APPLICATION OF DIGITAL ENGINEERING AND SIMULATION IN THE DESIGN OF PRODUCTS AND PRODUCTION SYSTEMS

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ABSTRACT

The paper presents the results of research & development done at the University of Žilina, Faculty of Mechanical Engineering in the area of Digital Engineering and simulation in the design of products and production systems. The digital technologies are used in innovation process of products and production systems. The paper describes the concept of Digital Factory being developed at the University of Žilina. Starting from the conceptual model of a product the whole chain of digital design processes of the given product and its production system are described. The digitization procedure is presented using 3D laser scanning technologies. The paper presents the theoretical research done in metamodelling based on computer simulation and used by the choice of the appropriate shop floor control system. The future research goals are presented as well.

KEY WORDS

virtual engineering, digital factory, simulation, reverse engineering, intelligent manufacturing systems

Introduction

According to the International Monetary Fund the European Union is the largest world exporter and simultaneously the second largest importer. EU became the largest world economic block with GDP over $12.8 trillion in comparison to the GDP of USA which was about $11.7 trillion.

The economic significance of intense and sustainable production basis in Europe is well supported by the fact that production employed over 28.3% of EU employees and created about 31.8% of European value added during 2007. More than 70% of this value added was produced by six main spheres: automobiles, electric and optic devices, food, chemistry, materials, semi-finished goods and mechanical engineering [Jovane et al., 2009].

European production sector keeps dominant position in the world international business. In 2004 EU partook of about 18% of the world production, while USA about 12% and Japan about 8%. EU dominates in chosen industrial sectors like: automotive industry, mechanical engineering, agriculture and some areas of telecommunication equipment [Manufuture 2004].

EU economic growth after 1990 has been declining behind USA, in spite of the fact that the EU population is in 50% bigger than that of USA.

Industrial research and development requires completely new approaches for designing and testing new products and production processes. Progressive approaches utilize the most advanced technologies of digitization, rapid prototyping, virtual designing, simulation, etc. The Virtual Reality can be used in the product development and in the design of production processes, workplaces, production systems, etc. The utilization of Virtual Reality and simulation by the design and optimisation of production processes and
systems is often entitled as Digital Factory [Gregor et al., 2006].

The Digital Factory technology provides the ways to reduce the amount of necessary time and thus, as well, to reduce the development costs to the level of 60 to 80% of costs required by conventional technologies. Digital Factory currently represents the most progressive paradigm change in both research and industry covering the complex, integrated design of products, production processes and production systems.

Different types of software are linked in PLM solutions, which control different parts of the manufacturing cycle. Computer Aided Design (CAD) systems define what will be produced. Manufacturing Process Management (MPM) defines how it is to be built. Enterprise Resources Planning (ERP) answers when and where it is built. Manufacturing Execution System (MES) provides shop floor control and simultaneously manufacturing feedback. The storing of information digitally aids communication, but also removes human error from the design and manufacturing process [Dreher, 2007].

The European Union has launched new project called ManuFuture – the future development of technologies and production systems in Europe. Its main goal is to foster the growth of EU’s competitiveness in production sphere. ManuFuture has published its Strategic Research Agenda (SRA) and ManuFuture – Vision for 2020, which present a vision of the future development of production in Europe [Manufuture, 2004].

New generation production systems are supposed to generate the high Value Added. New designed, sophisticated and complex production systems, are understood among current European scientists as the final products, which can be sold similarly as the other products. These new concepts are built on the principles of Advanced Industrial Engineering, which uses the Digital Factory concept and digitization as a main tool.

**Products Innovations**

There are many approaches used for products innovation. Starting from the conceptual design through the simulation of products properties (e.g. FEM Analysis) up to the prototyping a plenty of methods which support designing of products exists. Creative thinking methods became very popular during last years. It is not enough to have theoretical and expert knowledge or to be familiar with new information technologies as the experience of designers shows. It is important to be able to use creative thing-

![Image of Electro Gearbox](image_url)

**Figure 1. Innovation of the Gearbox Driving Lug**

a) Real Electro Gearbox; b) Basic solution (26 components, 13 from them non standardized), gearbox price: 1363,73 €; c) Innovative solution (18 components, 4 from the non standardized), gearbox price: 1328,22 €

Source: [Turcik, 2009].
The result of the above presented innovation shows that even small change in the product concept can result in interesting potential savings, especially by mass production.

