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VIRTUAL ENGINEERING: PRINCIPLES, METHODS AND APPLICATIONS

J. G. Ovtcharova

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1. Introduction

Current industrial development is challenged by a growing complexity of product and process requirements, while drastically reducing time-to-market is viewed as one of the key competitive factors. Recently, strategies are being established to significantly improve the overall development process using less testing on physical builds in favour of various assembly checks, diagnosis, simulation, and risk analysis on digital models. Despite successful practice of *digital engineering*, there is evidence that putting advanced IT systems into development processes cannot in itself lead to a real "quantum" change to manage complexity and to achieve a decisively new level of process performance. As "the significant problems we face cannot be solved at the same level of thinking we were at when we created them" (Albert Einstein), a new engineering methodology is required comprising significant technological and business improvements in products, processes and services. This leads to the idea of *virtual engineering*, which refers to a range of scientific, technological, organisational and business activities using advanced information and communication methods and tools with major focus on process and systems integration, immersive visualisation and "human-machine-human" interaction. In particular, virtual engineering means that design and validation activities occur collaboratively in order to prove early product designs, support decision making and enable continuous product optimisation within interdisciplinary and cross-enterpise partnerships.

This causes an important redefinition of the overall product development process for supporting the coordination, assessment and concretion of engineering results of all involved partners with the support of virtual builds. The views of virtual engineering are integration of powerful information systems and tools within different tasks, from data generation and management to data sharing and communication (system view), network of processes and activities through the entire product lifecycle enabling continuous product validation and optimisation (process view).

Although there is still a big amount of research and development work to be done, industrial development is already making use of recent achievements in systems engineering, product lifecycle management, virtual reality technologies, as well as findings regarding cross-enterprise and cross-cultural communication in order to realise benefits of virtual engineering in short term and to position itself to extend these benefits in near future.

This paper outlines the scope and objectives of virtual engineering, and introduces a methodology based on an iterative process definition and an integrated process and IT-system platform. The underlying iterative process is divided into six steps - definition, creation, analysis, virtualisation, validation and tracking - which, while significant in their own right, are part of a collaborative learning cycle, adding value to every step of the development process. The paper is organized as follows: Section 2 and 3 outline the problem definition and the methodology of virtual engineering. In Section 4, a main concept is outlined. Section 5 summarizes the key innovations and advantages of virtual engineering.

2. Problem definition

Radical advances in development and manufacturing of industrial products have been igniting efficiency explosions ever since Adam Smith introduced the division and specialization of labour, followed by Eli Whitney's idea of producing standardized and interchangeable machine parts and after Thomas Edison's idea of performing product development by a dedicated research and development group. These "quantum" breakthroughs are all examples of industrial processes which pushed industry to a new life competition leap. Even more recent quantum improvements of this nature have included the advent of *Computer Aided (CAx)* and *web-based* technologies, as well as of *Virtual Reality (VR).*

According to the representation of an innovation lifecycle, the radical process improvement is by nature almost "S"-shaped as shown in Figure 1, where the performance development of digital and virtual engineering are visualised by transition process curves. When a new methodology (in this case, virtual engineering) is initially implemented, performance improves slowly first, since there is a need of new engineering methods and tools causing an inertia (confusion, resistance, and a learning curve to surmount). After measurable success and increase of maturity, performance accelerates rapidly as the new methodology gains momentum, generates irrefutable results, adds value, and becomes widely adopted. This new methodology creates then an entirely new process performance curve that is discontinuous from the current one (in this case, digital engineering). It will use an entirely different methodological approach executing new business processes within entirely different organisational structures.

