Chapter 15
Major Technology 9: Digital Factory—DF

Executive Summary

This chapter deals with the following topics:

- Basics and advanced techniques of Digital Factory
- Providing insight into how engineers benefit from using Digital Factory (DF) technologies
- Describing functioning, benefits, and limitations of DF technologies in practice.

Quick Reader Orientation and Motivation

The intention of this chapter is:

- to give an overview of DF technology in Virtual Product Creation as driver and enablers for Digital Transformation in engineering
- to present DF technology as part of Virtual Product Creation from a practitioner's point of view to analyze the need and usefulness for day-to-day industrial work practice
- to give instructions on how to use DF technology
- to explain models, frameworks, and mathematical representations that help to grasp the internal working modes of DF technology.

Virtual Product Creation has the task to prepare for successful fabrication and production of products, which have been developed beforehand with the help of virtual models and tools. Similar to the digital modelling approach for products all involved elements of the production environment—as part of the overall factory—are treated in the same way. This means, that the factory layout, manufacturing resources, machines and tools, manufacturing process plans and tasks as well as the interaction with production workers and with the different states of the products during the manufacturing progression are subject for digital modelling, simulation, modification and maturation up to their final releases. This chapter, therefore, explains all major elements of umbrella solution framework *Digital Factory*, in some countries also referred to as (overall) *Digital Manufacturing* approach.

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15.1 Engineering Understanding of the Digital Factory

The term *Digital Factory (DF)* has been driven from the German understanding of establishing an equivalent term to the ordinary, physical factory in order to describe all critical digital modeling and simulation capabilities and opportunities as part of digital manufacturing engineering.

15.1.1 Why Does an Engineer Use Digital Factory?

The *Digital Factory* results from many years of dynamic change in economic conditions. Due to globalization, different areas such as economy, environment and culture intertwine, which has substantial effects on products and their life cycles. As a consequence of the transformation from a seller's to a buyer's market, products are becoming increasingly diversified and individual and manufacturing companies face major challenges, as they have to demonstrate increasing quality, and simultaneously, falling costs in shortened periods of time [1].

In order to master this dynamic progression, computer-aided tools and methods have been used since the 1980s to increase planning efficiency and shorten the implementation time of products and production facilities [1]. Yet how does the *Digital Factory* relate to these tools and methods? The next section explains this term and introduces the underlying principle of the *Digital Factory*.

The Definition:

Research and industry have been concerned with the definition of the term "*Digital Factory*" over many years. In practice, however, the different attempts to explain the concept have often led to divergent interpretations. In order to counteract the growing misunderstandings, the VDI Guideline 4499 has developed a generally applicable definition that brings together the views of experts and supports a cross-industry understanding of the term [1, 2]. It reads as follows:

> "The Digital Factory is the generic term for a comprehensive network of digital models, methods and tools—including simulation and three-dimensional visualization—that are integrated through integrated data management.
> It aims at the holistic planning, evaluation and continuous improvement of all essential structures, processes and resources of the real factory in connection with the product."

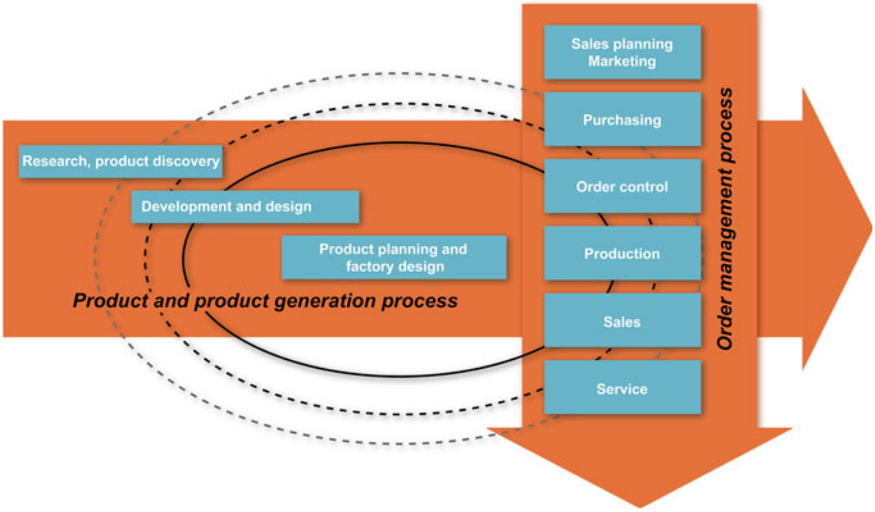

Fig. 15.1 Focus of the *Digital Factory* at the heart of corporate processes [2]

The *Digital Factory* is not solely a software-related topic, as the term may initially suggest. It rather focuses on production planning and factory design, which must be considered at an early stage in all business processes.

Figure 15.1 displays this focus in more detail. According to [2], production planning entails the planning of processes and production systems. Both, the requirements for the development and construction as well as those for the operative production process must be already considered in the early phases of the process in order to provide appropriate methods and tools that adapt to it. In addition, real production is to be continuously checked and improved by means of virtual instruments.

The *Digital Factory* is widespread in various industries. There is, however, a great difference within the implementation of its tools and methods. According to [1], automotive engineering and the aerospace industry play a pioneering role since the potentials were recognized early on and were incorporated accordingly into the individual processes. Taking an automobile manufacturer as an example, the progressive networking of planning processes can be illustrated. While in the 1990s isolated solutions with few interfaces were frequently used, the digital landscape has changed considerably over time. Processes that were not digitally supported could be transferred to the digital environment with new tools.

Tools used so far have also been further optimized and new interfaces have been added so that the overall picture of the *Digital Factory*, as shown in Fig. 15.2, is built up piece by piece.

Yet there are still hurdles to overcome, for instance, the implementation of standardization and data management. According to [1], the implementation of standardization is very advanced with regard to products, processes and sample solutions, since they represent a basic prerequisite for the introduction of IT tools and methods.

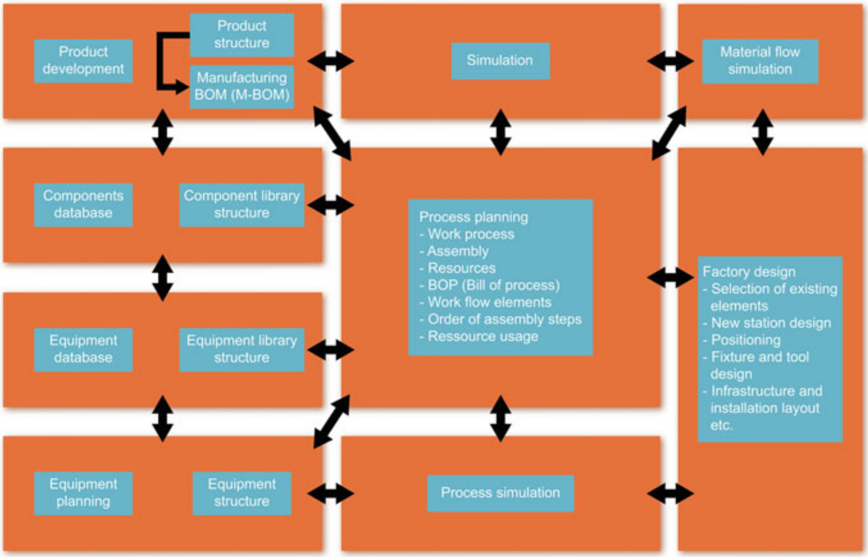

Fig. 15.2 Interaction of planning processes in the *Digital Factory* [1]

However, new requirements play an increasingly important role in the planning phase so that they can be determined and coordinated in every planning step. This creates a clear structure with which tools and methods can be introduced successfully.

On the topic of data management, significant efforts are required in the areas of change management and inventory data maintenance. Although interfaces between individual processes already exist, planning changes must still be recorded and maintained in the relevant systems so that all those affected receive information about any changes that occur. The completeness and consistency of the data and the relevant data management workflows and methods are critical to ensure high-quality manufacturing planning. The maintenance of inventory data appears as another major challenge, since it indirectly affects the planning data. In the first place, it involves the operational data that is available in the real production facilities and must be transferred to the *Digital Factory* repository. Due to the fact that a plant can always be modified during its operating life, it is important to record these changes. Primarily, those roles and individuals responsible for the data update in the information system have no direct advantage from this digital data maintenance. An analysis of these modifications can be only carried out effectively when these changes are transferred back to the planning systems, where process planning and manufacturing system design is carried out as part of modifications of the existing and the set-up of future plants.

In the entire value chain, not only the automotive industry strives to use the potential of the *Digital Factory*, but also the machinery and plant-engineering industry does so. In order to ensure that external plant manufacturers (suppliers) also support the internal planning processes of an automobile OEM manufacturer, the relevant data structures and formats need to be compiled. They are already specified in the invitation to tender for the specifications [1] and are finally detailed out as part of the statement of work. As a result, suppliers are faced with the challenge of meeting the requirements of different customers who, in turn, use different digital modeling, simulation and planning IT systems and resulting native modeling and data formats. However, this also holds the potential that machine and plant constructors will be short-listed for order placement if they have already been able to demonstrate support for the specified digital tools and methods in previous projects reliably.