**RAPID PROTOTYPING OF PRODUCTS**

The technologies of Rapid Prototyping are appropriate especially in case when the company has to offer a quick response to the customer requirements on innovation [Chlebus 2000]. The automotive industry requires fast response to customer requirements. The following example shows the results of long term scientific co-operation between the University of Žilina and company VW Slovakia [Gregor et al., 2006] in the application of Rapid Prototyping and Vacuum Casting technologies by the development and production of gear boxes.

In the DMU model of single parts of gearbox was developed on the basis of clouds of a point’s model. Figure 3 and Figure 4 show the results of design of chosen gearbox parts and the production of prototypes through Fused Deposition Modelling (FDM) method, Selective Laser Sintering Method (SLS) and Vacuum Casting technologies. This research was conducted in co-operation with the Technical University of Wroclaw (prof. E. Chlebus).

The DMU model (DMU – Digital Mock Up) of given gearbox was created by Reverse Engineering technologies (Minolta 3D Laser Scanner VI 900). Figure 2 shows the real VW Gearbox and its scanned clouds of point’s model [Gregor et al., 2006].

![First Design](image)

![STL Model](image)

![FDM Prototype](image)

**FIGURE 2. REAL VW GEARBOXES**

*Source*: The Authors.

**FIGURE 3. DEVELOPMENT OF THE PROTOTYPE**

*Source*: [Gregor et al., 2005].
Rapid Prototyping of Production System

The University of Zlina has conducted several research studies in industry focused on Digital Factory solutions. The DMU model of a real gearbox was developed using Reverse Engineering technology (3D laser scanning), in the framework of co-operation with VW Slovakia (Figure 5).

Based on the Gearbox DMU and a real assembly system a set of DMUs of VW production workplaces and transportation equipments was developed (Figure 6).

The design of workplaces was especially checked by ergonomics analysis whereas manikin concept of Delmia V5 Human was used. The static virtual model of a given gearbox assembly line was developed through integration of individual DMUs into manufacturing system scene. The dynamics of the real assembly system was checked in the 3D simulation environment Quest, as it is shown in figure 7. The set of simulation experiments was conducted with the developed simulation model which showed bottlenecks stations and the possibilities for performance improvement of gearbox assembly line.
Afterwards an FMU of the whole assembly line for gearboxes assembly in VW Slovakia was developed. This FMU represents the complex digital model of the entire assembly line. The final solution is shown in figure 8.

**Innovative Production Systems**

Global undertaking brings numerous troubles and difficulties to all manufacturers. Turbulent global markets, strong competition, growing costs, changing undertaking paradigms are only a few of what presses manufacturers to look for new approaches on how to effectively manage all manufacturing and logistics processes [Barczik, 2003].

The future cannot exist without innovation of production processes and production systems as it cannot exist without the innovation of products. Production systems require redesign, new machines and devices, transport systems, control systems, work organisation etc. Such changes are introduced by teams of specialists, designers and planners.

The production systems innovations are realised by principal, revolutionary changes of production, organizational or control principles which are conducted in long term time periods. Small, continuous changes are conducted in time between revolutionary
changes, sometimes signed as evolution changes. They are realised in a short term time periods, practically by any change of production systems or even production line or mix. These changes are comparable to known Kaizen, continuous process improvement.

The results of recent year’s research conducted in the framework of international Intelligent Manufacturing Systems (IMS) research program showed that the future for manufacturing lies with new forms of manufacturing strategies. The global networks of self-organizing and autonomous units will create basis for new production concepts [IMS, 2005; Montorio and Taisch, 2007a; Montorio and Taisch, 2007b].