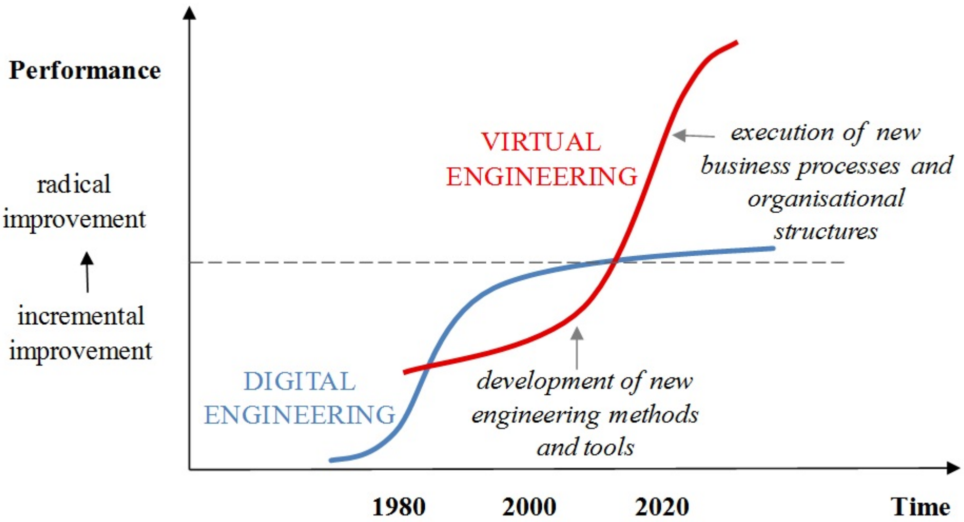

Figure 1. Transition process curve

The use of digital engineering is by now 2010 on the verge of a process curve as shown in Figure 1. It is time for a new radical change because of several reasons. *One of the main challenges* of staying competitive today is compounded by the globalisation and the *rapid change of knowledge and technology generations* occurring every 3–5 years in many fields, such as software engineering, electronics and telecommunication. This time period is usually shorter than the technology adoption into the business processes, which requires scalable, fast and easy to use tools, as well as teams networking and communication of knowledge from the beginning.

Looking in particular on the use of advanced *VR technology* for engineering, it is somehow limited to very specific tasks in the product development, supported as mostly as an advanced feature of various CAx systems. However, it is typically used as a visualisation technology for design reviews or visibility simulations. In the more recent years, the interactive options of VR technology have also been discovered for special tasks like functional simulations or immersive surface design. Several tools integrate VR into the context of the Digital Mock-Up for cabling, functional and ergonomic simulation. Moreover, current research in the field of VR is either directed to simply extend its applicability for various domains or to adapt the conceptual and technology basis to better exploit the options present today like increasing computing and graphics power, GRID computing, multi-modal interaction and so forth. Although there is a visible trend towards framework-based and component-based VR solutions for engineering, there is still a lack in at least two dimensions: *first*, with respect to technical concepts and interfaces for the integration of such solutions with specific IT and process infrastructures, and *second*, with respect to the methodological approach how to select the right technological option for a specific set of tasks in a given context.

Other main challenge for a transition towards virtual engineering is that an industrial product today has transformed from being just a means for fulfilling some function to something that can provide *customer* with options for enhanced comfort, emotional link, entertain
ment, and a mobility, etc. And, customer loyalty is quickly becoming elusive for most of the manufacturers as they can now gain or lose customers in the short term. Growing diversity of needs and wishes, higher subjective perception, increasing enthusiasm and emotional link as well as a stronger personal motivation for buying and using products are demanding superior quality products that meet specific, often unique, customer requirements. In this context, the optimization of development process up to serial production requires amongst others an early support of product review and validation as well as an integration of customer feedback.

3. Methodology

As far as the virtual engineering addresses complex engineering development topics with their interdependencies and interrelations, the consideration of the *entire product life cycle* gains more and more importance for the operational day-to-day business (Figure 2). Consequently, the overall mission of virtual engineering is the *early, continuous, networked (process view) and integrated (system view) support* of the entire product life cycle concerning collaboration, assessment, concretion and validation of products and processes with participation of all partners using virtual builds.