In addition to the various possible uses of the *Digital Factory*, the question arises as to who works with digital tools and methods. In [2] target groups are identified, which can be enumerated as follows:

- External planning participants
- Internal planning participants
- Management of the company.

The external planning participants are primarily parts and module suppliers, plant suppliers and planning service providers. Different planning results are generated according to the specifications of the company-internal planning groups, which can be integrated in the subsequent processes. The internal planning participants consist of the areas involved in factory planning. They create, store and structure different types of planning information. They also use the results of the external planning participants in further planning steps in order to initiate the plant construction. A special target group is production staff, who are asked to incorporate their practical expertise into the planning process. Capturing such heuristic knowledge, however, is still limited within today's manufacturing and factory models and are subject for further research. Company and factory management refers to the people to whom the planning results are presented and to whom complex issues are explained so that they can drive the most relevant decisions. Company and factory management is the key stakeholder group who needs to be overall responsible and accountable to the overall planning results and associated budgets. It is still a dilemma, today, that most of the times digital data management tasks are not yet (fully) taken serious enough by company and factory management. This dilemma oftentimes is caused by the fact that company and factory management has a shortage in basic understanding and a lack of personal experience in such new digital engineering tasks.

Having positioned the role of the *Digital Factory* within the overall manufacturing planning situation and within the business scenarios of companies it is now time to explain the mission of the *Digital Factory* as key enabler within the *Virtual Product Creation* solutions portfolio. Figure 15.3 shows the major three mission elements:

- Part a explains the change of digital efforts upfront as part of the virtual front loading with the help of the *Digital Factory*
- Part b outlines the different layers of the *Digital Factory* (from the factory level down to the product level)

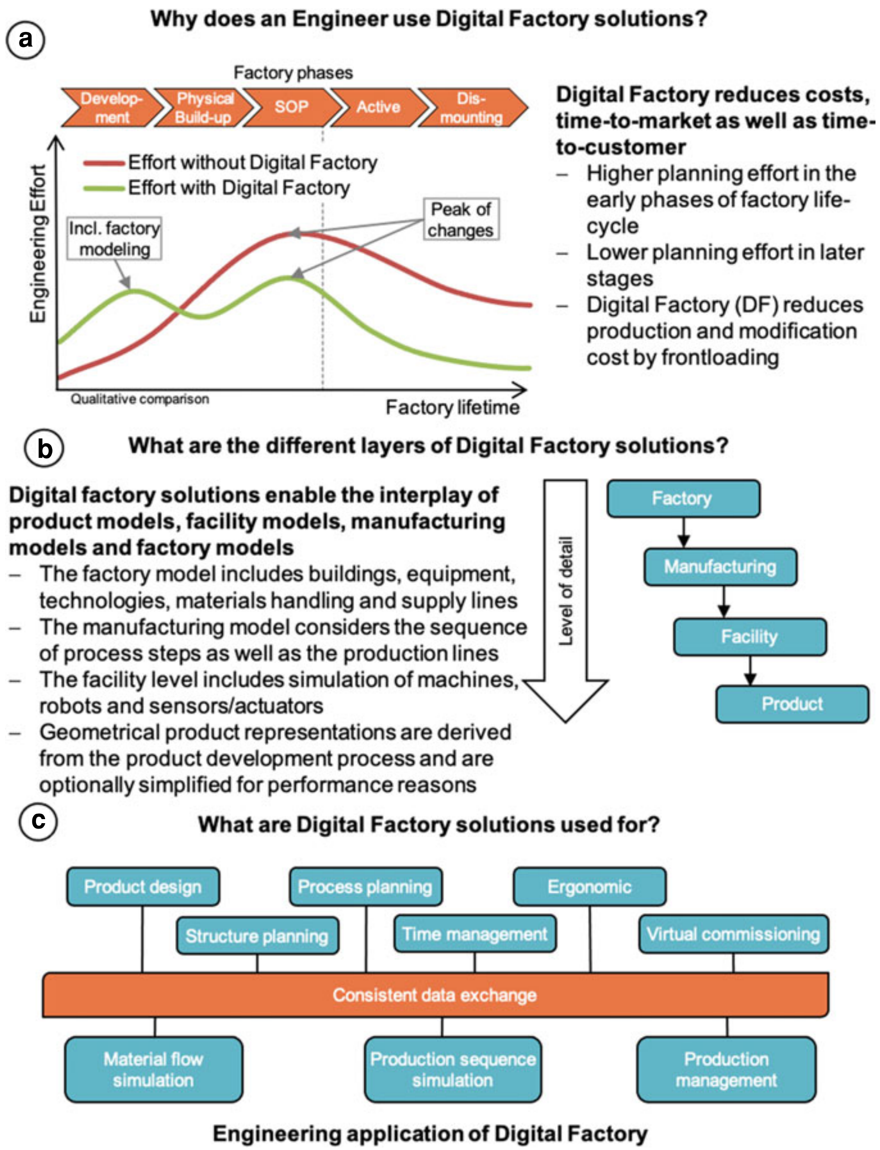

Fig. 15.3 The mission of the *Digital Factory* with motivation, layers and applications

- Part c shows the individual engineering applications of the *Digital Factory* including the critical integration element consistent data exchange (which requires a solid data management strategy and capability).

It should not be underestimated that the establishment of this *Digital Factory* mission does require substantial buy-in and support from both, corporate and factory management as well as the manufacturing planer and workers. It takes between five and ten years with a dedicated *Digital Factory program* to introduce and consistently set-up the engineering capabilities of a successful *Digital Factory* within enterprises.

15.1.2 What is Digital Factory Doing for an Engineer?

The *Digital Factory* influences the basic organization of projects with its tools and methods. As shown in Fig. 15.2, it causes planning processes to be networked, which in turn have various effects on the profitability of the company, the quality of the product and communication between the parties involved. Whereas in former times it was common to view product development and production planning as two separate, sequential project steps, the *Digital Factory* made it possible to increasingly parallelize these steps (simultaneous engineering). This not only positively affected reduced timeline of development projects, but also cost targets (reduction of change cost due to earlier feasibility and compatibility reflection). Nevertheless, it was and it is still necessary to invest continuously into digital engineering competence and operation, which in many cases remains a tedious effort in companies due to long living business habits of physical prove out approaches. The parallelization and shortening of the individual processes in early planning phases shown in Fig. 15.4 makes it possible to create and evaluate different variants with minimum effort.

Such "digital frontloading" leads to an intensive communication between product development and production planning, allows errors detection early on and reduces

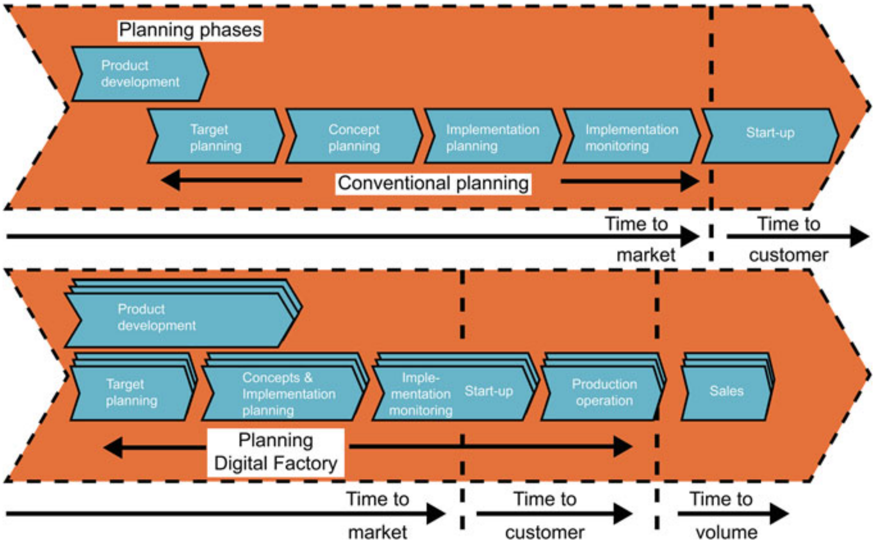

Fig. 15.4 Parallelization of planning processes through simultaneous engineering [2]

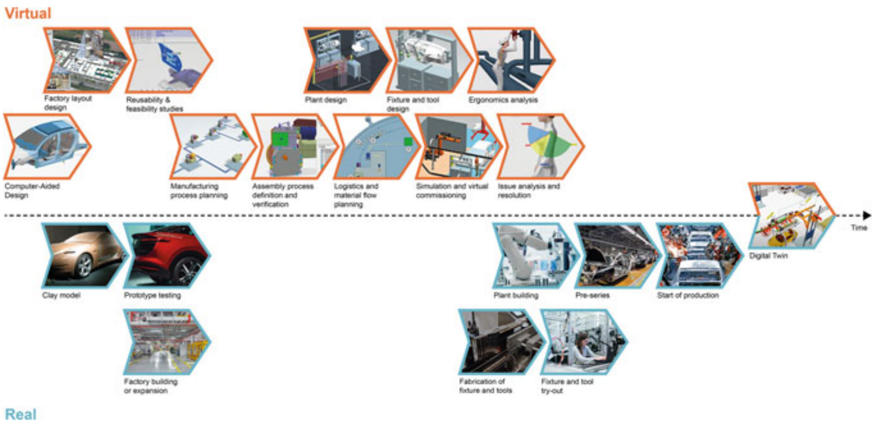

Fig. 15.5 Connecting *Digital Factory* virtual tools with real-world implementation

change efforts [1]. The *Digital Factory* offers possibilities of quality assurance of products already in the digital planning process as shown by the example of automotive virtual prove-out steps in Fig. 15.5.

