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THE DEVELOPMENT OF DIGITAL FACTORY IN TODAY'S WORLD

Abstract: *Digital manufacturing has been considered, over the last decade, as a highly promising set of technologies for reducing product development times and cost as well as for addressing the need for customization, increased product quality, and faster response to the market. Digital Factory (DF) represents a virtual picture of a real production. It is the environment integrated by computer and information technologies, in which the reality is replaced by virtual computer models. One of very important properties of Digital Factory is the vision to realize process planning and product development with parallel utilisation of common data. It is very important to gain all required data only one time and then to manage them with the uniform data control, so that all software systems will be able to utilize it.*

Keywords: *digital factory, model, simulation, virtual reality, automotive industry*

1. INTRODUCTION

The last decade has brought forth enormous changes in world economy. Markets in industrial countries have reached a level of maturity, where quality, technical superiority and short delivery lead times of products have become mere prerequisites for market success. Companies today can only compete if they offer products and services that meet the customer's individual needs. This has lead to an increasing number of products, product variants and configurations offered. Concepts such as mass customization and individualization promise the creation of unique items for nearly every customer. Decreasing product lifecycles leave only short and transient windows of opportunity for companies to profitably produce and sell a particular product or service using a given value chain. Corporate managements have had to accept the fact that market forecasts have turned more complex and that rapid changes in the marketplace cannot be controlled. At the same time, globalization has intensified the worldwide competition and imposed a permanently growing pressure on production costs. Digital manufacturing would allow for, first, the shortening of development time and cost, second, the integration of knowledge coming from different manufacturing processes and departments, third, the decentralized manufacturing of the increasing variety of parts and products in numerous production sites, and, fourth, the focusing of manufacturing organizations on their core competences, working efficiently with other companies and suppliers, on the basis of effective IT-based cooperative engineering.

2. CONCEPT OF DIGITAL FACTORY (DF) – LITERATURE REVIEW

Kühn [1] uses the VDI definition and describes several DF methods and tools (Figure 1a) such as planning, modeling, production, simulation, and visualization, to support product, process, and factory modeling. These methods and tools share the data in the DF through a consistent data management system. e technical and organizational tools The goal is the holistic planning, evaluation and ongoing improvement of all essential processes and resources of the factory. Zülch [2] defines a DF as a set of comprehensive technical and organizational tools for design, visualization and running of future production system in a digital model. Westkämper and Zahn [3] describe DFs as a development method and a platform that uses centered data and integrates many different tools and concepts. Westkämper and Zahn [3] discuss different modules of DF (figure 1b), e.g.: production, material flow, planning, supplier, product design, etc. as well as their tasks in a DF. Furthermore, they emphasize the significance of DF for factory and production planning. In the research project DiFac (Digital Factory for Human Oriented Production System), Sacco *et al*. [4] describe ergonomics, presence, and collaboration in an industrial virtual environment. Presence contains function components such as training, product development, and factory design.

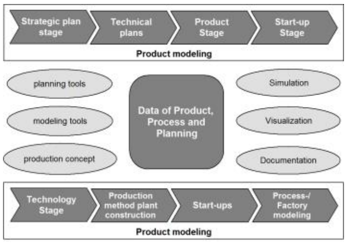

Figure 1a. DF methods and tools [1]

Figure 1b. DF modules [3]

Digital Factory entitles the virtual environment for the lifecycle design of manufacturing processes and manufacturing systems using simulation and virtual reality technologies to optimize performance, productivity, timing, costs and ergonomics [5]. Digital Factory environment uses 3D digital models (DMUs) and associated information for visualizing, modelling, and simulating production processes and production systems with the target of effective and productive real production within resource constraints. It enables to design, analyse and predict the future behaviour of designed production systems supported by computer simulation. Computer simulation plays very important role in the study of behaviour of real and artificial systems, almost in any scientific area [6]. Digital Factory (DF) represents a virtual picture of a real production. It is 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 of factories and to design optimised solutions [7]. One of very important properties of Digital Factory is the vision to realize process planning and product development with parallel utilisation of common data. It is very important to gain all required data only one time and then to manage them with the uniform data control, so that all software systems will be able to utilize it. The integration is one of the main conditions for the implementation of Digital Factory.

Digital Factory integrates three main elements [8]:

- **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.