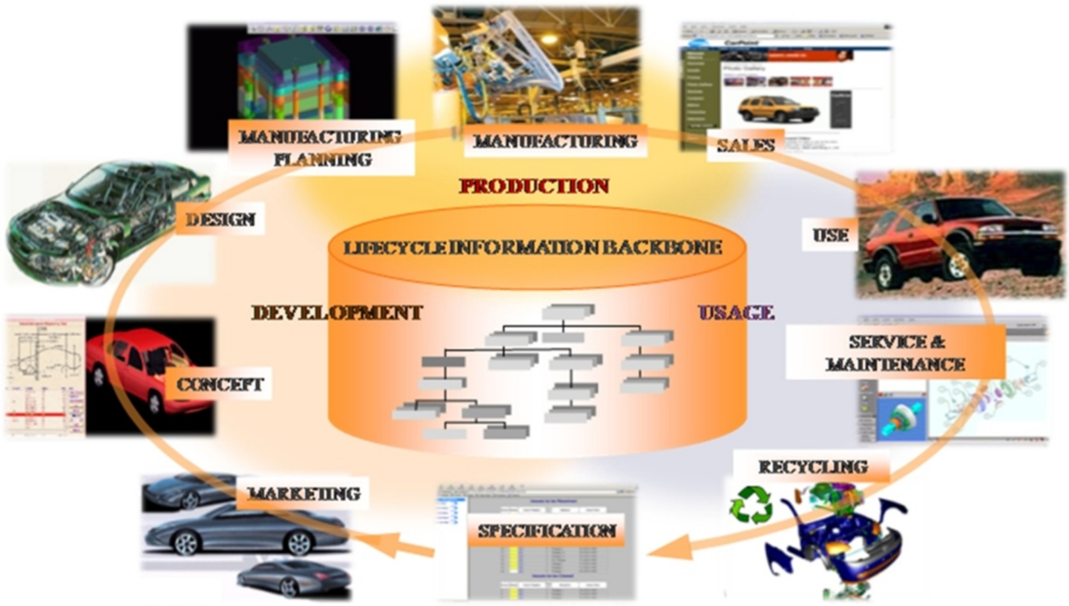

Figure 2. Product lifecycle focus (according to automotive engineering)

The subject of virtual engineering not only affects processes on the operative level of product development but also aspects of early corporate and strategic development. In particular, the goal is to achieve a significant reduction of product development time through early completion of the product concept by means of *collaborative "design-build-test" activities* and early allocation of resources. Looking closely at early product development, the key problem to be solved lies in the early uncertainty resolution (Figure 3). The more uncertain the upstream activities, the more engineering changes will occur during the development. As well-known, engineering changes become more difficult to implement the later they occur, as it takes more time to adjust work by other activities that are done concurrently. Where uncertainty originates (e.g., rapidly changing market requirements, insufficient definition of early development phases, inadequate organizational capabilities, lack of appropriate information management and decision support tools, etc.) and how it can be estimated is still a subject for future research. In an industrial context however, early uncertainty resolution is recognized as a *collaborative learning activity*, characterized by various "design-build-test" loops and a highly iterative process which relies on experiencing product development performance and quality based on validation.

