A CAD-based Layout Environment for a Semi-automated Test Bench Assembly

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ABSTRACT

Today, several technical components still need to be tested physically to verify their reliability under real-life conditions. For example, automotive powertrains have to be checked in particular test benches, before they are released to market. The creation of these test benches requires the development of a functional pre-layout with a subsequently performed design of a geometrical layout within 3D-CAD. The entire process turns out as a time-consuming and iterative task, whose success primarily depends on the experience of the involved engineers. The present paper describes a method for a semi-automated creation of powertrain test bench assemblies. This method includes knowledge-based engineering methods coupled with a 3D-CAD environment and a knowledge database for semi-automated layout and part creation.

Keywords: knowledge-based design, automated assembly, functional integration, automated geometry creation, powertrain test bench layout optimization.

1. INTRODUCTION

Besides extensive physical testing, virtual development methods represent an inevitable task in mechanical product creation. Automotive drivetrains, or particular components of them, are typical examples for virtual and physical testing, when focusing a failure-free operation during their lifetime. Test benches for powertrains are very complex, mainly consisting of the specimen, machines as drive and brake units, additional intermediate gearboxes for adjustment of torque-speed characteristics, instrumentation and support services as well as additional components such as drive shafts to couple all these parts. Fig. 1 exemplarily illustrates a typical test bench with a full vehicle powertrain as specimen including a combustion engine as drive unit and four electric motors as brake units which simulate the driving resistances on the four wheels. Test benches for vehicle powertrains or sub-powertrains (= trains) can use either an internal combustion engine as drive unit or one or several electric motors, which substitute the combustion engine. Electric motors are commonly used in test benches because they are able to simulate the driveline dynamics and combustion pulses and have advantages regarding logistics, availability,

test bench requirements and of course in view of environmental aspects. Frequently, powertrain test benches are designed in a way, that they are able to test lots of different powertrain configurations. Normally, these multi-configuration test benches allow positioning of the drive and brake units and the other test bench components on a large test plate with grooves or holes, depending on the specific powertrain configuration, as shown in Fig. 1. These test benches may vary considerably regarding layout, power rating and performance. The buildup, or just the modification, of a modern powertrain test bench requires many different specialized engineering skills.

The main challenges are represented by the functional and geometrical dimensioning, selection and assembling out of a huge amount of required available standard components. As an important boundary condition, already existing components have to be used, so that the number of newly created and manufactured parts is kept to a minimum. The setup of a new test bench layout is usually done by experienced and skilled engineers, who are familiar with the functional characteristics and the actual availability of the majority of all components, [3].

Fig. 1: Typical test bench configuration for a complete vehicle powertrain, [1].

In state of the art development, a new test bench layout is initially designed by use of common assembly environments of commercial 3D-CAD software. Fig. 2 shows a typical test bench assembly with all crucial components in 3D-CAD. First of all, the specimen which has to be tested is usually mounted on a specific console. Depending on the required load spectrum, intermediate transmission gear boxes between the drive or brake unit and the specimen are necessary. To connect these so-called functional components, coupling elements, like shafts or flange adapters, are essential parts of a test bench assembly. In addition, there are several measurement instrumentations and supporting devices to mount the functional parts or to stabilize coupling elements.

Generally, components are mounted on a large test plate which allows a flexible positioning of all components.

Usually, a new test bench configuration starts with the functional layout, which is primarily depending on the defined test case followed by the geometrical assembling within 3D-CAD. Depending on the required type of the specimen, such as a differential gear box or a complete all-wheel drive powertrain, there are numerous possibilities of test bench layout configurations. However, the main functional components that are used are almost the same, as well as their technical and geometrical characteristics. Tab. 1 gives an overview of typical components and their relevant information. As an example, there are different
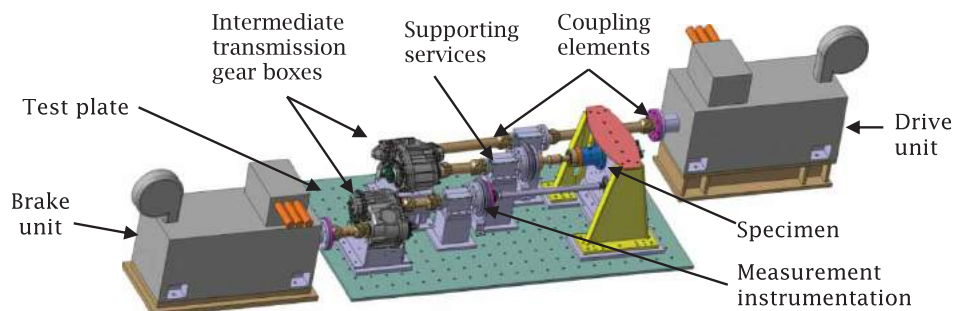