Digital Factory concept prioritizes the six most significant areas, according to their influence on production process flow. Any area covers the set of tools which all together integrate the whole production process, from product design to its production [9]:

1) **product design systems** (including modelling and simulation)
2) **process planning systems** (process and production plans, assembly plans, welding plans, tools, jigs, work standardization, value analysis, cost analysis, etc.)
3) **production process detail and validation systems** (NC production process simulation, assembly, inspection, maintenance, production operations etc.). The utilisation of process plans, graphs and special BOMs which offer clear view about relationships between processes and resources already in conceptual design phase
4) **production engineering systems** (complex production scenarios, layout, industrial engineering, time analysis, ergonomics analysis, design and analysis of production and assembly systems, loading of machines, determination and optimisation of workers loading, etc.)
5) **production planning and control systems** (ERP planning systems, scheduling, pull control, levelled production, mixed production, etc.)
6) **automation and process control systems** (automatic generation of control programmes for control and monitoring of automated production systems, PLC, industrial robots, etc.)

3. MODELING AND SIMULATION IN DIGITAL FACTORY

Initiated by the increasing computer support in product development, a variety of tools and simulation techniques have been introduced to the domain of production planning throughout the last two decades. With 3D-CAD as one of the main enabling technologies, companies started in the late 1980s to create computer models of entities in their production. Tools like robotic offline-simulation or discrete event simulation provided the possibility to preview and to evaluate dedicated aspects of a production system. Driven by the idea to interlink product development and production planning by means of digital tools and a common data basis, these tools were permanently being enhanced in functionality. Their integration and exchangeability of data became important issues. This way, a diversity of computer aided tools for production planning have evolved throughout the 1990s, nowadays referred to by the commonly known notion of the digital factory. This term comprises not only software tools but also the staff involved and the processes which are necessary for creating the virtual and real production respectively. The digital factory can be seen as a set of methods, tools and user interfaces, whose focus and applicability range from enterprise-wide aspects to plants, production systems and processes [10, 11].

The approaches in this field have reached a level of maturity, where the goal of an integrated, experimental planning, evaluation and controlling of production by means of digital models has become realizable [12]. The idea of the digital factory has become very popular also in industry in the last few years. Considerable effort has been made to implement software and to train people. In particular the OEM in the automotive industry have announced special programs to support the whole process of manufacturing (product development, engineering and production) by dedicated tools of the digital factory.