Before manufacturing and assembly of the product takes place in the real physical factory, all process steps are virtually verified and product design as well as manufacturing systems might get improved along the process chain progression.

15.2 How Does the Digital Factory Work?

The *Digital Factory* is regarded as the "generic term for a comprehensive network of digital models, methods and tools" in the definition already presented. In order to describe this network, Fig. 15.6 presents an overview of different techniques of DF. Product creation is divided into three phases: product development, production planning and production. In each one of these phases, different methods and tools are used.

According to [1], a method is a systematic target-oriented approach that leads to a meaningful solution for a large number of problems. The methods shown in this context mainly describe organizational processes and procedures, which describe how an employee should use a certain tool at a specific time in principal terms. In addition, the detail digital working methods of using IT tools to create and use *Digital Factory* models are also considered. Simultaneous Engineering as an overall development approach represents an exemplary organizational procedure to enable collaboration between different functions such as Product Development and Manufacturing Engineering. The specific method how to model a virtual manufacturing assembly station belongs, however, to the portfolio of IT based digital working methods and is part of the *Digital Factory* solution.

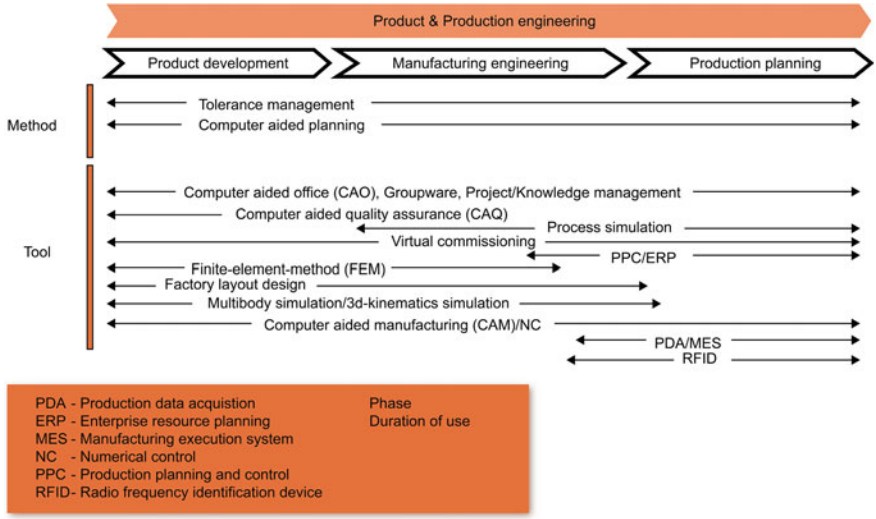

Fig. 15.6 Techniques of Digital Factory during product development (compare [1])

According to [1], an IT-supported tool is the software-technical implementation of a method or a combination of several methods, so that these can be used computer-supported, i.e. that a working method can be digitally executed. One example of such a digital working method is the Finite-Element-Method, which is used to carry out virtual tests on the load-bearing capacity of various machining components prior to the actual implementation of such a resource in a production line.

Another example is the RFID (Radio Frequency Identification) technology, which is suited to support manufacturing process execution. The simulation of such a RFID sensor as part of the overall manufacturing process execution can be used, for example, to locate vehicles manufactured in the automotive factory. In order to control cycle time and individual vehicle tracking in the *Digital Factory*, it helps to simulate the throughput from body construction up to final quality inspection.

In the *Digital Factory*, there exist many different methods and tools that differ in usage as part of manufacturing and assembly build feasibility, manufacturing process plausibility and overall factory management optimization. Increasingly, the degree of software integration into manufacturing resources are subject for latest innovations in *Digital Factory* capabilities. The author cannot present all of those methods and tools in the following sections. Rather, the focus will remain on those methods and tools that have already proven themselves through widespread practical implementation and are therefore safe in being deployed successfully.

15.3 Process and System Implementation of the Digital Factory

The methods and tools of the *Digital Factory* can be divided and categorized into three major areas. In order to implement factory planning digitally and to apply it throughout the *plant development process*, the areas of automation technology (1), plant logistics (2) and manual assembly (3) must be considered. These can be digitally mapped mainly in phases 3 to 5 of the plant development process, i.e. from the phase of *concept planning* to *preparation for implementation and final installation* (compare Fig. 15.7).

In addition, they can also be leveraged as reference for virtual commissioning and during the product launch phase. Therefore, it can be achieved digital plant-engineering activities can rely on digital layouts and simulation models created beforehand as part of the *Digital Factory.*

In addition to the integration into the plant development process, it is necessary to establish the technical set-up of the Digital Factory with respect to the IT system architecture and deployment framework, see Fig. 15.8.

In order to comprehend the importance and power of *Digital Factory* solutions to enable digital manufacturing and to conclude the specific application areas, each company has to analyze the relevant application and target areas, with corresponding use cases. Figure 15.9 depicts three potential areas and explains their major digital model arrangements.

Please find below the explanation of these three application/target areas in more detail.

15.3.1 Logistics- and Production Flow Simulation

In the area of logistics planning, the entire material provision for the production process of the product to be manufactured is defined and secured based on either a general or a detailed layout. In addition to the commissioning of production and purchased parts, station concepts and conveyor technology as well as their individual performance are calculated, simulated and validated against the target definitions

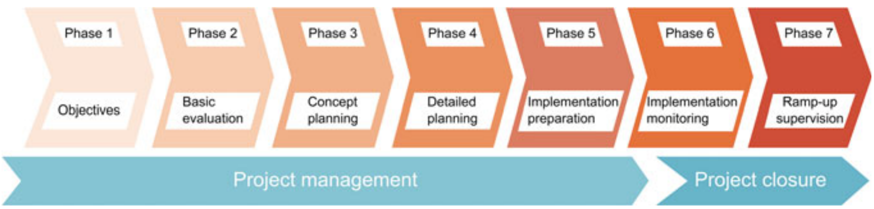

Fig. 15.7 Phases of the plant development process, according to [3]