Fig. 2: Main components of a typical powertrain component test bench.

Main component	Extract of component types	Relevant functional information
Specimen	• Entire powertrain • Powertrain component	• Required load spectrum • Gear ratio
Drive/brake unit	• Electric/combustion engine • Mechanical/electrical brake	• Nominal/maximum power • Torque-speed characteristic
Intermediate transmission	• Gear box • Differential gear box • Transfer box	• Gear ratio • Maximum torque and speed
Coupling elements	• Shaft • Flange adapter	• Maximum torque • Critical speed
Instrumentation	• Torque load cell • Revolution counter	• Maximum torque • Maximum speed

Tab. 1: Components with relevant information for functional test bench layout.

types of intermediate transmission gear boxes, which all have the same relevant functional information: a specific transmission ratio between two flanges as well as maximum input and output torque and speed.

2. CHALLENGES IN TEST BENCH ASSEMBLING

As discussed above, the buildup of test benches, especially for vehicle powertrains, afford a lot of experience and engineering knowledge. It is inherent, that the complexity of a test bench significantly increases with the complexity of the examined powertrain.

Typical test bench projects include the evaluation of strength, efficiency, durability, lubrication, vibrations or other mechanical characteristics of complete powertrains, or single components (like differential gears or transfer boxes). In an initial step of test bench planning, a virtual pre-configuration of the test bench within CAD environment is inevitable. During the development process, the responsible engineer simultaneously has to consider a wide range of different functional and geometric boundary conditions. Functional boundary conditions are mainly defined by given testing programs, which have to be performed with the specimen. Within these testing programs torque, speed, duration, as well as boundary conditions like the lubrication situation or the temperature, are defined. Geometric boundary conditions are primarily given by the present testing plate, the geometrical dimensions and interfaces of the components and limits concerning packaging and clashes. In addition, engineers have to consider that they provide sufficient space for accessibility, maintenance, possible repairs or protective measures.

A typical design process of a test bench represents a more or less uncoordinated, iterative, repetitive and time-consuming task. Test benches, which exist for many years gather a huge amount of components. In order to handle the information and data volume, the management of test bench components is supported by PDM (Product Data Management) systems. In the course of creating test bench layouts, PDM systems support the search of parts and the buildup of new test benches within a 3D-CAD environment. No or insufficient stored metadata of particular component functionalities, geometrical dimensions or connection characteristics may be responsible for problems in the scanning process of suitable parts for specific test bench configurations. On the other hand, parts may be found and used within the virtual design process, even though the hardware parts are not available at that time. The reason for the lack of information is often based on missing options for the definitions of metadata within PDM systems, because the number of entries for each part is predefined and restricted.

An efficient and successful search for specific and existing components is a necessary condition in all phases of test design. Even though the sequence in conventional test bench design processes is not continuous or predefined, a basic course of action may certainly be found. Before a design process is started, an appropriate and available test bench environment, which is able to fulfill the framework conditions for the specimen, has to be found. Basic framework conditions, e.g. the required space or the number of trains, are predominantly deduced from the specific type of the test object. After a suitable test bench environment has been defined, the design of the functional layout starts. The functional layout guarantees, that operational characteristics of the specimen, mainly defined by specific sequences of torque and speed, are fulfilled. Therefore, engineers select from a pool of different drive units, intermediate gear boxes and brake units, which are available at the respective test bench. These functional parts are typically

arranged train-wisely in a proper way to fulfill the required test bench specifications. Intermediate transmission gear boxes are added to balance differences in speed or torque characteristics.