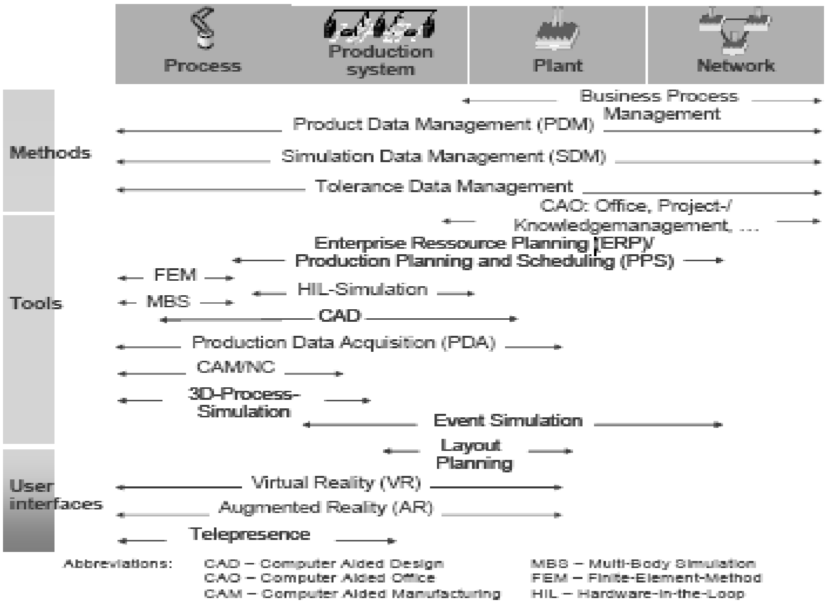

Figure 2. Tools of the Digital Factory

More than one decade ago, the concept of CIM attracted a similar attention. A lot of money was spent without realizing the vision of this concept. Therefore it is legitimate to question the relevance of the digital factory and to analyze its impact on other frameworks which may strengthen the competitive position of manufacturing companies. As described before, changeability is one of those concepts. Technically speaking, today’s PDM and PLM systems mainly focus on the administration of computer files, without, however, having much access to the actual content of these files. Instead, the CAD systems are used for developing product models, since geometry data constitute the major part of the product defining characteristics [13]. On the other hand, PLM systems often include amature collaborative product design domain and aim at encompassing design and management of the manufacturing processes and digital manufacturing, the latter representing a strategic and important milestone in the advancement of PLM. Digital manufacturing has arrived as a technology and discipline within PLM that provides a comprehensive approach for the development, implementation, and validation of all elements of the manufacturing process, which is foreseen by researchers and engineers to be one of the primary competitive differentiators for manufacturers. In today’s state of the art, the PDM and PLM solutions in one of the most complex industrial domains, the automotive industry, use concepts such as the generative template: a solution aiming to reduce design cycle time in several development processes by employing computer models to incorporate component and knowledge rules that reflect design practice and past experience.

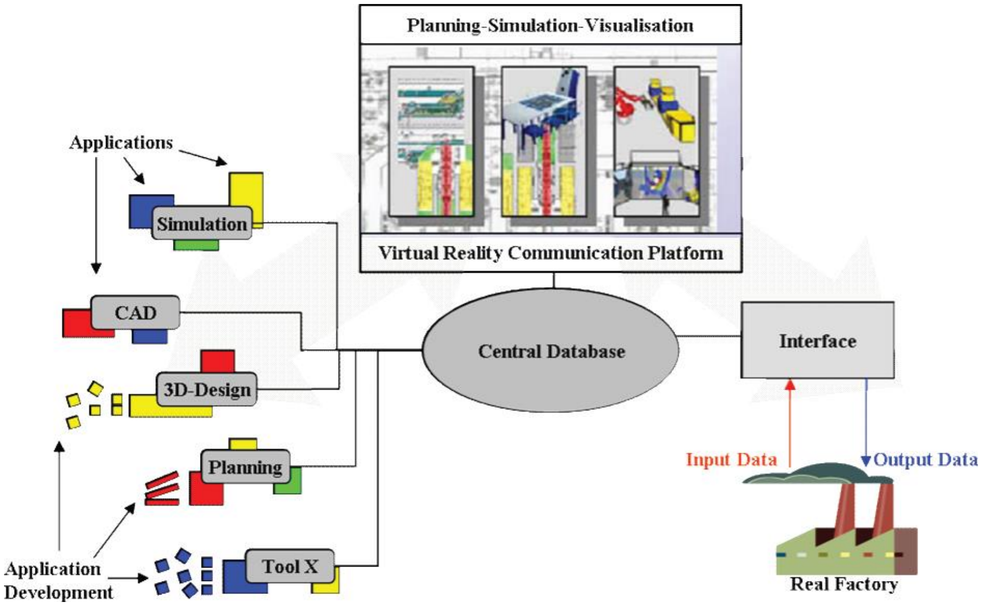

Figure 3. DM links product development, production planning, and facility planning [18]

In the templates, various elements included in product design are combined. The templates are then reused either by the same team, project, or company, or through the extended enterprise by way of exchanges between original equipment manufacturers (OEM) and suppliers. This components-based approach accelerates and simplifies the design. More importantly, embedded systems and small-footprint industrialstrength operating systems will gradually change the prevailing architecture, by merging robust hardware with open control. Integration of control systems with CAD and CAM and scheduling systems as well as real-time control, based on the distributed networking between sensors and control devices [14] currently constitute key research topics. For instance, [15] developed a methodology of compensating for machining errors aimed at maximizing conformance to tolerance specifications before the final cuts are made. While factory digital mock-up (DMU) software allows manufacturing engineers to visualize the production process via a computer, which allows for an overview of the factory operations for a particular manufacturing job, the discrete event simulation (DES) helps engineers to focus closely on each individual operation. DES may help decision making in the early phases (conceptual design and prestudy) on evaluating and improving several aspects of the assembly process such as location and size of theinventory buffers, the evaluation of a change in product volume or mix, and throughput analysis [16]. Recent developments in digital manufacturing may be categorized into two major groups. The developments of the first group have followed a bottom-up approach considering digital manufacturing, and extending its concepts, within a wider framework, e.g. the digital factory or enterprise. The developments of the second group have followed a topdown approach considering the technologies in support of individual aspects of digital manufacturing, e.g. e-collaboration and simulation. According to the Verein Deutscher Ingenieure [17], the digital factory includes models, methods, and tools for the sustainable support of factory planning and factory operations. It includes processes based on linked digital models connected with the product model. At a theoretical level, several researchers have contributed to the definition of the digital factory vision and suggested how this vision could be implemented in reality (Figure 3). Data and models integration has been a core research activity to support implementation. The introduction of consistent data structures for improving the integration of digital product design and assembly planning and consequently supporting a continuous data exchange has been investigated in the literature [18]. Similar activities have focused on the definition of semantic correlations between the models distributed as well as the associated databases and the introduction of appropriate modelling conventions [19]. On top of these developments, a number of methodologies for computer-supported co-operative development engineering, within a digital factory framework, have been published. Some researchers further suggested software architectures for relationship management and the secure exchange of data [20].