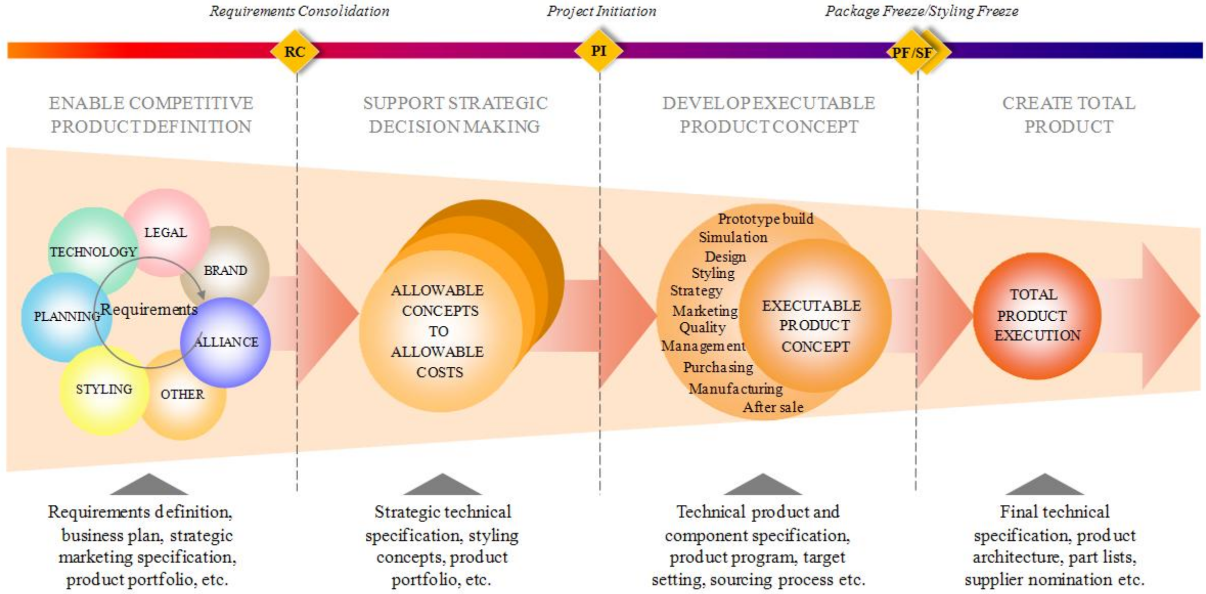

Figure 3. Early product development phases (according to automotive engineering)

In particular, virtual engineering in the early product development means learning how fast sufficient knowledge about the product can be accumulated in order to put it into a final product design. The current design and engineering praxis involves the *extensive use of digital models*, which are helpful, but not particularly efficient for testing and learning. After building digital models, problems are identified and fixed allowing the continue climbing of the knowledge curve. However, a test-based problem-solving creates large, time-consuming loops of remediation, as problems are successively and disruptively analysed, investigated, and then solved. This process, which progresses from the early prototypes through product validation builds, results in a product development path that doesn't follow the ideal time-and-cumulative-knowledge path toward product completion (Figure 4).

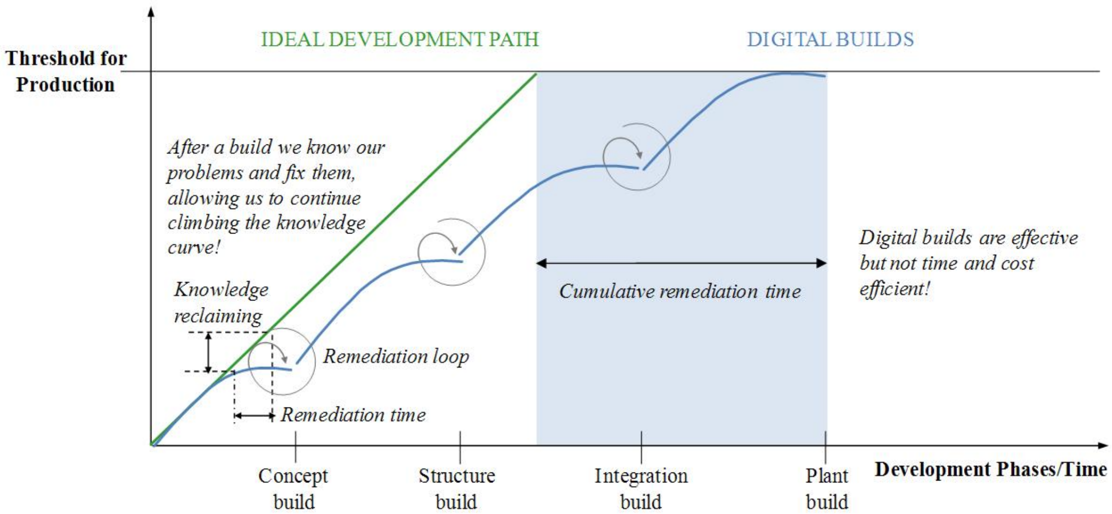

Figure 4. "Design-build-test" with digital engineering (according to automotive engineering)