Usually, the conventional design of basic functional layouts takes place without any automated calculation support. Required transmission ratios as well as resulting transmission ratios, torque and speed behavior are calculated manually. In case that several transmission units are used and several development loops have to be done, this repetitive task is time-consuming and inefficient.

After the functional layout has been defined, the test bench is built up within a 3D-CAD environment. The actual assembling process represents a more or less uncoordinated, usually time-consuming and mainly trial and error based task. After the pre-selected parts, which were defined in the functional layout section, have been inserted into the CAD environment, first work- and time-intensive prepositioning tasks are done. The next step is the attempt to complete the individual trains of the test bench by insert and connection of instrumentation, coupling and support components. Therefore, specific components need to be found in the database and inserted into the CAD environment. The required coupling components are mainly represented by cardan or homokinetic shafts. The choice of these components represents an especially critical task, because they are clearly one of the most stressed components in the test bench configuration. For this reason, engineers generally have to assess the existing loading conditions and compare them with the specified maximum values of each component. Besides functional requirements of coupling components, engineers also have to take care, that connection interfaces between the selected components fit together. As couplings are normally realized by different types

Pre- design of the functional test bench layout
Start / Basis: System test — End / Result: Principle design of functional layout

Tasks	Challenges	Conventional tools and methods
Definition of the test case	Identification of the test case	Specification book
Definition of principle functional powertrain layout	Selection of an appropriate test bench environment	Type of specimen, experience
Dimensioning and selection of functional parts	Analysis of the tested operational points	Torque, speed, duration, temperature, position of installation
Selection of drive and brake units	Find available drive and brake units with sufficient power	Data sheets, calculations
Elaboration of necessary intermediate transmission ratios	Calculation of necessary intermediate transmissions ratios	Performance curves, tested operational points, hand calculator
Selection and insert of intermediate gear boxes	Find intermediate gears with required functionalities	PDM system, data sheets, hand calculator
Calculation of the resulting transmission ratios, speeds and torques	Train-wise calculations for operational points	Hand calculator, data sheets

Design within 3D- CAD
Start / Basis: Principle design of functional layout — End / Result: 3D- CAD test bench layout