Intelligent Manufacturing Systems (IMS) represent the future of manufacturing. The main target of IMS is to increase manufacturing competitiveness, flexibility and productivity.

Recently conducted research and development on this area is focused mainly on new directions in development of intelligent machine tools, intelligent tools and jigs, intelligent transportation system, intelligent control system, etc. The research is underlined with the utilization of Artificial Intelligence technologies like: Artificial Neural Networks, Fuzzy Logic, Expert systems, Genetic Algorithms, Automatic Speech Recognition (ASR), control of manufacturing processes through voice control, pattern recognition, etc.

The University of Žilina and the Central European Institute of Technology (CEIT) have been conducting research in development of subsystems of Intelligent Manufacturing System. It covers many areas like: autonomous AGVs, monitoring and control system for intelligent transportation and handling, autonomous hall navigation system, etc. Figure 9 shows the result of research of autonomous, intelligent low cost mobile robotic system done in the Central European Institute of Technology in co-operation with VW Slovakia.

Any change, even the smallest one, brings risk. The change has to be realised by real people who make mistakes. The quality and fastness of changes can be supported by 3D digital models of production systems. The dynamic development currently undergoes in the companies running business in the HighTech sphere by the application of Digital Factory systems. Some years ago the University of Žilina and the University of Bielsko Biala have started to build such complex Digital Factory system [Gregor et al., 2006]. The Digital Factory system utilises 3D digital models of real objects. DMUs have firstly begun to be used in the sphere of products design and analysis. They are starting to be used in the sphere of complex production systems or even of whole factories (for instance in automotive industry). Such digital models are called FMUs – Factory Mock Ups, i.e. digital models of factories.
Digital Factory

Digital Factory entitles virtual picture of a real production. It represents the environment integrated by computer and information technologies, in which the reality is replaced by virtual computer models. Such virtual solutions enable to verify all conflict situations before real implementation and to design optimised solutions.

Digital Factory supports planning, analysis, simulation and optimisation of complex products production and simultaneously creates conditions and requires team work. Such solution enables quick feedback among designers, technologists, production systems designers and planners. Digital Factory represents integration chain between CAD systems and ERP solutions.

Digital Factory principle is based on three parts [Gregor et al., 2006]:
- digital product, with its static and dynamic properties,
- digital production planning,
- digital production, with the possibility of utilisation of planning data for enterprise processes effectiveness growth.

Global markets require short time to sell, high quality products with the lowest possible price. Digital Factory seems to be a good approach for solution of the above introduced requirements.

How to become Digital?

Mainly classical approaches are being used for digitalisation and geometric analyses of the existing production systems. Information about the real state of the production system is, in case of complex production systems, obtained using the measuring tape, or laser measurers. Using such approach makes digitalisation of the whole enterprise extremely time-demanding and expensive. It is also a potential source of waste, inaccuracies and errors.

It is much faster, much more effective and qualitatively better to create the 3D models of the existing production systems using the 3D laser scanners. These make possible to transform the existing, real 3D word, into its exact 3D digital copy which correctly reproduces the exact geometry of the recorded space and can simply be used for any computer analyses, in a matter of a few moments [Westkaemper, 2001].

Thus obtained 3D digital model (so-called master model) can be used in all designer professions; it can be used by analysts as well as by the factory's management. Using the internet it is possible to share such model from anywhere worldwide. Its accessibility makes it easier to eliminate errors. Designers from all over the world can simultaneously work on new projects without any need to travel on to the spot and manually do all the measurements required before they start to design.

Extensive research is currently underway, all over the world, in the sphere of utilising the digital methods for digitization, modelling, analysing, simulation, recording and presenting of real objects [Furmann, 2007; Gregor et al., 2008; Gregor and Matuszek, 2005; Hromada, 2005; Košturiak and Gregor, 1995; Škorík, 2009].