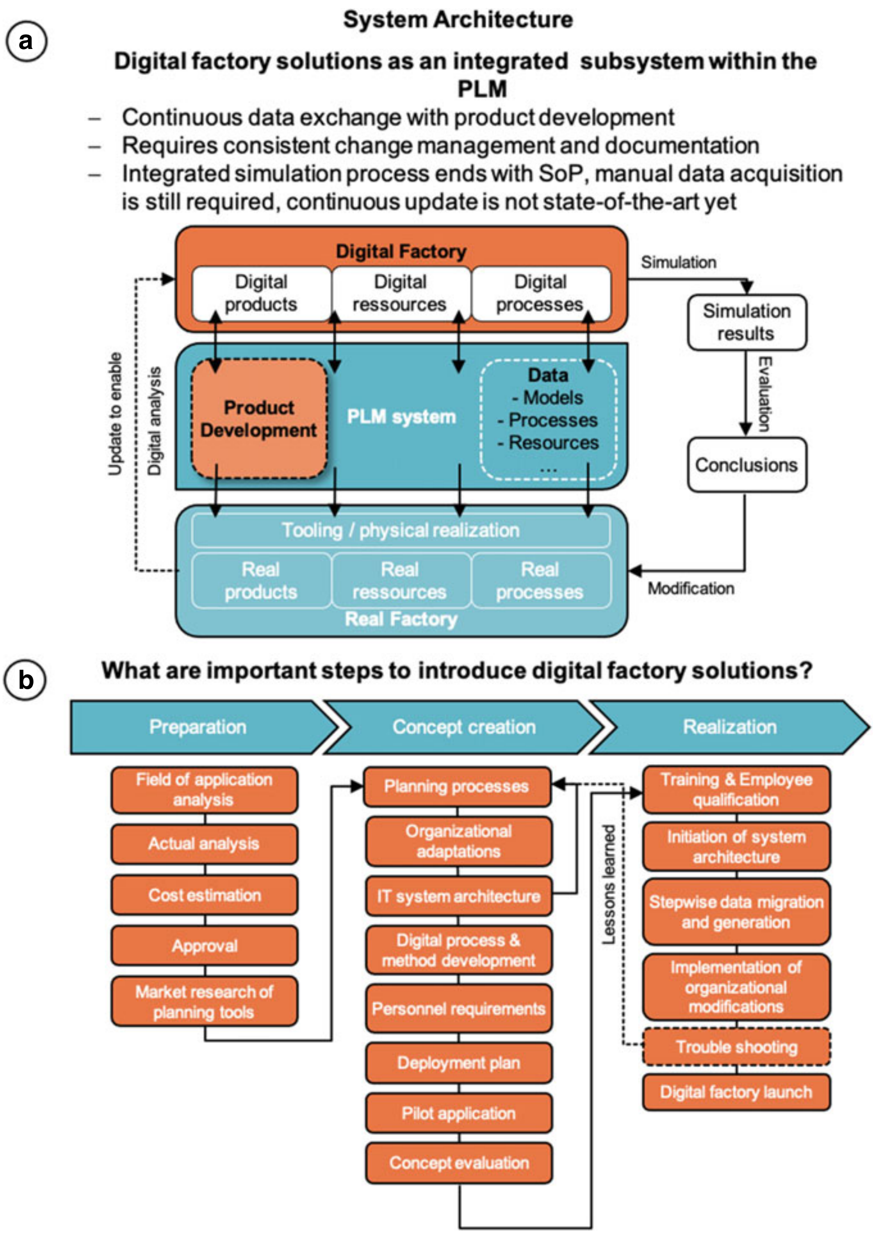

Fig. 15.8 The technical and deployment set-up of the *Digital Factory*

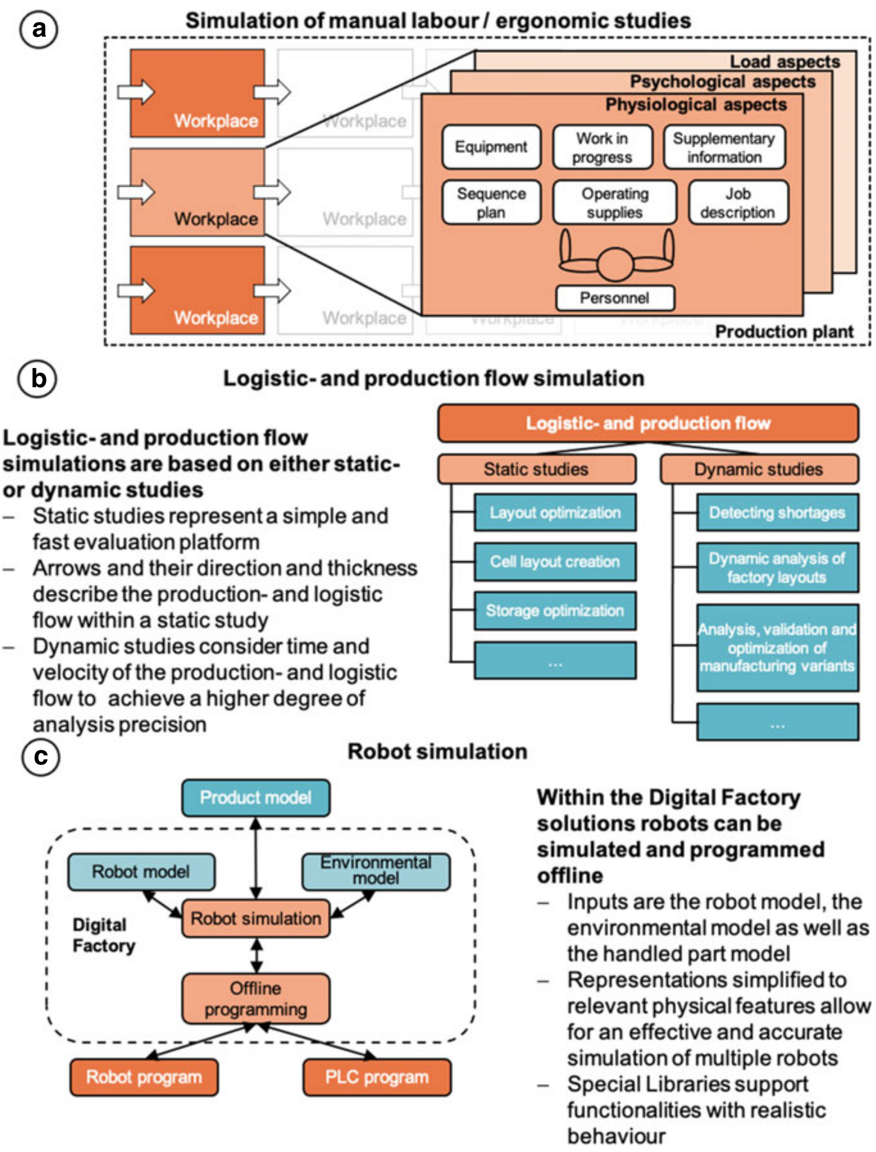

Fig. 15.9 Examples for application and target areas of the *Digital Factory*

(Phase 1). In particular, the material flow simulation also allows assisting the start-up support according to the simulation results.

15.3.2 Automation Technologies/Robotics

In the context of automation and robotics, any handling and manufacturing processes that have to be secured based on highly automated manufacturing processes are considered, simulated and validated. The goal is to optimize the production flow as much as possible with the help of tools from the *Digital Factory*. In terms of logistics and material flow simulation, these tools serve as input and output variables for automation and robot planning. The goal of robot planning is, for example, to handle components within a workstation in an optimized way (e.g. according to the limited space of the work cell) or to optimize their integration into the production processes (e.g. matching to the overall cycle time).

15.3.3 Simulation of Manual Labor/Ergonomics

In addition to automation technology protection, manual workstations must also be considered in production planning. *Digital Factory* tools support the production planner in the design and validation of workstations where manual assembly activities are carried out. In particular, simulation software is used in the following areas: route analysis, installation and removal studies, and ergonomics studies at virtual assembly workstations.

15.4 Digital Factory Technologies

In order to execute *Digital Factory* investigations, one should be aware of the different modeling approaches of the individual production environment and systems as well as understanding the associated simulation opportunities. This section will introduce the major modeling and simulation technologies in order to provide a solid understanding for typical *Digital Factory* investigations and deliveries.

15.4.1 Digital Factory Basic Modeling Technologies

One of the main tasks of the *Digital Factory* is the planning of the entire factory. According to [1], there is a distinction between a completely new planning (Greenfield) and the re-planning of already existing structures (Brownfield). In order to achieve an optimal result, in both planning cases an ideal planning without restrictions should be assumed, so that an optimized production process can be examined.

An important basis in factory planning is the plant model. In this model, support structures, walls, windows, roofs and other building elements are drawn according to

[1], so that it serves as a basis for the next planning steps. Based on the plant model, various participants can conceive and plan their ideas. Different structures can be created in a factory because different focal points exist. In logistics planning, for example, a low-crossing material flow can be tracked, whereas fire protection will focus on rescue and escape routes. Each of these participants can also use special software for modeling or commission corresponding planning service providers, so that the factory data can be available in different 3D formats for the planning results. This makes it necessary to transfer the data into a common Digital Factory model based on specified 3D CAD and/or 3D visualization data formats.

15.4.2 Layout Planning

In order to meet the challenge of an appropriate *Digital Factory* model, the required 3D CAD model is designed using the common factory layout. The main purpose of such a factory layout is to enable planners and decision-makers to visualize the respective results quickly so that they can understand and verify the functioning of the factory. Consequently, not all design details are relevant, as only the major geometric outer shape of the objects is required. Figure 15.10 shows a section of a 3D CAD model of a robot cell as part of the Body-In-White (BIW) production line of an automotive manufacturer that is used as a plant layout in planning.

According to [1], data reduction is necessary when creating such a model. This enables a fast display of the entire model on PC systems and handheld devices without much waiting time.

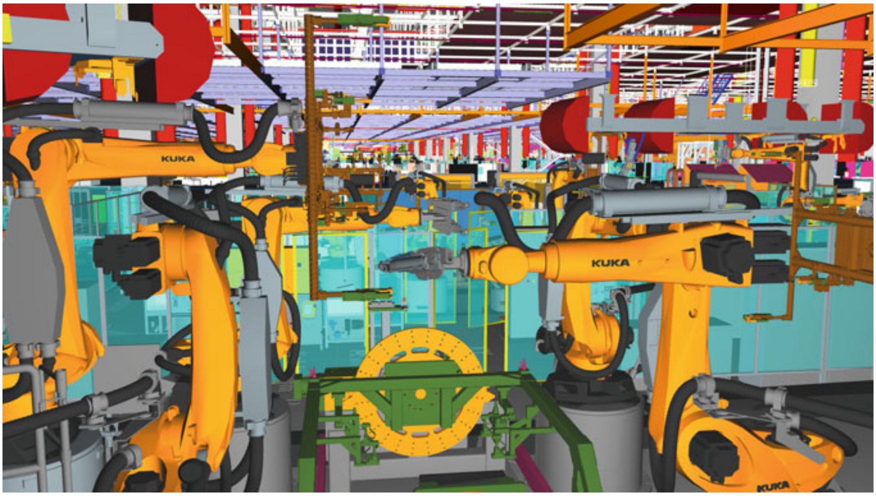

Fig. 15.10 Extract from a 3D model of a robot cell in BIW production [5]

15.4.3 *Factory-Digital Mock-Up (DMU)*

As mentioned earlier in this sub-chapter, different groups (internal and external planners) are involved in factory planning. Therefore, according to [1], it is necessary that a regular coordination between these individual areas takes place so that the respective results can be incorporated into the 3D overall model. This procedure is shown in Fig. 15.11 and it is called Factory Digital Mock Up (Factory DMU)—please also compare details of a DMU in Chap. 12.