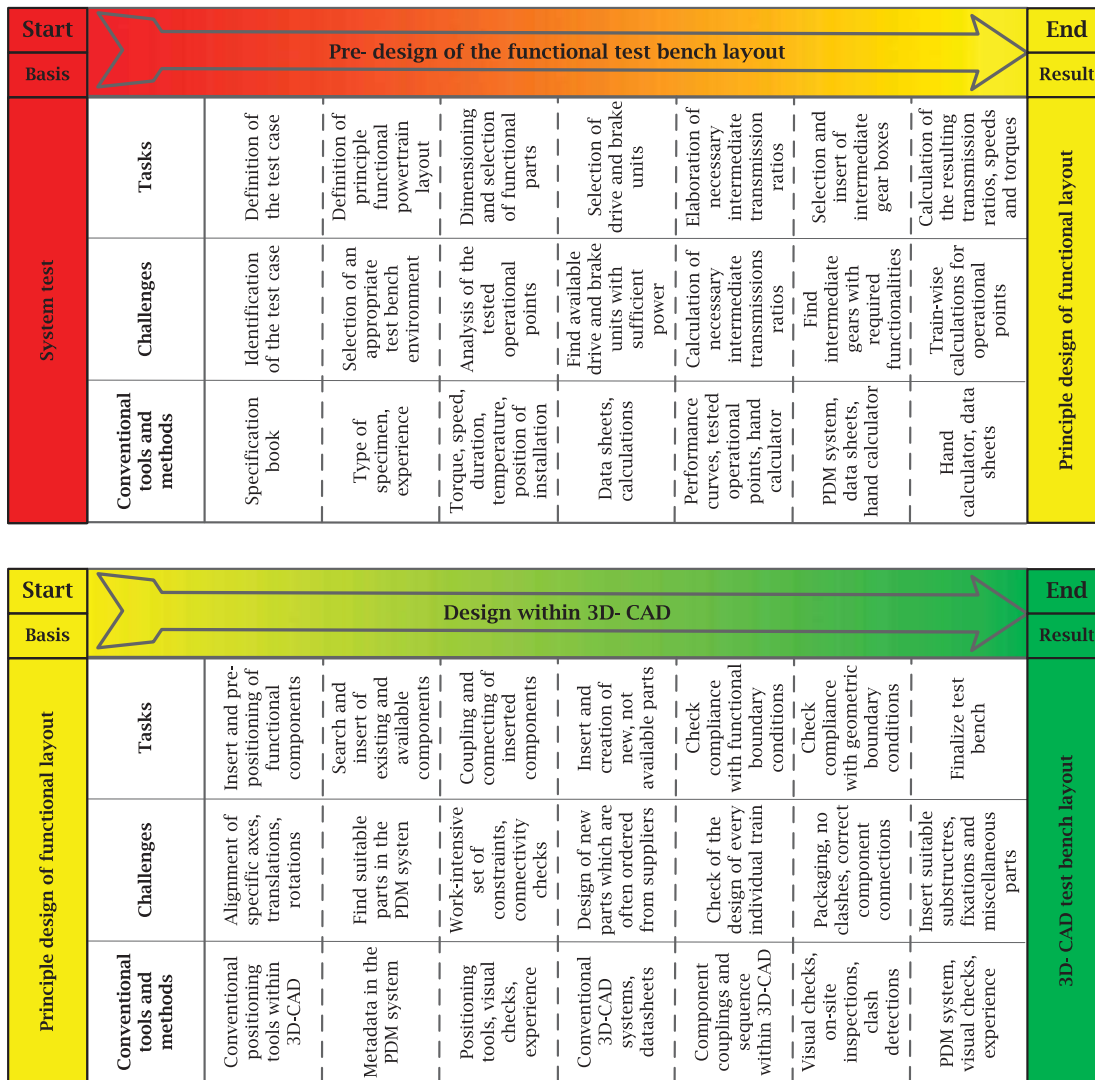| Tasks	Challenges	Conventional tools and methods
Insert and pre-positioning of functional components	Alignment of specific axes, translations, rotations	Conventional positioning tools within 3D-CAD
Search and insert of existing and available components	Find suitable parts in the PDM system	Metadata in the PDM system
Coupling and connecting of inserted components	Work-intensive set of constraints, connectivity checks	Positioning tools, visual checks, experience
Insert and creation of new, not available parts	Design of new parts which are often ordered from suppliers	Conventional 3D-CAD systems, datasheets
Check compliance with functional boundary conditions	Check of the design of every individual train	Component couplings and sequence within 3D-CAD
Check compliance with geometric boundary conditions	Packaging, no clashes, correct component connections	Visual checks, on-site inspections, clash detections
Finalize test bench	Insert suitable substructres, fixations and miscellaneous parts	PDM system, visual checks, experience

Fig. 3:   Typical procedure for the creation of test bench configurations.

of flanges, connectivity checks need to be done for every intended coupling, before or while the actual coupling process takes place. These repetitive and laborious coupling processes are realized by conventional sets of constraints in 3D-CAD, which have to be applied manually. In case, that flanges do not fit together, suitable flange adapters have to be taken and inserted into the assembly. If no suitable flange adapter can be found in the database, a new flange adapter has to be designed under boundary conditions, which are given by a possible supplier. The creation of not available components such as shafts or flange adapters represents another repetitive and time-consuming task, which hinders engineers to build up powertrain test benches efficiently.

After the basic configuration and design of the test bench have been completed, the current buildup has to be checked regarding its compliance with the given functional and geometrical boundary conditions. Its design is finished by the insert of support and miscellaneous components, like substructures, covers or screws. In the end, the assembly of the test bench configuration within virtual environment includes the complete test bench layout according to its functional and geometrical requirements, in which primarily already existing and available parts are used. Fig. 3 summarizes a typical procedure for the creation of virtual powertrain test benches in terms of its main tasks, challenges and conventionally available tools and methods.