The sphere of creating, modelling and storing 3D digitalised virtual models of real objects is one of the most significant spheres, which are able to radically influence the effectiveness of producers. Research and development in this High-Tech sphere is technically and financially demanding. The most significant automotive and electronics companies are well aware of the constant need to innovate their products, which is why they release a new model every 2-3 months. Innovation can only be successful if it is swiftly put on the market. To fulfil the requirement to shorten the whole production cycle of a product from its design to delivering it to the customer keeping the costs as low as possible is the most important prerequisite of success of every enterprise. The launch of a new product is always connected with the initial chaos, which increases the realisation costs behindhand.

The system for the creation of 3D production layouts and the generation of DMUs of production halls or FMUs is what Digital Factory solutions miss today. It is principally possible to design the DMU of production halls and production layouts using the direct CAD system approach. Such solution is convenient when designing new production systems. However, the more frequent case is that the production halls do already exist. That is the reason why it is often more effective to create production hall DMU using the Reverse Engineering technologies (e.g. 3D laser scanning).

Reverse Engineering is the step needed to take to be able to achieve high efficiency and accuracy of digitization, not only considering the existing equipment, but also when the production layout themselves come into question. It opens up new opportunities to realize virtual designing. Creation of 3D-DMU of large objects using the 3D scanning is, at the moment, the joining link between virtual reality and real virtuality.

Figure 10 shows the new approach to digitizing of real production halls and large objects.
FIGURE 10.
DIGITIZING OF PRODUCTION HALLS THROUGH 3D LASER SCANNING

Source: Authors elaboration.

FIGURE 11.
DIGITAL FACTORY CONCEPT

Source: [Gregor et al., 2006].
The University of Žilina and the University of Bielsko Biała are among the universities using software solutions for Digital Factory in education and research [Gregor et al., 2006]. Booth Universities in co-operation with the Central European Institute of Technology (CEIT) started to build their own Digital Factory concept, whose structure is shown in Figure 11.

The above introduced concept increases the borders of current Digital Factory solutions. It endeavours to integrate activities conducted by designers, technologists, designers of manufacturing systems, planners, etc. It simultaneously tries to increase the offer of individual existing modules. The concept design goes from theoretical studies as well as practical experience gained in industry (VW Slovakia, Whirlpool Slovakia, Thyssen Krupp – PSL, Power Train, Farmet, etc.).

Current research focuses on development of such Digital Factory environment which will enable to develop off line the entire Digital Factory model (e.g., FMU). After validation, such FMU will be on-line transferred to the real factory and used for its management and control.

**DIGITAL FACTORY IN RESEARCH**

The production managers can operate production system either by low throughput times and inventories or by high utilization of capacities. Those control strategies are mutual exclusive [Acél, 1993]. Figure 13 shows the so-called “Production Control Dilemma”.

There exist a plenty of production control strategies focused on the production control dilemma solution. Among them, the most known are [Košturiak and Gregor, 1995]: Material Requirements Planning (MRP), Load Oriented Control (LOC), Drum Buffer Rope (DBR), Constant Work In Process (CONWIP), KANBAN and Input/Output Control. Figure 14 describes the basic principles of the chosen shop floor production control strategies.

**DIGITAL FACTORY SUPPORTS THE CHOICE OF AN APPROPRIATE SHOP FLOOR CONTROL STRATEGY**

Digital Factory model has to integrate buildings, people, technologies, transport, control, energies and energy system, maintenance, etc.
Production Control Dilemma

- Short throughput times
- Low inventory
- Lower WIP
- Targets conflict
- Higher WIP
- High loading

**FIGURE 13. PRODUCTION CONTROL DILEMMA**

*Source: Authors’ elaboration.*

**M/RP - Push Principle**
Permanent high loading of all working stations in the FMS, high utilization, high WIP and throughput times and their variance, complicated scheduling by using priority rules.

**KANBAN - Pull Principle (Toyota Production)**
Consumption oriented production - every consumer (i.e., producer of the next operation) has a possibility to order (by KANBAN card) all the required materials and parts at the right time, in the required quality and quantity. Unnecessary inventories and over-production have not been made.