In the first step of this procedure, the 3D data is checked in advance using checklists. Here the focus lies on the compliance with drawing regulations, such as for element design or specified colors. This step is followed by a collision check, so that it can be statically and dynamically examined whether there is contact between the production plants and building structure. An example of a static collision check is shown in Figs. 15.12 and 15.13 shows how dynamic movement space can be represented by a space placeholder for the clash analysis as part of a Factory DMU.

Through the visual control, a collision can be detected early in the planning process. The third and last step of the examination is the technical evaluation. With the help of such checklists, for example, it is examined to which extent there exists free

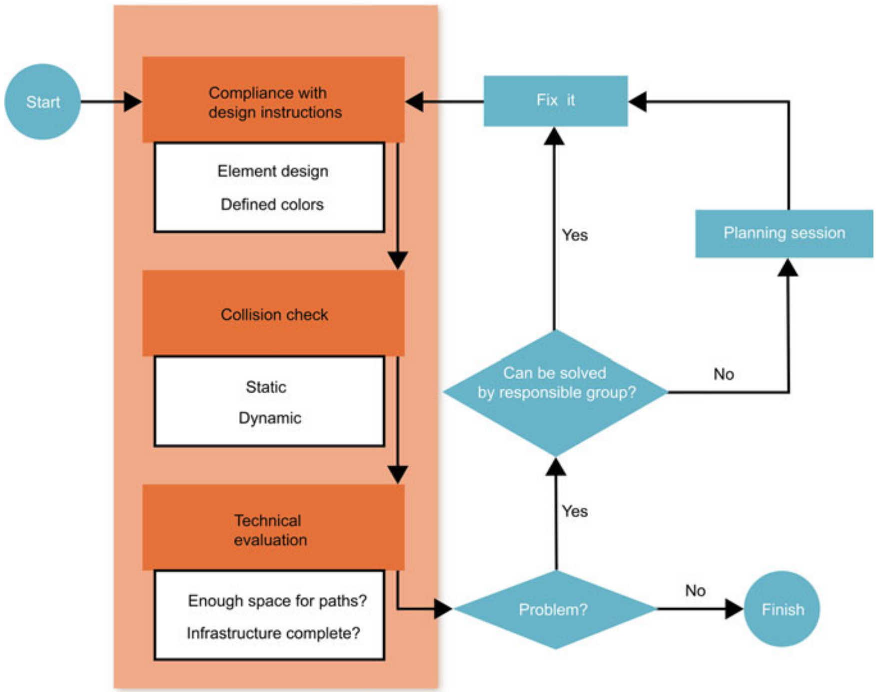

Fig. 15.11 Procedure of using a Factory-DMU for creating new 3D-CAD factory models, see [1, 4]

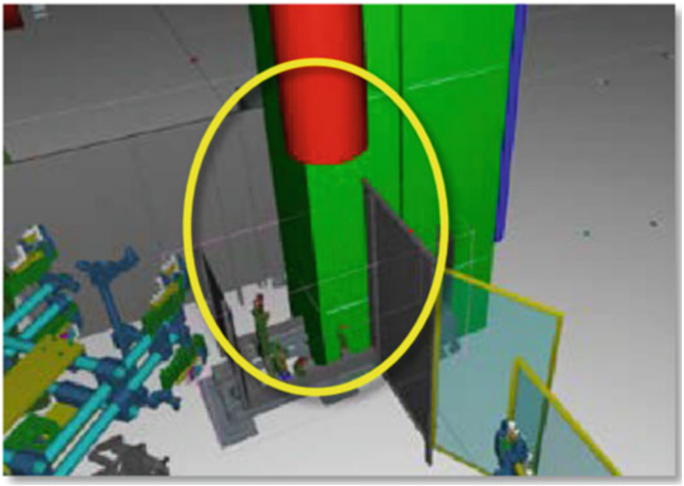

Fig. 15.12 Example of a collision between a pillar and a safety fence [4]

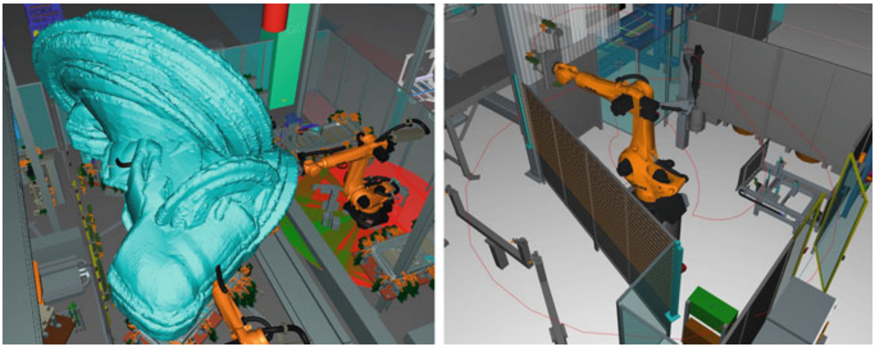

Fig. 15.13 The shrink-wrap volume of the roboter dynamic movement in the working cell as a static representation in the Factory DMU clash analysis [4]

space for tool and logistic paths and whether all necessary infrastructure installations are complete and accessible for maintenance. If problems arise in a particular area during this procedure, the responsible group is asked to rectify them. However, problems can also occur in different areas and therefore several groups could be asked to solve them together. In such cases, appropriate planning team meetings are scheduled in order to solve all issues and to agree on the appropriate industrial engineering solutions.

The presented process is iterative and with every iteration step, the planners and engineers improve the 3D factory model continuously. If all specifications have been met and there are no ambiguities any longer, the procedure is considered complete. In the construction of the entire factory, this final 3D overall model offers many advantages. It serves as a master source of information to derive various layout dimensions from it. In addition, it is leveraged to export certain points from the factory model into different manufacturing application tools. For example, it is used to display quickly the positions of drill holes for fixing plant components with a laser marking at the construction site as part of the physical set-up.

15.4.4 Behavior Models

In addition to purely spatial design modeling of a factory and the 3D layout mapping of the corresponding production stations, behavioral models of factory equipment are required as a basis for an accurate validation of manufacturing process and operations. Based on the *kinematization of geometric model data*, these behavioral models map dynamic and time behavior of plant components. With the help of the associated modeling steps, the entire behavior of the production plant is mapped according to previously planned cycle times. Manufacturing Engineers and Factory Planners use behavioral models for various aspects of production planning. In the context of the *Digital Factory*, the focus is usually placed on time behavior and its associated cycle patterns in order to map the simulation of material flows between the station concepts. In robot planning, the use of behavioral models is also very useful, especially during end effector path planning. The traverse paths of the robot body, arms and end factors as part of their work fulfillment (positioning, welding, screwing, painting etc.) and the sum of all cell robots' trajectories in their interplay are checked for mutual clash avoidance, clearance safety, are optimized in addition towards overall cell cycle time as well as wear minimization.

15.4.5 Electronics and Controls

For a holistic illustration of the planned production processes, an interdisciplinary modeling approach is advantageous. In addition to the 3D models created in the factory DMU, kinematization and behavioral modeling of the entire production plant, it is also necessary to describe it from the perspective of electrical project planning and control programming. The aim is to achieve consistent data continuity, starting with the factory DMU, through the complete wiring diagrams, to the initial control system design. Compared to the factory DMU described above, in electrical planning and control development the focus lies less on the three-dimensional representation of production plants. The wiring and pin assignment of the production plant as well as its function and performance are primarily secured. In the field of electrical planning, this can be ensured by means of circuit diagrams and I/O tests based on such diagrams. In the area of control development, first the function of the control code is developed. Then the real-time-capable response behavior of the planned production plant is considered and further optimized.