The *use of virtual builds*, however, promises to significantly shorten product development time. Because the virtual build and validation processes occur concurrently, the number of learning circles is higher but the learning time is significantly shorter. As a result, the product development path is optimised, the cumulative remediation time is reduced, and there is the potential to save a substantial amount of development time and costs from the final outcome (Figure 5). Furthermore, the use of virtual reality as visualisation and validation environment allows developers, suppliers, manufacturers, and customers alike to virtually handle the future product from its specification to service and to realistically assess it with regard to features and performance.

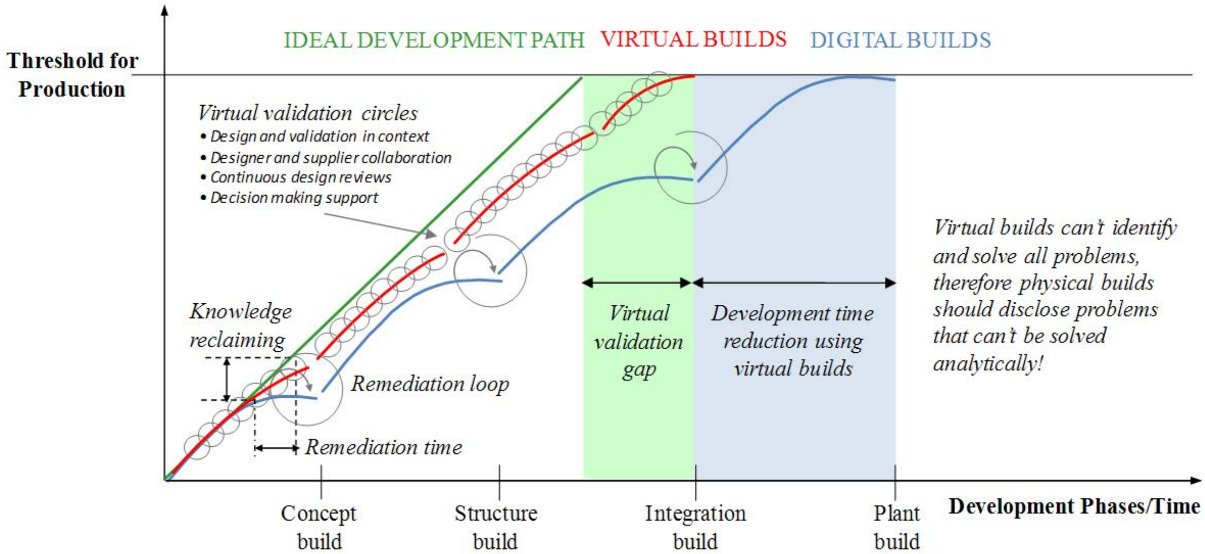

Figure 5. "Design-build-test" with virtual engineering (according to automotive engineering)

Despite some success stories in using virtual builds and validations concurrently, there is recent evidence that simply overlapping activities can lead to additional expenses of development rework. Such rework may outweigh the benefits of parallel task execution. Therefore, in making its transition to virtual engineering, a concept is proposed that avoids the trade off by focusing on two major issues: *first,* iterative process definition divided into six main steps (definition, creation, analysis, virtualisation, validation and feedback) as parts of a collaborative learning cycle, and *second*, integrated process and IT-system support for data generation, data management, engineering operations, organisation and cross-enterprise collaboration.