**CONWIP - COnstant Work-In-Process - Pull Principle (Generalized KANBAN)**
Consumption oriented production - last consumer has a possibility to order (by CONWIP card) the required materials and parts at the right time, in the required quality and quantity. This type of control is generalized KANBAN control.

**LOC - Load Oriented Control (H.P. Wiendahl)**
A production order is not released into the FMS if it exceeds the load limit of a station by at least one of its operations. Load limit limits the total allowed level of the inventories on the working stations and the total level of WIP in the FMS.

**DBR - Drum Buffer Rope (E.M. Goldratt)**
Production order release is controlled by bottlenecks in the production. Every bottleneck station has defined a load limit which determines its high utilization. The bottlenecks limit the system throughput and crucially influence all the system parameters.

**FIGURE 14. SHOP FLOOR PRODUCTION CONTROL STRATEGIES**

*Source: [Gregor et al., 2008].*
Many researchers did research on the area of pull control systems [Sarker and Fitzsimmons, 1989; Wang and Xu, 1997; Košturiak and Gregor, 1995; Wu et al., 1994; Yavuz and Satir, 1995].

The Digital Factory offers the simulation and virtual reality, in general, as the support tools for the analysis of complex systems. The authors developed and validated the procedure for the choice of an appropriate shop floor control strategy for a given production system configuration. This procedure was than applied in a decision making process by the choice of an appropriate production control strategy in industry. Further on, the authors have used metamodelling to simplify the chosen control of the given production system.

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Modelling and simulation have became the decisive analytical tool of the 21. Century. Modelling of large systems such as hierarchical models of entire enterprises requires high computing power which is multiplied by the utilisation of 3D animation with virtual reality features. Simulation is a time consuming technique. The possibility to replace very complicated and complex simulation models by validated metamodells exists and it would fasten the decision making process in industry. Metamodelling offers practical approach to the statistical summarisation of simulation results. It enables a given extrapolations in the framework of simulated conditions borders and the fast approximate manufacturing systems control. The principle of metamodelling is similar to the hierarchical modelling. Figure 15 shows the proposed procedure for the design and validation of metamodells.

The below described manufacturing system metamodell was developed, to be able to achieve a short response in forecasting of manufacturing system behaviour under a given control strategy. Simulation was used for testing the responses of the production system to the proposed changes of chosen control factors. The set of possible control strategies (KANBAN, CONWIP, DBR, LOC and MRP) was tested with using of the proposed metamodell.

Following part, taken from a comprehensive theoretic and applied study conducted in Slovak industry, contains chosen results for CONWIP control strategy.

The number of CONWIP cards directly determines the level of work-in-process (WIP) inventories in the system and so influences the average throughput time (TPT) of production orders and the total throughput of the production system as well. The mathematical relationships and their graphical presentation are shown in table 1, table 2 and figure 16, respectively.
TABLE 1. SUMMARIZATION OF THE SIMULATION RESULTS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
<th>E7</th>
<th>E8</th>
<th>E9</th>
<th>E10</th>
<th>E11</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Conwip Cards (pcs.)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>11</td>
<td>14</td>
<td>17</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>Average throughput time (min.)</td>
<td>61,04</td>
<td>61,27</td>
<td>62,06</td>
<td>64,11</td>
<td>75,87</td>
<td>118,91</td>
<td>158,47</td>
<td>197,42</td>
<td>233,13</td>
<td>268,01</td>
<td>299,26</td>
</tr>
<tr>
<td>Throughput (pcs.)</td>
<td>16</td>
<td>32</td>
<td>47</td>
<td>60</td>
<td>63</td>
<td>63</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>63</td>
<td>64</td>
</tr>
</tbody>
</table>

Source: Authors elaboration.