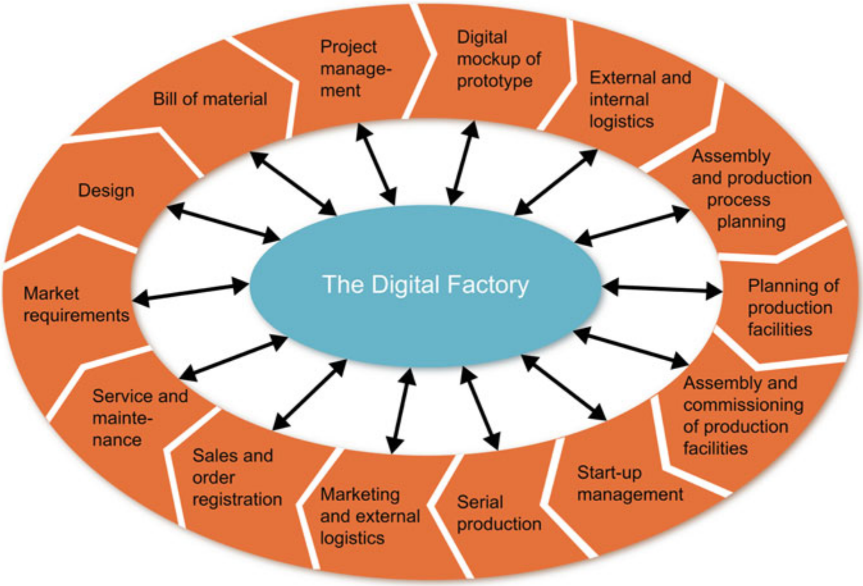

Fig. 15.14 *Digital Factory* operations as a part of the *Digital Factory* process (see [2])

15.4.6 Basic Simulation Technologies

During the last ten years, *Digital Factory operations* offer a wide range of digital solutions to cope with the increasing product diversity of companies as part of the overall *Digital Factory* process solution. As shown in Fig. 15.14, the operations mainly deal with the subordinate processes of production process planning, assembly and commissioning of plants up to series production, so that, according to [2], different methods and tools of the *Digital Factory* can be leveraged. Obviously, the *Digital Factory operations* have numerous contact points with the other Virtual Product Creation technologies as described and explained in this book. This is necessary since the *Digital Factory* simulations are dependent on the existence of and linkages between digital models and information databases of products, (manufacturing & material) process and logistics as well as all involved resources (PPR concept).

15.4.7 Virtual Commissioning and Robotic Simulation

Before a product can get started in series production, it is necessary to digitally (instead of only physically) anticipate, check, prove-out and analyze all manufacturing process in the individual plants in order to avoid all possible problems that usually can occur during production operation. Since such thorough check for manufacturability (or manufacturing feasibility) is applied to test the start-up of plants and their equipment as well as the execution of real manufacturing processes, it is also referred to as *commissioning*.

With the large number of product variants, as it is usual in many industry branches, many companies face severe economic and time line challenges: exceeding cost targets, delayed time line to launch the product and quality issues during ramp-up of production. In order to overcome these challenges, *virtual commissioning* has established itself as an important sub-process in *Digital Factory* operation over the past few years. With the help of *virtual commissioning*, a significant higher number of digital tests can be mastered at the same time, which results in shortening of factory start-up time. As shown in Fig. 15.15, *virtual commissioning* is located before the start of physical plant realization.

To carry out *virtual commissioning* analysis, it is necessary to provide the corresponding data available in a mechatronic library. Figure 15.16 shows an example of how such a library can be set up. In order to generate the digital plant model, mechanical, electrical and fluidic designs as well as robot, PLC and NC programs must be created in advance. Since plant designers as well as internal and external plant engineers deal with these tasks, the data of the individual participants are usually combined. To build up this library, referred guidelines have to be taken into consideration.

In the following step, the created plant must be linked to other plants as well as processes and resources. According to [2], the interdisciplinary cooperation of different trades as well as consistent data management can enable a holistic view of the entire life cycle of a plant. In addition to data management, change management also poses a major challenge since changes made during the operation of a plant should also be fed back into the digital model.

As illustrated in Fig. 15.17, planned changes to the digital model can be tested in advance prior to commissioning; nevertheless, they can also occur during plant operation. There exist several ways in which a *virtual commissioning* can be carried out. Figure 15.18 displays these possibilities.

In a system simulation, the *virtual commissioning* takes place with the help of a computer model. In the simulation environment, a complete virtual test can be

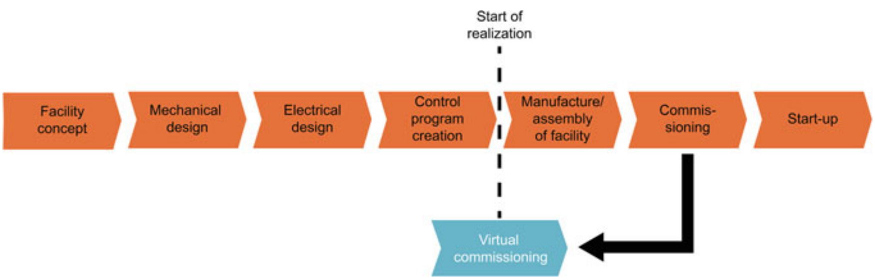

Fig. 15.15 Frontloading of commissioning into the virtual engineering process (see [2])

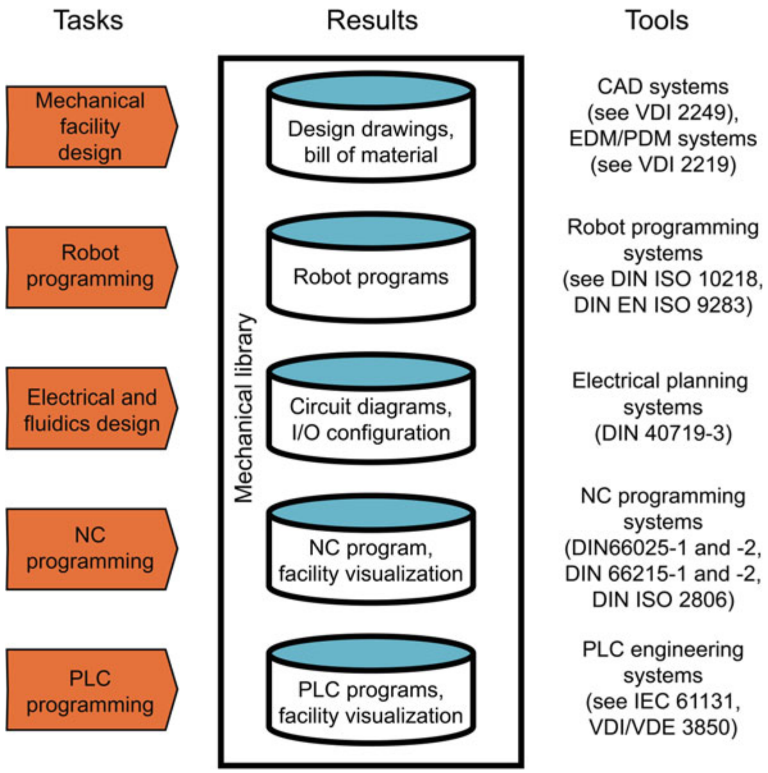

Fig. 15.16 Interdisciplinary factory planning tasks and tools [2]

carried out based on the computer model, so that analysis results can be obtained quickly with respect e.g. to function, timing and clash [2].

Another possibility would be a *Software-in-the-Loop simulation* (SiL), in which control and regulation algorithms under development are linked to the real plant and tested in real time. The advantage of such a simulation is that coding can be checked independently of control hardware [2].

As opposed to a SiL simulation, the created algorithms are imported into the control hardware and tested on the virtual plant model during the execution of a *Hardware-in-the-Loop* (HiL) simulation. This way, statements about the functionality and safety of the planned plant can thereupon be made [2]. A HiL simulation from the automotive industry for the plant area “body-in-white construction” is deployed meanwhile as a standard case. A very high degree of mechanization prevails in the body-in-white construction, since many production steps can be processed by robots and other tools. Typically, the control hardware is available for *virtual commissioning*, so that only the digital plant model has to be procured.

For a simplified representation, an exemplary plant model consists only of a single work cell. This work cell contains a robot that performs a welding task. In step one,

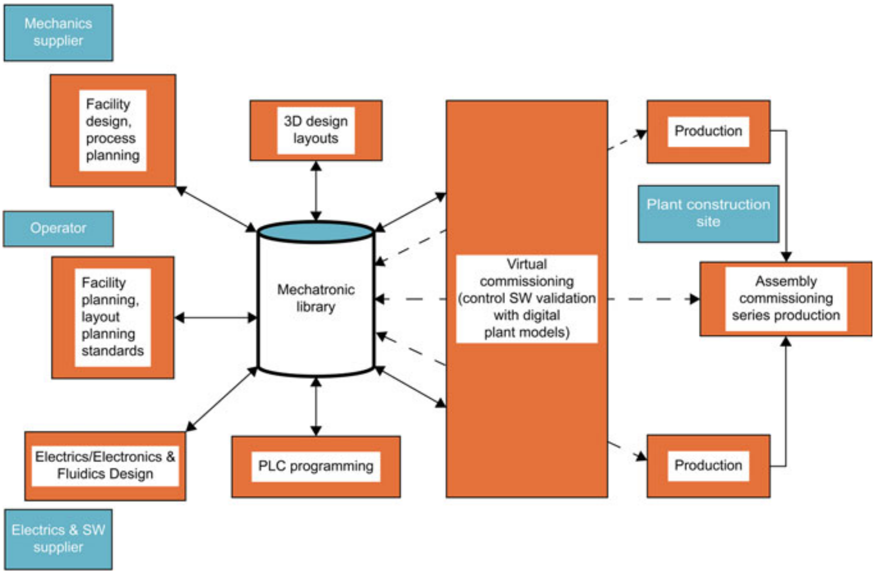

Fig. 15.17 Shared planning and development model (see [2])

		Production facility	
		Virtual	Real
Controller	Virtual	System simulation	Software in the loop (SIL)
	Real	Hardware in the loop (HiL)	Real operation

Fig. 15.18 Types of virtual commissioning (see [2])

the robot picks a sheet from the first feed and places it into the fixture. In the next step, it picks up a second sheet and sets it down next to the first sheet. The fixture serves as the robot's workbench so in the meantime the robot changes his gripper from gripping tool to welding tool. The fixture also has clamping elements to hold the sheets in their defined places during the welding process. After welding, the gripping tool is selected again and the welded sheets are transferred to the next work cell.