4. THE VIRTUAL REALITY IN DIGITAL FACTORY

An extension to simulation technology the virtual reality (VR) technology has enabled engineers to become immersed in virtual models and to interact with them. Activities supported by VR involve factory layout, planning, operation training, testing, and process control and validation [21, 22]. The new concept of digital enterprise technology (DET) has also been recently introduced as the collection of systems and methods for the digital modelling of the global product development andrealization process in the context of life-cycle management [23]. As such, it embodies the technological means of applying digital manufacturing to the distributed manufacturing enterprise. DET is implemented by a synthesis of technologies and the systems of five main technical areas, the DET cornerstones, corresponding to the design of product, process, factory, technologies for ensuring the conformance of the digital environment with the real one, and the design of the enterprise. On the basis of the DET framework, a new methodology has been suggested that focuses on developing novel methods and tools for aggregate modelling, knowledge management, and test on validation planning to bridge the gap that exists between conceptual product design and the organization of the corresponding manufacturing and business operations (Figure 4) [24]. The advances in DMU simulation technologies during the 1990s were the key stone for the emergence of VR and human simulation in digital manufacturing. These advances have led to new frameworks that integrate product, process, resource, knowledge, and simulation models within the DMU environment [25]. The VR technology has recently gained major interest and has been applied to several fields related to digital manufacturing research and development. Virtual manufacturing is one of the first fields that attracted researchers interest. A number of VR-based environments have been demonstrated, providing desktop and/or immersive functionality for process analysis and training in such processes as machining, assembly, and welding [22, 25]. Virtual assembly simulation systems focusing on digital shipbuilding and marine industries, incorporating advanced simulation functionalities (crane operability, block erection simulation in virtual dock, etc.) have also been introduced by Kim *et al*. [26]. Human motion simulation for integrating human aspects in simulation environments has been another key field of interest (Figure 5). Several methodologies for modelling the motion of digital mannequins, on the basis of real human data, have been presented. Furthermore, analysing the motion with respect to several ergonomic aspects, such as discomfort, have been reported [28, 30, 31]. Collaborative design in digital environments is another emerging research and development field. The development of shared virtual environments has enabled dispersed actors to share and visualize data, to interact realistically, as well as to make decisions in the context of product and process design activities over the web [29]. Accessible Information Technology (AIT) Initiative and its offspring projects launched during the 1990s by the automotive and aerospace industry in Europe have been pioneering in driving digital manufacturing advances, aiming at increasing the competitiveness of industry through the use of advanced information technology in design and manufacturing [32]. On that basis, the automotive industry still drives today a number of relevant developments in digital manufacturing. In BMW, the three series at Leipzig has been BMW's best launch ever, as they achieved 50 percent fewer faults per vehicle and have recorded far better process capability measures than in the past because of the use of the simulation of production processes at a very early stage of design [33]. Similarly, General Motors has utilized a threedimensional workcell simulation (iGRIP) provided by digital enterprise lean manufacturing interactive application (DELMIA), allowing the engineers to generate threedimensional simulations and to translate models created in other commercially available packages. During 2002, Opel utilized DELMIA for the simulation of the production process of its Vectra model allowing for a very fast production launch [34]. Finally, computer-aided three-dimensional interactive application (CATIA) machining simulation tools have given manufacturing experts at Daimler a chance to test virtually the choreography for the production of parts, ensuring that the finished product will meet precise design expectations. At Volvo, DES has been used as a tool for continuous process verification in industrial system development [35]. BMW and Daimler Chrysler are also among the users of similar applications [36]. General Motors has used DES in several case studies and has demonstrated the ability of using simulation for optimizing resources and identifying constraints [37]. Ford has also been using computer simulation, in some form or other, for designing and operating its engine manufacturing facilities since the mid-1980s. Case studies in advanced manufacturing engineering for a powertrain at Daimler Chrysler, have identified virtual modelling as an emerging technology for automotive process planners [38].