4. Concept Outline

The *first crucial step* in implementing virtual engineering is the iterative process definition. The following interdependent sub-processes build an iterative loop, as shown in Figure 6:

- DEFINITION**.** At the beginning of each project a global (master) product structure is available for supporting design and validation activities for all product variants through all building phases.
- CREATION. Designing in the context of a product family requires the ability to easy create or modify parts linked into virtual assembly of any specific product variant. Primary input for this sub-process is the list of work parts, product year and family, product development stage and purpose of the design session (resulting in a revision rule), the product configuration, options, variant rules and filtering for those parts that are of interest, kept in the master product structure.
- ANALYSIS. On the basis of part models, specific tests are performed using geometric analysis, topology optimizations, kinematic and dynamic multi-body simulations, as well as elasticity and deformation analyses. Because of the high data complexity usually a limited number of parts and components can be digitally tested.

- VIRTUALISATION. In this sub-process, high-end visualisation of the parts of interest after specific product configuration is generated. The users are all working in the same context and collaboration is essentially instantaneous. They easily use visualisation tools to verify if certain changes are feasible. (Note that "high-end visualisation" means immersive projection, e.g., for VR, enabling real time interaction with large data sets, e.g., full virtual builds. It is suitable for supporting working sessions of large development teams.)
- VALIDATION: There are several functions for virtual analysis, such as clearance and collision detection, assembly check, check for serviceability, kinematics and dynamics checks, as well as accessibility (e.g. for assembling in the production) and ergonomic verifications.
- FEEDBACK: The feedback sub-process supports different tracking scenarios including team reviews, conferencing with suppliers as well as management reviews. Based on the results of the design reviews, the user may need to select a new design context and visualize it (new visualization) or to update, add, replace, or remove components, thus generating a new product version (new configuration and update).