3. METHOD FOR SEMI-AUTOMATED TEST BENCH ASSEMBLY

As a conventional design process of a powertrain test bench typically consists of several inefficient, repetitive and time-consuming tasks, a method has been elaborated, which can improve, semi-automate or even automate sub-tasks in all development phases of a virtual test bench design. The method has been built up in CATIA V5, but it actually can be applied in all enhanced CAD-systems which allow parametric associative design and assembly, the integration of knowledge-based design methods and enable programming data and user interfaces, as well as automated routines. The main idea of the presented method is to support the engineer in the layout and design process of a test bench assembly by providing smart applications, which use knowledge-based engineering methods coupled with a commercial 3D-CAD environment, [2, 4]. These applications are defined to support engineers to efficiently build up test benches, under the consideration of above mentioned challenges. Thereby, the method uses conventional functions within 3D-CAD and databases, where generally known information is stored and accessed. Specific analysis methods, like Finite Element Analysis or Multi Body Simulations, are not considered in this method. The basic architecture of the so-called semi-automated test bench assembly method consists of three components, see Fig. 4. All three components, the semi-automated layout creation, the knowledge environment, and the automated part creation are interlinked efficiently in order to guarantee a proper operation. The method is designed in a way, that it supports, but does not restrict the engineer during the test bench design process.
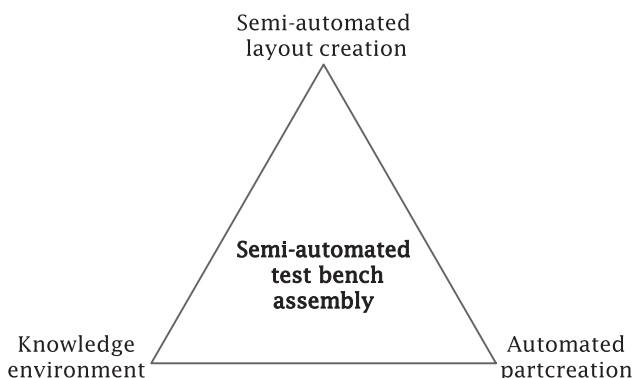

Fig. 4: Basic architecture of the semi-automated test bench assembly method.

3.1. Architecture of the Semi-Automated Test Bench Assembly Method

For a better understanding of the basic principle of the semi-automated test bench assembly method, its general architecture is described in detail. Basically, the interaction between a user and the method is realized by a Graphical User Interface (GUI), see Fig. 5. With that, the user has access to several implemented tools, which altogether represent the so-called semi-automated layout creation component. The component itself is connected to a knowledge environment and an automated part creation procedure. These connections are necessary for a proper work of the presented method. It is obvious, that the individual tools have to interact with a 3D-CAD assembly environment as well.

The knowledge environment includes the entire knowledge, which is used by the present method. This environment contains three members:

- **PDM system:** In the PDM system, besides test bench relevant components, all created and available components are stored and managed. For every individual component specific metadata is provided, so that components can be filtered and chosen according to certain criteria.
- **Layout database:** The layout database consists of several lists, which include all participating components of the present test bench layout. Due to the design of the lists, the layout of the train-system as well as the buildup of individual trains can be represented by the database. This
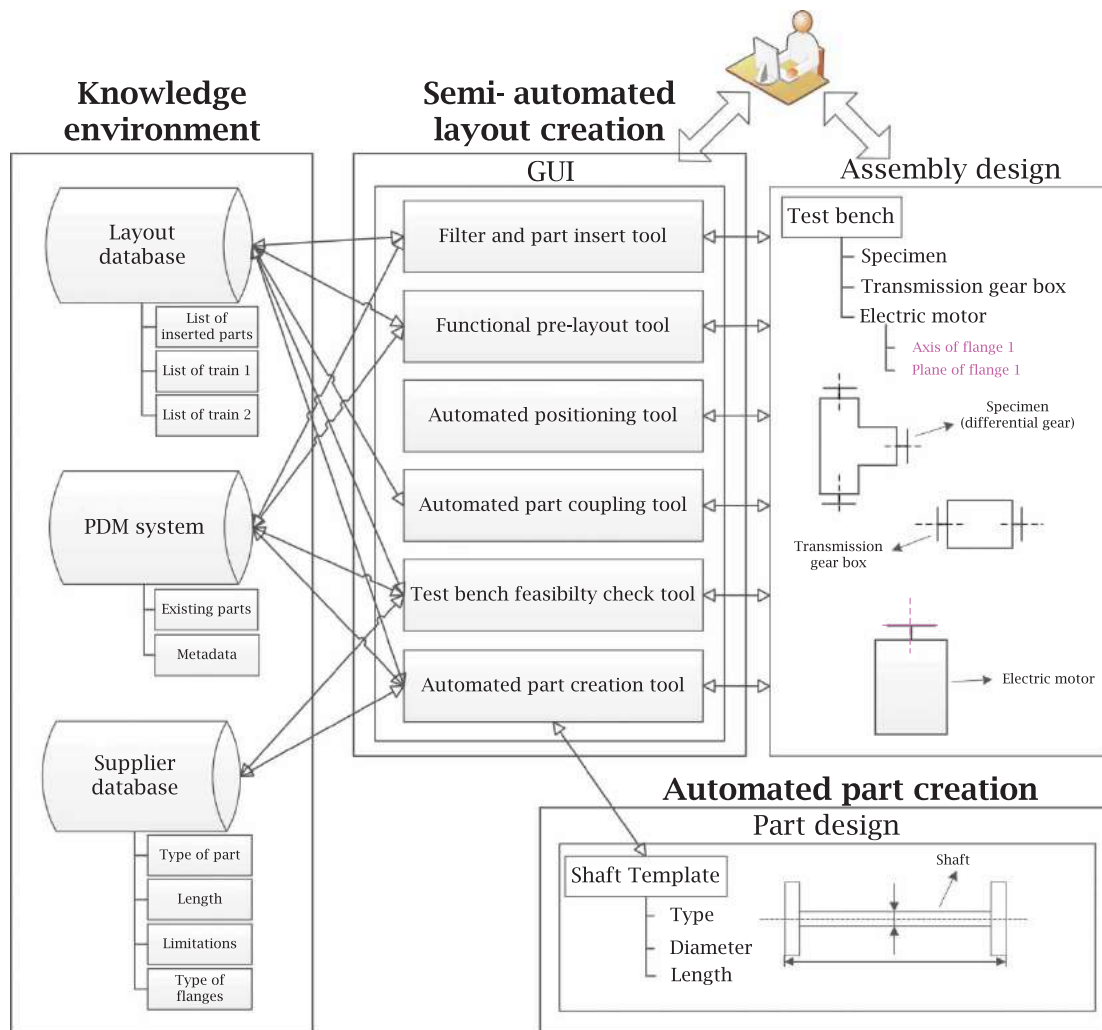
Fig. 5:   Detailed representation of the semi-automated test bench assembly method.

leads to number of advantages and possibilities, which are described below.

- **Supplier database:** As specific test bench components and standard parts are frequently ordered from suppliers, the creation of an own supplier database establishes as an effective way. The database contains relevant data of several products in the supplier's product range. Relevant data are for example connectivity options, functional or geometric boundary conditions and maximum supplier-defined torque or speed characteristics of the individual parts.

The automated part creation component represents a collection of different part creation templates. Every template is designed for a specific type of test bench components. By definition of selected parameters, a new component is created virtually in desired geometrical dimensions. The automated creation of new parts takes place within the part design environment of the 3D-CAD environment.

As discussed above, the semi-automated layout creation component consists of several tools, which interact with members of the knowledge environment as well as with the part creation procedure. Every individual tool offers certain functionalities, which are applied by the method. In particular, these tools are:

- **Parts filter and insert tool:** This tool enables an efficient filtering of the PDM system for existing parts, which fulfill predefined search criteria. Selected parts are automatically inserted into the assembly and corresponding entries are automatically done in the layout database.
- **Functional pre-layout tool:** The functional pre-layout tool enables a supported and guided basic design of a powertrain test bench, which is able to meet the given functional requirements. Therefore, the tool interacts with the PDM system in order to get functional metadata of qualified components. After the pre-layout

design process has been finished, the selected functional parts are inserted into the assembly as well as into the layout database.