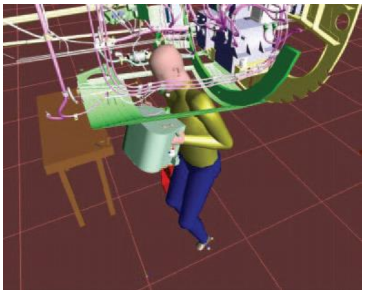

Figure 4. Human simulation in DM environments

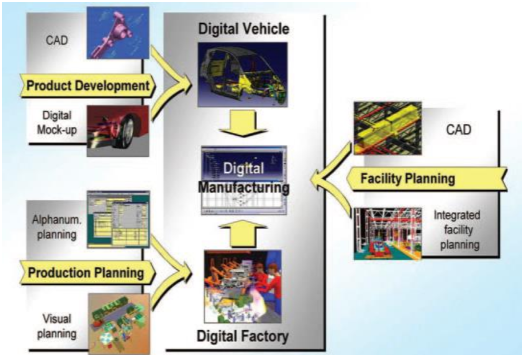

Figure 5. Digital manufacturing links product development, production planning and facility planning

The method of digital planning validation (DPV) has recently gained some interest (Figure 5) [39]. Based on a validation process running in parallel to that of digital planning, the DPV method developed by Daimler Chrysler consists of both the continuous checking of digital planning results as well as the process reviews at certain points in time, the so-called process days. During the process days, the current planning states are validated through geometrical checks of the assemblies, the simulation of processes, or detailed examinations of layouts. The DPV method is based on the DMU techniques and simulation. In analogy to the product, DMU for the product development, can be regarded as a kind of process DMU of production planning within the digital factory. The so-called virtual process week is another relevant method applied to BMW working practices [40]. This method addresses the assessment of the assembly planning by a group of people responsible for the process. Based on the product structure, visualization scenes are created. By using the group function of visualization the system parts are shown subsequently according to the assembly plan. The participants use eight criteria to assess the operation. All results are documented in a database online. In the end, statistical evaluations of the database show where operations have to be clarified in more detail, or where the geometry of parts will have to be changed because of bottlenecks during the online operation. New methods and technologies for virtual assembly in the digital factory have been investigated by Volvo, Daimler Chrysler, Fiat, and Ford in the context of the Eu Integrated Project „MyCar“, driven by Volvo and Laboratory for Manufacturing Systems and Automation, University of Patras [41]. The OEMs are seeking novel approaches to achieving an improvement in the data communication and to providing a foundational IT CAx architecture that enables the various tools to interoperate seamlessly and the processes to be managed efficiently. Digital validation of production of body-in-white and assembly as well as simulation for virtual **ramp-up** of production cells and lines, including virtual commissioning, are investigated. The human simulation of manual, automated, and mixed processes for improving the consideration of human factors is another topic of major research. Nevertheless, digital manufacturing needs to be further exploited in order to close the gap between the product definition (configuration of components and required manufacturing processes) and the actual manufacturing production activities within the enterprise [42]. Simulation and VR can now be used in order to significantly reduce costs and time to market. Manufacturing is only 30 per cent of the product development cost but the remaining 70 per cent is locked during the design phase of new product development. Based on responses from industry, Dalton-Taggart [43] defined digital manufacturing as ‘the ability to describe every aspect of the design-to-manufacture process digitally – using tools that include digital design, CAD, office documents, PLM systems, analysis software, simulation, CAM software, and so on’. The concept is that the passage of data from one department or discipline to another should be seamless so that the data created are immediately reusable in a different discipline. Several benefits can then be derived. By exploiting digital manufacturing, manufacturing enterprises expect to achieve the following [42]:

- Shortened product development.
- Early validation of manufacturing processes.
- Faster production ramp-up.
- Faster time to market.
- Reduced manufacturing costs.
- Improved product quality.
- Enhanced product knowledge dissemination.

