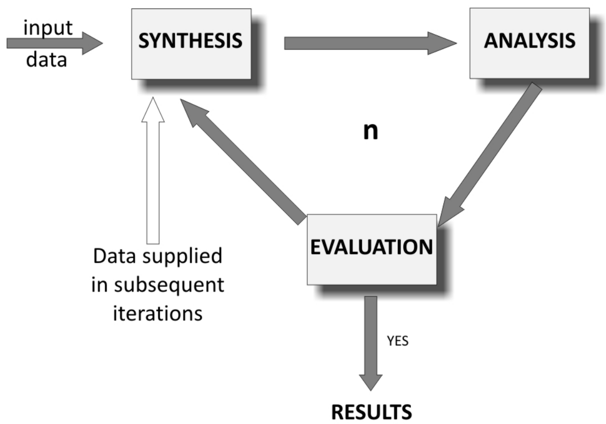

Fig. 3. Iterative loop in design

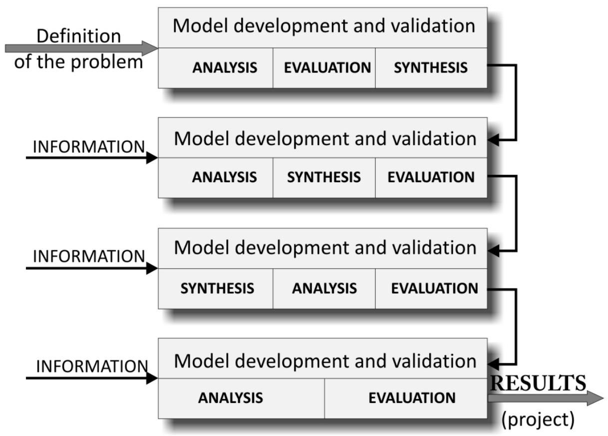

Fig. 4. Stages of virtual design

The structures in the system support the processes, enabling their execution. When processes are not displayed, what is revealed is just the static structure of systems. The dynamic form of the system leads to the goal achievement (for example the effect of the manufacturing process i.e. the casting) through transforming input into output parameters (inputs- outputs). This transformation is determined by internal processes within the system associated with engineering and manufacturing aspects of the process. Operational parameters of machines, plants and transport systems also contribute to the transformation processes. In the case of foundry plants, these should include sand preparation, die casting, melting, finishing of castings in accordance with the process technology.

The basic principle in the general systems theory has it that operations are performed on artificially created models (artefacts) which are transformed into material systems representing real systems through dynamic relationships and input-output parameters, in the form of data or aspects of matter or energy. This definition is applicable to material and manufacturing systems (such as foundry plants).

In simulations, models are transformed into active system through defining the characteristics of the system's behaviour. Simulations of systems involve five main stages [4]:

1. Definition of the problem.
2. Model development and validation.
3. Experiment planning.
4. Simulation procedure.
5. Analysis and interpretation of results.

The system simulation procedure is shown graphically in Figure 5.

From the standpoint of methodology, the starting point in model construction should be a block structure given as the set of the system's inputs and outputs, defining the interrelations within the system.

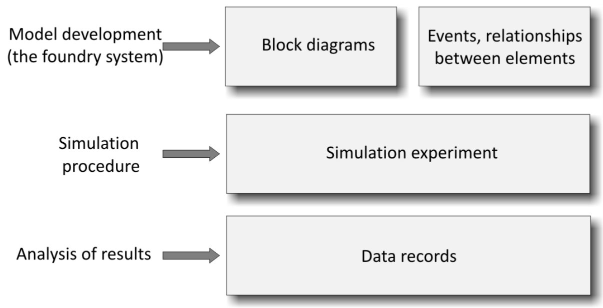

Fig. 5. Stages of the simulation procedure

The first stage of the procedure involves:

– list of inputs and outputs from the system and sub-systems forming the structure of the foundry plant,
– a detailed characteristics of operational and structural elements given in qualitative and quantitative terms,
– adjusting the set of inputs to the set of outputs, taking into account the goals confirming the goodness of the solution.

The second stage of the procedure involves:

– defining the subset of inputs and outputs to provide the backgrounds for specifying the sub-systems and elements in the system's architecture, in accordance with the manufacturing process requirements in the foundry plant,
– analysis of input-output conformity, which determines the outcome of the iterative procedure.

The schematic diagram of the sub-system synthesis is shown in Figure 6.

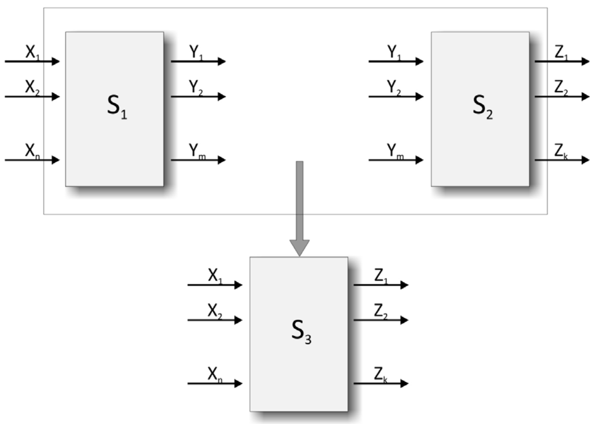

Fig. 6. Schematic diagram of synthesis of sub-systems S1, S2 into system S3

The final goal of expressing inputs and outputs as quantities' parameters and their mutual interrelations, becomes the development of the formalised notation using equations and inequalities so that the system and sub-systems should be governed by mathematical models.

5. Conclusions

This paper outlines a methodology of virtual foundry design. The method involves the simulation of systems performed to determine the characteristics of the system's behaviour. Further, the principles and merits of the iterative method involving analysis, synthesis and evaluation of results are explored.

A virtual foundry would be intended to support the design and restructuring of foundry plants, particularly for handling the following design tasks:

- planning the locations of machines and installations as well as materials handling facilities,
- generating the design documentation and specifications,
- adjustment of production capacity levels to the sales plan,
- harmonising and synchronisation of manufacturing processes,
- cost assessment and financial viability of proposed solutions,
- selection of the optimal technology,
- verification of the production scheduling method,
- restructuring of business processes.

The proposed approach can be used when handling research tasks different from purely design problems. Modelling of market conditions and sales processes is useful in testing the efficiency of marketing strategies or selected distribution channels. A virtual foundry is also an ideal educational tool as it helps engineering and business students to grasp the factory dynamics, an issue most difficult to lecture and impossible to experiment in real foundries.

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