TABLE 2. RESULTS OF REGRESSION ANALYSIS

<table>
<thead>
<tr>
<th>Type of trend</th>
<th>Trend function</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>$y = 11,734x + 30,209$</td>
<td>0,9899</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>$y = 79,8651 \ln(x) - 6,099$</td>
<td>0,8097</td>
</tr>
<tr>
<td>Exponential</td>
<td>$y = 53,637 e^{0,0825x}$</td>
<td>0,9642</td>
</tr>
<tr>
<td>polynomial II</td>
<td>$y = 0,0767 x^2 + 9,9704 + 35,993$</td>
<td>0,9913</td>
</tr>
<tr>
<td>polynomial III</td>
<td>$y = -0,0277 x^3 + 1,0712 x^2 + 0,5603 x + 54,248$</td>
<td>0,9973</td>
</tr>
<tr>
<td>polynomial IV</td>
<td>$y = 0,0028 x^4 - 0,1603 x^3 + 3,0816 x^2 - 10,028 x + 68,259$</td>
<td>0,9994</td>
</tr>
<tr>
<td>polynomial V</td>
<td>$y = -0,0002 x^5 + 0,014 x^4 - 0,399 x^3 + 5,189 x^2 - 17,241 x + 75,134$</td>
<td>0,9997</td>
</tr>
</tbody>
</table>

Source: Authors elaboration.

Figure 16. Relationship – The Number of CONWIP Cards and the Average Throughput Time

Source: Authors elaboration.

The relationships among control factors and production parameters were described by using of regression analysis. The behaviour of complex manufacturing system using given control strategy was substituted by its simplified mathematical models (metamodells). The statistical validation (fitting of mathematical model to the simulation output data) was tested by $R^2$.

$R^2 = 1 - \frac{SSE}{SST}$, $0 \leq R^2 \leq 1$,

Where $SSE = \sum(Y_i - \bar{Y})^2$ and $SST = \sum(Y_i^2) - \left(\frac{\sum Y_i^2}{n}\right)$.

In figure 17 the comparison of several models with the original simulation data is shown. It is evident that the trends with $R^2$ close to one give the best results.

Figure 17. Comparisson of Chosen Models

Source: Authors elaboration.
The developed metamodel offers possibility to find out quickly and without using simulation the production parameters (e.g. average throughput time, WIP, etc.) by the given combination of input factors (control variables). The mutual comparison of results from simulation and metamodelling shows insignificant difference.

The part of results of the metamodel validation is shown in the Table 3. The designed metamodel is valid on region from one to 22 cards.

In figure 18 the whole region of metamodel validity is shown. The problem started by using the number of cards over 22. The deviation by 30 cards was significant. Validation process showed inappropriateness of using polynomial equation of the 5-degree as a substitution of simulation data for number of cards over 22.

<table>
<thead>
<tr>
<th>Comparison of average TPT</th>
<th>Number of Conwip cards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Simulation</td>
<td>89.52</td>
</tr>
<tr>
<td>Metamodelling</td>
<td>89.20</td>
</tr>
</tbody>
</table>

Source: Authors elaboration.

The results of the study showed the possibility to simplify the decision making process by the control of complex production systems in the framework of Digital Factory environment.

**Conclusions**

The future outlook shows that next generation products can benefit from digital manufacturing. Any type of process elements are stored so that as modifications are made at any stage of product development, they are made to the entire design and manufacturing process.

The University of Žilina, in co-operation with the University of Bielsko-Biała, have long been investing their human and financial resources into obtaining and developing advanced technologies. They have gained extensive experience in application of such technologies as: digitalization, Reverse Engineering, 3D laser scanning, visual data processing, creation of 3D digital models of objects, modelling and simulation of real objects’ properties, creating copies of real object using additive technologies, Rapid Prototyping, Vacuum Casting, simulation of production systems, planning and control of advanced manufacturing systems etc.

The common intention of the above introduced research effort is to establish a fully integrated system for the design of sophisticated products and production systems with its main focus on automotive and electronics industries. Such a system should enable to bring new technologies into industry as well as into education and simultaneously to support the education of future designers, designers of manufacturing systems, technologists and managers.

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