- Reduction in errors.
- Increase in flexibility.

The industries that benefit the most from utilizing these methodologies are those with capital-intensive manufacturing and those with very complex products but very low production, even single-unit production. For the capital intensive manufacturers, the return of investment is calculated on the basis of the decrease in the time to market by 30–50 per cent, due to efficient concurrent engineering, reducing the product cost by 10–25 per cent through multiple iterations of design for manufacturing and design for assembly, and reducing the costly engineering changes to product design and production tooling, during launch, by 80–90 per cent [44]. Organizational issues including technical teams and efficient product change management constitute an important challenge, which has already started to be investigated [45]. Enterprises already exploiting these benefits are showing great potential for future growth. Daimler Chrysler, General Motors, Boeing, and Lockheed Martin have publicly declared that digital technologies have saved them millions of dollars in just a few years. Similar savings have been realized in the semiconductor industry [44]. Further research effort is, however, required to be able to simulate the assembly process fully and to avoid costly installations and lengthy start-up periods. This is because digital simulation and planning of assembly processes are based on various enabling technologies such as immersive VR, collaborative virtual design and digital human simulation for manual assembly system, and ergonomic assessment. In digital manufacturing, the ambiguity of tacit knowledge in manufacturing should be eliminated thoroughly, and the tacit knowledge should be transformed into tangible knowledge, namely numerical values and/or equations and finally into digital values. This is expected to minimize the production performance diversities frequently observed between globally distributed production sites of extended enterprises.

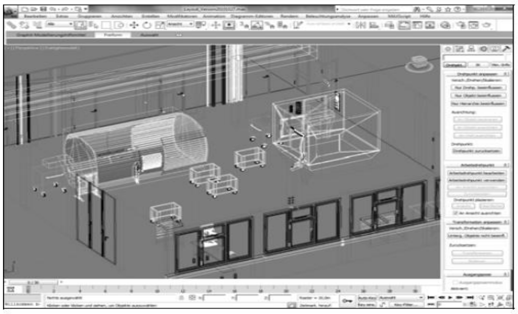

Figure 6. and 7. Geometric modeling of digital factory

5. THE REAL EXAMPLES OF DIGITAL FACTORY

The European researchers consider the future factories as products. These products are socio-economic systems, and are very difficult to design and to run and that is why a special attention to their development has to be paid. The competitiveness in future production will be provided by such production systems in particular. The effort of current research in Europe is focused into design of highly productive, flexible, effective and safe factories. To fulfil all above mentioned requirements the designers of future factories will have to apply quite new approaches and techniques e.g. Digital Factory concept. Therefore it is the goal of EU researchers to develop visionary approaches of organizing and realizing the future production. Any change, even the smallest one, brings risk. The change has to be realised by real people who make mistakes. 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 has started to build such complex Digital Factory system. The Digital Factory system utilises 3D digital models of real objects. DMUs (Digital Mock Ups) 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. The 3D virtual models of production halls were developed using 3D laser scanning (Faro LS 880 HE) and modelling in Bentley HLS. The following example shows the result of production halls DMUs development through 3D laser scanning and modelling, including detailed energy networks and transportation systems (Figure 8).

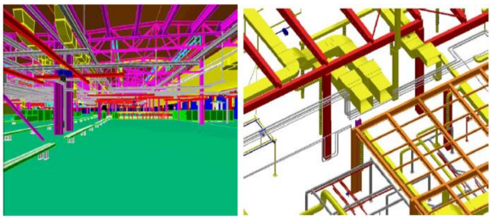

Figure 8. DMU model VW Slovakia

Figure 9. FMU model Thyssen Krupp PSL factory

The designer of manufacturing systems can use the existing 2D production hall model and to develop new 3D digital model in CAD system. It is often advantageous to generate the 3D model on the basis of existing 2D model platform. A comprehensive research was done, in co-operation with Thyssen Krupp – PSL, in which the complex digital cycle was conducted. After 3D model of production hall was developed in Bentley HLS system, based on 3D laser scans, all objects (e.g. production hall, machine tools, handling devices, etc.) were integrated into 3D model and through this approach the comprehensive DMU was developed. Then the new assembly concept with optimized material flow was developed. Consequently 3D simulation model of complex production system was developed and used by optimization of control of the designed production system. The final solution represents a comprehensive model and the research on this area continues. Figure 9 shows the part of FMU of Thyssen Krupp – PSL factory.