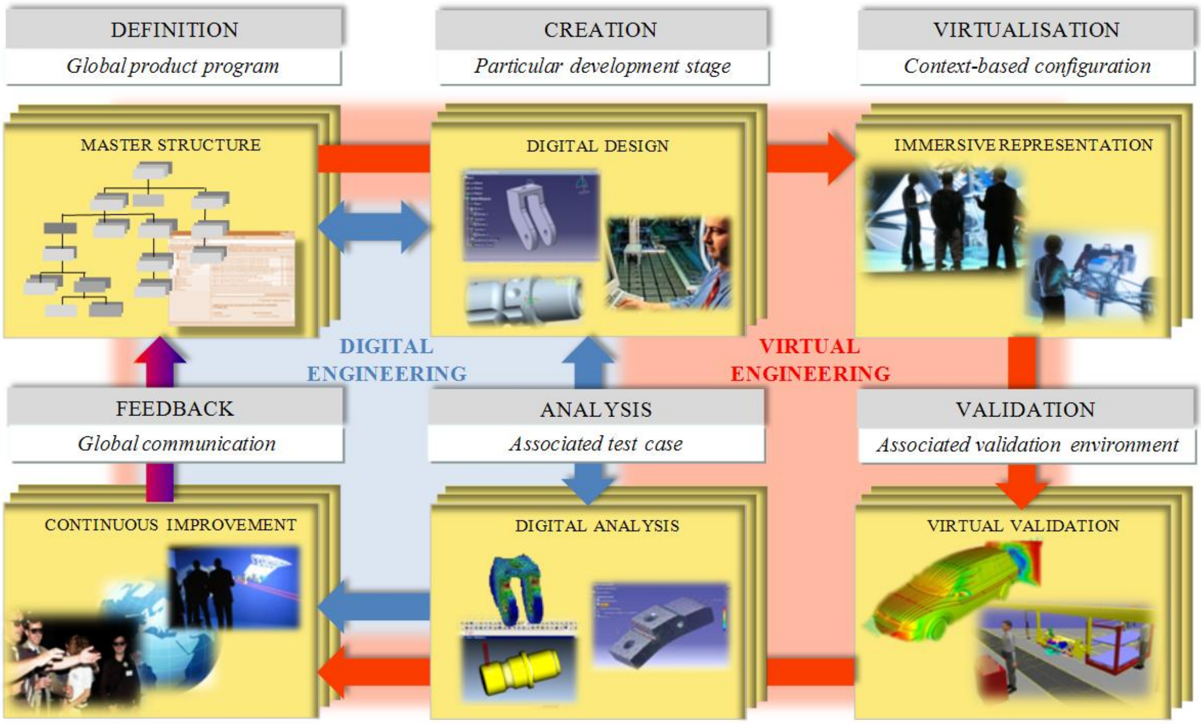

Figure 6. Overview of the iterative process definition

The *second crucial step* in implementing virtual engineering is the integrated process and IT-system support. The following building blocks are necessary and sufficient as shown in Figure 7:

- DATA GENERATION. The product data, generated in different formats are continuously used for further development, simulation, visualization and validation. Product data generated at this level are usually stored locally.
- DATA MANAGEMENT. The structured and consistent management of product data concerning development, as well as enterprise resource planning, supply chain and customer relationships is the basis for efficient data integration between different phases of the product development process as well as data exchange between different organizations. The main functions of data management are amongst other change management, configuration management, enterprise wide document management, product structure management, etc.

- ENGINEERING OPERATION. Engineering operations require data integration corresponding to particular engineering tasks, fulfilling preconditions such as the use of modular and standardized software packages, and the automated (bi-directional) interfaces between software packages for fast and complete data exchange using web-based services, etc.
- ENGINEERING ORGANISATION. The engineering organisations are intended to support dynamic product adjustments, quantitative and qualitative resource distribution and management, variable workflows, rules and guidelines, changes of objectives and deadlines throughout the course of the projects, as well as distributed project knowledge. Resulting requirements for virtual engineering are establishment and support of a process network, assurance that all processes and project relevant information are up to date, introduction of a goal and deliverable planning of processes, management of working (incomplete, fuzzy) process and project information, as well as a methodological support of process and project documentation. The virtual engineering supports the process network through establishment of virtual teams using e-collaboration, transition from predefined to dynamic workflows, integrated engineering workflow management, web-based project management, focus on a product maturity instead of milestone-based project progression and validation-driven development process using immersive visualisation for better understanding of interrelationships of results and boundary conditions.
- ENGINEERING COLLABORATION. The focus of this building block is the adaptation of a process network to different projects and tasks, and the communication of results in different access profiles (planner, designer, project manager, etc.) for specific activities, for example distributed project management, dynamic access profile adaptation, etc. In particular, engineering portals (project portals, team portals, business portals, etc.) assure co-operation within and between OEMs and suppliers early, improve communication between OEMs and customers, integrate the knowledge of a continuously growing number of external experts, establish global engineering networks, manage complexity in global projects, etc.