In order to reproduce this manufacturing process in the *virtual commissioning*, the specification of the robot and the kinematic 3D model are first required. With this information, the robot's processes can be calculated and visualized. After that, another essential element, the layout of the plant (work cell) and the building, is required in order to detect possible collisions during the robot movement. In a further step, the 3D data of the objects to be welded (sheets) and the fixture are requested, so that the gripping, depositing and welding processes can be analyzed in detail. As a final step, the control model is integrated into the simulation, whereupon the plant model for a HiL simulation contains the required data.

This simplified example already shows the complexity of a larger plant model. In actual practice, the body-in-white construction is made up of many plants, whereby these consist of several work cells. Each plant and its work cells must be secured before series production. In the case of real commissioning, short-term changes, e.g. geometric optimization of sheet metal, are associated with a high expenditure of time, as the real work cells must be changed and secured on site. In a virtual environment, however, the modified 3D data of the plates are already available, so that only the corresponding 3D models of the tools as well as the layout and the control model of the plant have to be optimized. This shows how promising *virtual commissioning* capabilities are.

This will also be evident in the following sections concerning material flow simulation and ergonomics investigation. In order to explain those digital technologies consistently a work cell example is taken from the collaborative research project VIB-SHP (compare [5, 6]) that concentrated between 2015 and 2017 with the future virtual engineering commissioning capabilities; the use case was take from automotive industry and is illustrated in Fig. 15.19.

15.4.8 Material Flow Simulation

By means of the material flow simulation, the delivery of the components to be manufactured can be mapped, simulated and secured along the production process. The material flow simulation is often based on flow charts in which the manufacturing and joining sequence is stored. In the initial rough planning, this sequence is transferred from a textual or graphical representation to a 2D or 3D representation, which is known as the layout plan. The layout plan can be used to display both the production and auxiliary goods to be considered and the associated assembly and manufacturing stations. Different station concepts, production processes as well as their material flow can now be simulated and optimized based on an allocation of time-based behavior models to manufacturing stations and on the material flow of the production goods. Material flows between different work stations as well as within a station can be modeled and they can also conveniently be combined with the method of *virtual commissioning* by means of the simulation of virtual signals and the positions of the production goods resulting from the behavioral models, see Fig. 15.20. In such a process, a real controller is connected to the material flow simulation and controls it so that errors in the programming of the plant control system can be detected at an early stage and can, at the same time, be optimized when compared to a plant that does not yet exist in reality (see also [6]).

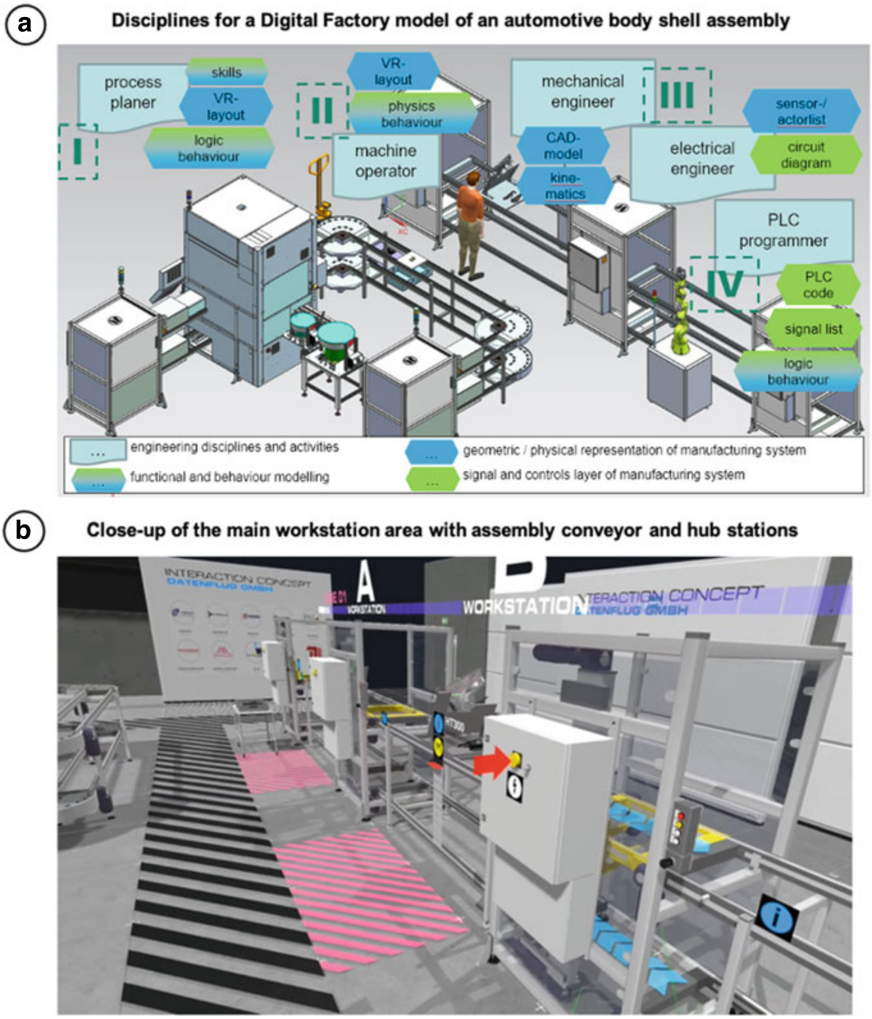

Fig. 15.19 *Digital Factory* work cell model [5, 6]

15.4.9 Ergonomics Validation

In addition to the material flow, as described above, each individual assembly and manufacturing station of the production process must be secured before it is started up. Especially for manual assembly stations, this represents a high challenge for the installer concerning the requirements for operational safety and for the long-term execution of the assembly work with no health risks.

During assembly validation, the arrangement of each assembly workstation is examined in terms of a number of influencing factors. Such factors can range from

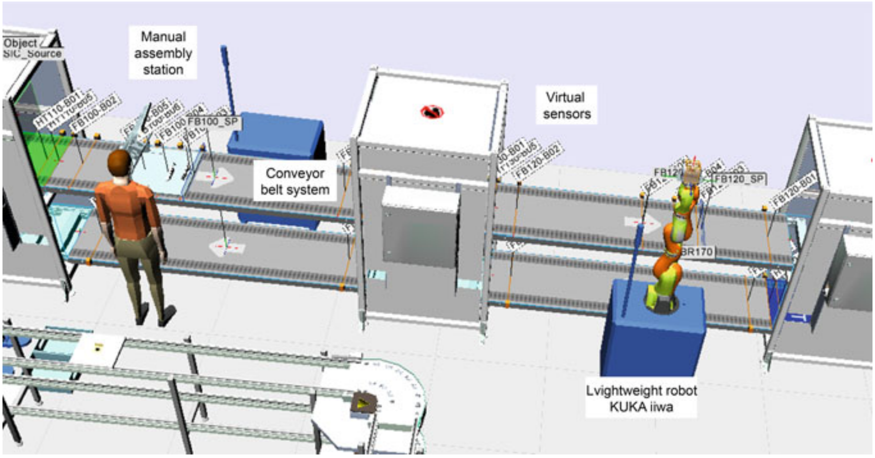

Fig. 15.20 Material flow simulation of manual assembly task

the spatial arrangement of the assembly workstation to the positioning of auxiliary equipment and tools for the manual assembly process. For a precise assessment of the real assembly activity, visual and accessibility analyses can be carried out during the validation process. This allows the temporal and spatial performance of the workers to be optimized and the assembly process to be more intuitively conducted. In this area, it is common practice to use so-called digital human models (DHM), which can be employed to simulate and analyze the installation of the production goods to be assembled in combination with the posture of the assembly worker. These ergonomic load analyses take into account influencing factors such as the mass of a component to be lifted, the posture of the technician and the frequency with which the technician has to lift this component during their shift.