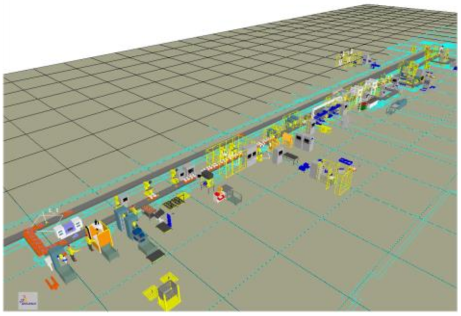

Figure 10. FMU line VW Slovakia

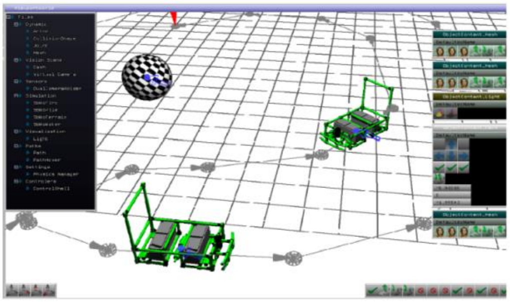

Figure 11. ELLA simulation platform

The design of workplaces was especially checked by ergonomics analysis whereas manikin concept of Delmia V5 Human was used. The final solution of designed workplaces was tested through the static simulation/animation (figure 10.). 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. 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 VW assembly line. The final solution is shown in Figure 10. Central European Institute of Technology (CEIT) has long time been developing the simulation-emulation software platform ELLA, based on digital models of control system hardware and software elements supported by virtual reality environment. ELLA consists of many subsystems, e.g.: monitoring and control system WATCH for mobile vehicles control, modular production system, pattern recognition subsystem, quality control system with laser measurement and control units, etc.

Figure 11 shows the framework of ELLA simulation & emulation environment. Material transportation and handling system belongs among the most decisive parts of effective production systems. Future production systems will require Intelligent Automatic Handling System (IAHS) equipped with industrial robots, autonomous mobile robotic systems, etc. Recent development on this area showed the growing interest in AGVs (Automated Guided Vehicles). There exists a plenty of solutions for automatic transportation and handling of material in production, e.g.: inductive AGVs, through magnetic type controlled AGVs, radio frequency controlled AGVs, mechanically (hanged systems) controlled AGVs, AGVs with artificial intelligent control, etc. CEIT has developed the platform of low cost AGV solutions for automotive and electronics industries which has been successfully implemented in VW and is currently in testing phase in Continental and Whirlpool factories. The robotic platform control system was fully developed and tested in ELLA environment. The basic principle of simulation resides in a simplified representation of a real (conceptual) system, which we are interested in (simulation target). The analyst does, after verification and validation of a simulation model, a set of simulation experiments. The experimentation with simulation model, aided by a computer, allows examining the variants of system's behaviour in a longer time period and in assumed conditions. New knowledge gained through such simulation experimenting is used for the optimization of a real (conceptual) system.

Figures 12. and 13. Models of digital factory

Figures 14. DMU model in CAVE environment

6. CONCLUSION

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 global business environment requires high flexibility of advanced manufacturing systems. Future manufacturing systems will be designed with new approach using simulation and emulation in the framework of Digital Factory. Such solution will enable designers to develop manufacturing systems which will be able to work effectively during their lifecycle. Such system should enable to bring new technologies into industry as well as into education. This solution will support the education of future designers, designers of manufacturing systems, technologists and managers. Digital manufacturing incorporates technologies for the virtual representation of factories, buildings, resources, machine systems equipment, labour staff and their skills, as well as for the closer integration of product and process development through modelling and simulation. Closing the gap between the product definition and the actual manufacturing production activities within the enterprise, fully transforming tacit manufacturing knowledge into tangible, and, finally, digital knowledge, optimizing data management, and developing standard models are some key priorities.

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