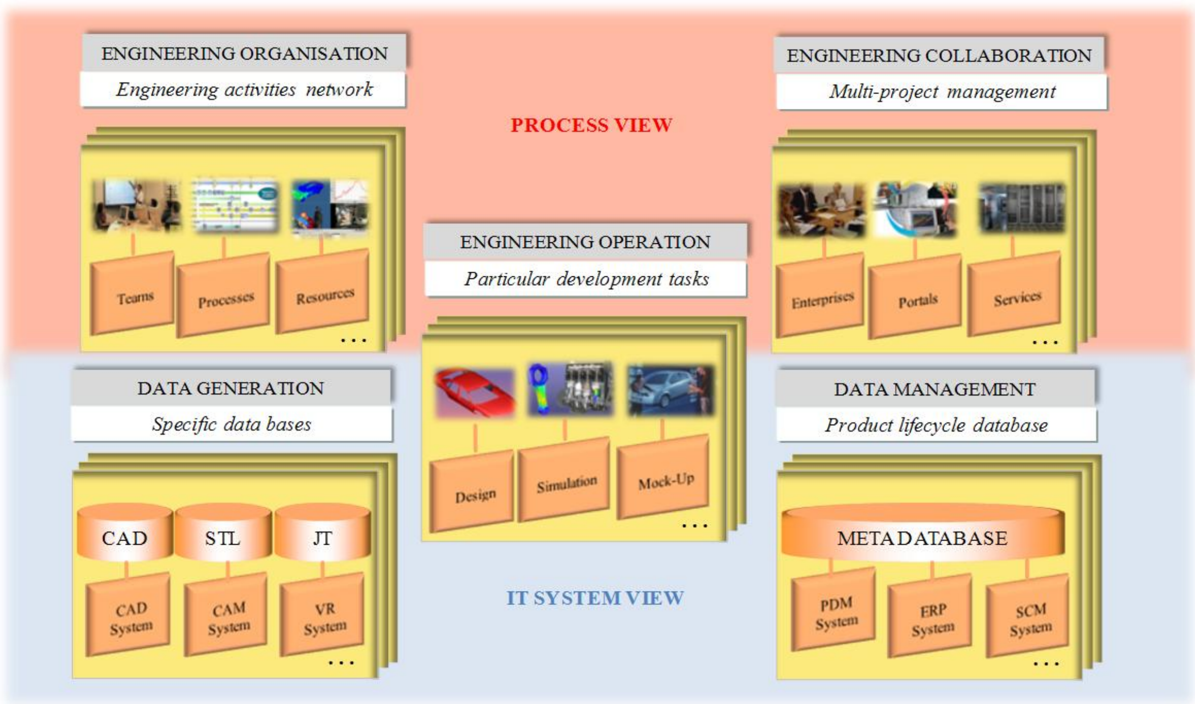

Figure 7. IT-system und process view

5. Conclusion

This paper outlined shortly the scope and objectives of virtual engineering, and introduced a methodology based on an iterative process definition and an integrated process and IT-system environment. The key innovations and benefits of the outlined approach can be summarized as follows:

- Correct assembly & parts are persistently available through product data management from the beginning, eliminating "data shopping", as well as consistent "design in context" capability.
- Design context configuration, enabling an easy background configuration while eliminating the build and maintenance of design assemblies. Repeatable way to configure revision and variant context while minimizing the amount of data that needs to be loaded to the CAD and VR systems.
- Quickly view of configured parts, components and product builds through easy manipulation of small and large assemblies and no preparation work for visualisation.
- Staging time to produce configured, correctly positioned, and visual models practically eliminated: opportunity to execute very short problem identification, solving & decision loops. Discrete design reviews no longer require long stating events, move from a detect error to a prevent error.

The savings using virtual engineering are result from a shorter development time through the elimination of data shopping and the elimination (through prevention and detection) of errors. All background data is present in everyone's session without the need to build up an individual design environment.

The *potential business impact* of virtual engineering consists of visibility of the up-front validation process, development of complete product and sub-systems rather than just component parts, management of overall product data eliminating data shopping, design in product context and in quality from the beginning, significant reduction of assembly errors and increased re-use of common component, automate design reviews as well as a fast product development.

Future development in virtual engineering focuses, among others, on providing seamless, transparent and intuitive interfaces between users and VR environments. The interfaces should follow human cognitive processes as well as natural interaction methodologies and allow engineering users to focus on their specific task. As a result, any incorporation to the machine interface should be minimized or even be made obsolete. As such, natural and intuitive human mindset and behavior should be assigned to the interaction within a virtual engineering environment.

Prof. Dr. Dr.-Ing. Jivka Ovtcharova
Head of Institute
Karlsruhe Institute of Technology (KIT)
Institute for information Management in Engineering (IMI)
Adenauerring 20a, Bldg. 50.41 (AVG), Room 103
Telephone: +49 721 608-2129
Telefax: +49 721 661138
Email: jivka.ovtcharova@kit.edu
URL: http://imi.kit.edu