15.5 Advanced Technologies

The increasing individual needs of customers for the product as well as the expectation of a high degree of adaptability of production planning to short-term changes before and during the manufacturing process poses new challenges for the *Digital Factory* methods and tools. In order to cope with such challenges, new perspectives on the upcoming problems are emerging. The mechatronic plant model already presented, which is used for virtual commissioning, is an example of them. The model represents a detailed digital copy of the plant until the phase of the real commissioning arrives. Therefore, there exists the possibility to link the digital model with the real plant in order to represent the real conditions during the running production in real time.

15.5.1 Consistent Data Modeling and Exchange

The prerequisite for a consistent, *Digital Factory* model is the cross-disciplinary model description and simulation of the planned production plant. For this purpose, it is necessary to understand the production plant as a mechatronic system and to build the corresponding factory data management upon it. Decisive interactions between the disciplines, such as in drive and sensor technology, must be consistently mapped across the boundaries of model data of the individual disciplines. In the above-mentioned example, the spatial positioning of a sensor within the layout of the production plant can have an influence on its function as well as electronic influencing variables and vice versa. Especially in the field of model data exchange and change management, these cross-disciplinary interfaces are of great importance.

15.5.2 Virtual Reality Used in the Context of Digital Factory

The use of virtual reality or augmented reality tools in the *Digital Factory* is still relatively low. Advantages of these technologies are particularly evident in the visualization of an entire production plant. In Design Reviews, the planned plant can be inspected spatially and on a scale of 1:1. For the observer such 3D Virtual Reality (VR) technology enables a realistic perception of distance, in which, for instance, the accessibility of plants and work stations can be checked, see Fig. 15.21.

Figure 15.22 shows the difference between a traditional expert observation of a 3D *Digital Factory* model which has been set-up for replay on a 2D screen and a

Fig. 15.21 Layout of an assembly station in virtual reality (VR) [5]

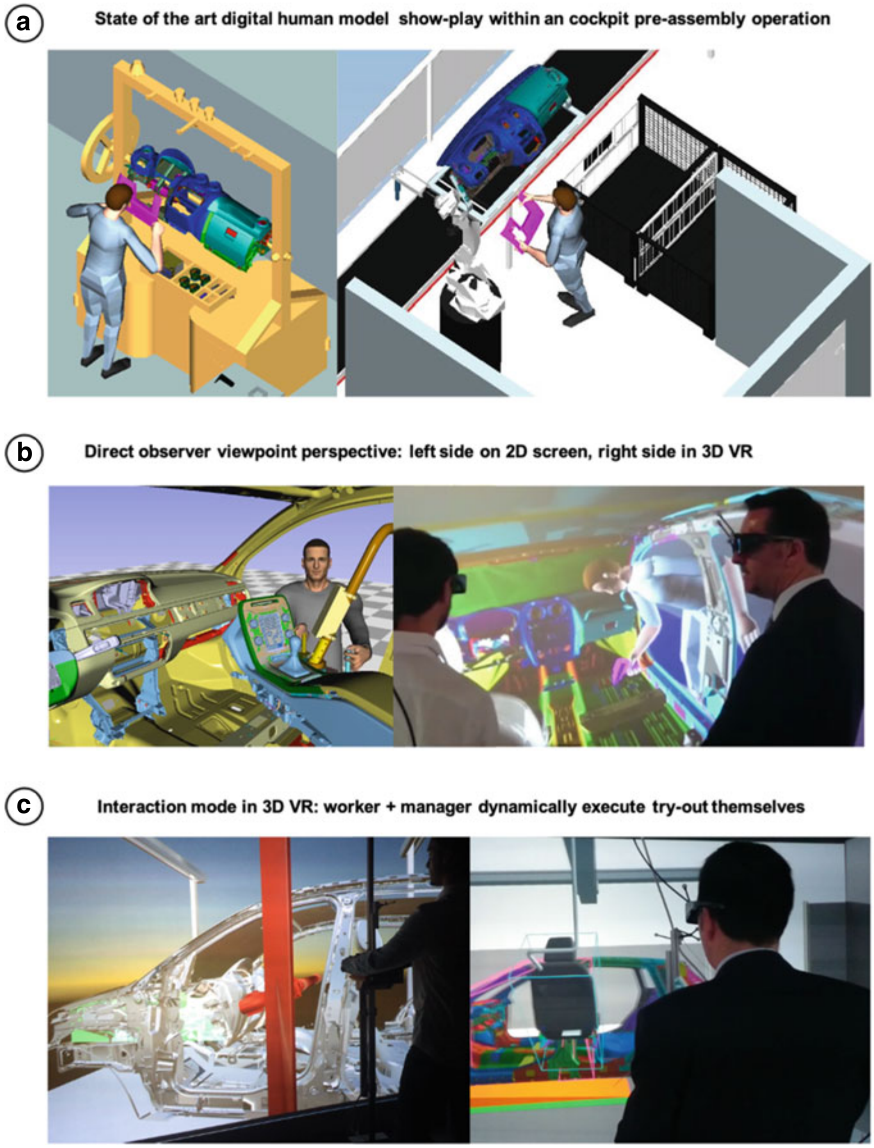

Fig. 15.22 Different observer and interaction possibilities for assembly tasks; comparison between 2D screen mode versus 3D Virtual Reality mode

3D *Digital Factory* model which can be either passively reviewed in 3D VR or even interactively used in 3D VR.

Figure 15.22a shows a perspective from a 3D *Digital Factory* model which has been set-up with the Tecnomatix process simulate software from Siemens. It shows the interaction of a digital human model (DHM) from an appropriate upper camera position for two different cell and process proposals of an automotive cockpit pre-assembly.

Figure 15.22b outlines the difference between two alternative analysis approaches of an automotive assembly line example. On the left side the dynamic digital human operating activities to assemble a console at the center are of a body shell compartment is shown in state-of-the-art 2D screen view. The 3D model has been created with the software IMMA, the Swedish Digital Human Modelling software of Fraunhofer Chalmers in Gothenburg.

On the right side, a 3D *Digital Factory* model created with the Tecnomatix tool suite of a similar task but enabled to be viewed and observed within a 3D Virtual Reality Cave. The 3D Factory model is enhanced by transporting the graphic stream in real time onto the VR screen with the help of the software TECHVIZ. The advantage is that the assembly experts together with Management easily can follow all analysis details in a 1:1 immersive view, which boosts the engineering understanding.

Figure 15.22c shows the innovative way of *Digital Factory* engineering of the chair of Industrial Information Technology of TU Berlin. With the help of the *Smart Hybrid Prototyping* technology, it is possible that a worker or a manager can try-out the interaction of an assembly resource like a semi-automated assembly fixture with the product to be assembled into another product (the example shows the installation of a cockpit on the left side and of a seat at the right side). The term *Smart Hybrid Prototyping* designates in this case the direct interaction of a 3D (Virtual) scene with a real physical device supported by real time contact collision and logic process control.

In contrast to virtual reality tools, augmented reality applications are nowadays mainly used for the visualization of operating data or the remote maintenance of a plant. This allows an untrained service employee to be instructed remotely by an expert, for example. Based on a consistent actual model (CAD model data) of a production plant, corresponding sections of the *Digital Factory* must be visually prepared and presented to the management, e.g. within the scope of a design review.

15.5.3 Human–Robot-Collaboration

The purpose of human–machine collaboration is to combine the advantages of an automated assembly or manufacturing station with the advantages of a manual workstation. On the one hand, the flexibility of an automated workstation should be increased and on the other hand, the repeatability of a manual station should be optimized.

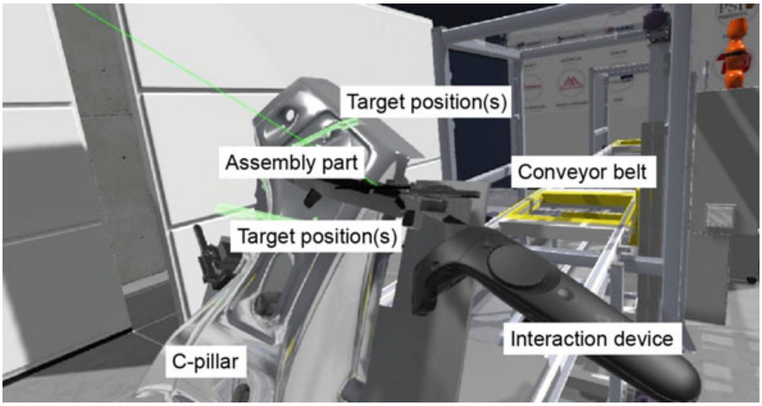

Fig. 15.23 Assembly validation in virtual reality (VR) [6]

The symbiosis of these two approaches can, for example, reduce the error rate in production and increase the number of variants of the production goods that are manufactured at the same station. With the combination of worker and automation technology and robotics, however, increased risk potentials also affect the operator, see Fig. 15.23.

The hybrid workstation must therefore be equipped with particularly high-performance safety mechanisms to allow workers and robots to collaborate effectively and safely. Digital security tools in the field of human–robot collaboration are often used with digital human models, but are not yet widely available in the *Digital Factory* or only as specialized simulation software.

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