- **Automated positioning tool:** This tool allows a quick prepositioning of parts within the 3D-CAD environment. Therefore, pre-defined reference elements within parts or products, like axes or planes of flanges, are automatically detected by the tool and can be selected by the user. After the selection, parts can be positioned relative to each other in the desired way.

- **Automated part coupling tool:** The automated part coupling tool checks if interfaces of parts fit together and connects them automatically and correctly. The individual flanges within parts are represented by pre-defined axes and planes. The tool automatically detects and directly visualizes the axes and planes in the CAD environment in order to enable an option for selection to the user. The connectivity of the chosen flanges is then checked by the comparison of the respective flange types, which are found in the layout database. The automated coupling process itself works similar to the automated positioning process. Pre-defined axes and planes of the flanges are set coincident.

- **Automated part creation tool:** The automated part creation tool allows an automated part creation of frequently used components, like shafts or flange adapters, in desired geometrical dimensions and under consideration of given limitations. The geometric dimensions of the components are controlled by parameters and are limited by boundary conditions, which are defined within the supplier database. The individual parts are automatically created by different templates within 3D-CAD part design and saved as new parts, after the geometric dimensions have been defined.

- **Test bench feasibility check tool:** The test bench feasibility check is restricted to the feasibility of the train system. The tool checks the present test bench layout regarding its confirmation with the pre-defined functional layout, sufficient load capacity and proper connections of the individual components of the train system. It checks existing constraints between the individual components of the train system and performs clash detections to check geometric boundary conditions. For its execution, interconnections to the layout database, to the PDM system and to the supplier database are required. Within the PDM system and the supplier database, information about the maximum torque and speed of the used transmission components can be requested and then compared with the actual loading conditions of the individual trains to check components regarding sufficient dimensioning.

3.2. Application of the Semi-Automated Test Bench Assembly Method

The mentioned architecture represents a framework of the presented method. Besides a common and continuously working filter function, the semi-automated test bench assembly method may be applied in all steps of a test bench design process.

As shown in Fig. 6, the workflow of the method can be divided into a functional section and a geometry section. In the initiating functional section, the definition of the functional layout takes place. At this development stage, geometric boundary conditions are not considered yet. As it is performed without the use of a 3D-CAD environment, it might be described as 0-dimensional development step.

The design of the functional layout again can be divided into several steps, see Fig. 7. During the entire process, the functional pre-layout tool is applied, which defines the basic workflow and automatically filters qualified functional components. First of all, the user has to define the test case and select the specimen and its type. Possible types are for example differential gears or manual transmissions. After that, tested operating points, in the shape of torque and speed, have to be prompted. With this information, possible test bench environments are filtered out automatically and can be selected by the user afterwards. After a test bench environment has been defined, the user can select from a pool of possible and available drive and brake units. The drive and brake units are assigned train-wise, whereby the basic shape of the train-system and the number of trains is fixed by the type of specimen. Intermediate transmission ratios are then calculated automatically with the help of deposited performance curves of the drive and brake units and the entered operational points. Suitable intermediate transmission gear boxes can be selected subsequently and added to or removed from the individual trains in order to reach the required speed-torque characteristics. When the selection of the gear boxes has been finished, the tool automatically calculates the resulting transmission ratios, speeds and torques for the individual trains of the test bench.

After the functional layout, geometric aspects are considered and the actual assembling process within 3D-CAD begins. Therefore, the chosen components from the functional layout are inserted into the assembly automatically. Then the automated positioning tool enables a fast prepositioning of the individual components along their respective trains. The tool detects specific, pre-defined reference elements, like axes or planes of flanges, within user-selected parts and quickly aligns or rotates them in the desired manner.

As shown in Fig. 8, 3D-CAD parts are normally not aligned in the desired manner when they are inserted into the 3D-CAD environment. In order to align them by the automated positioning tool, the
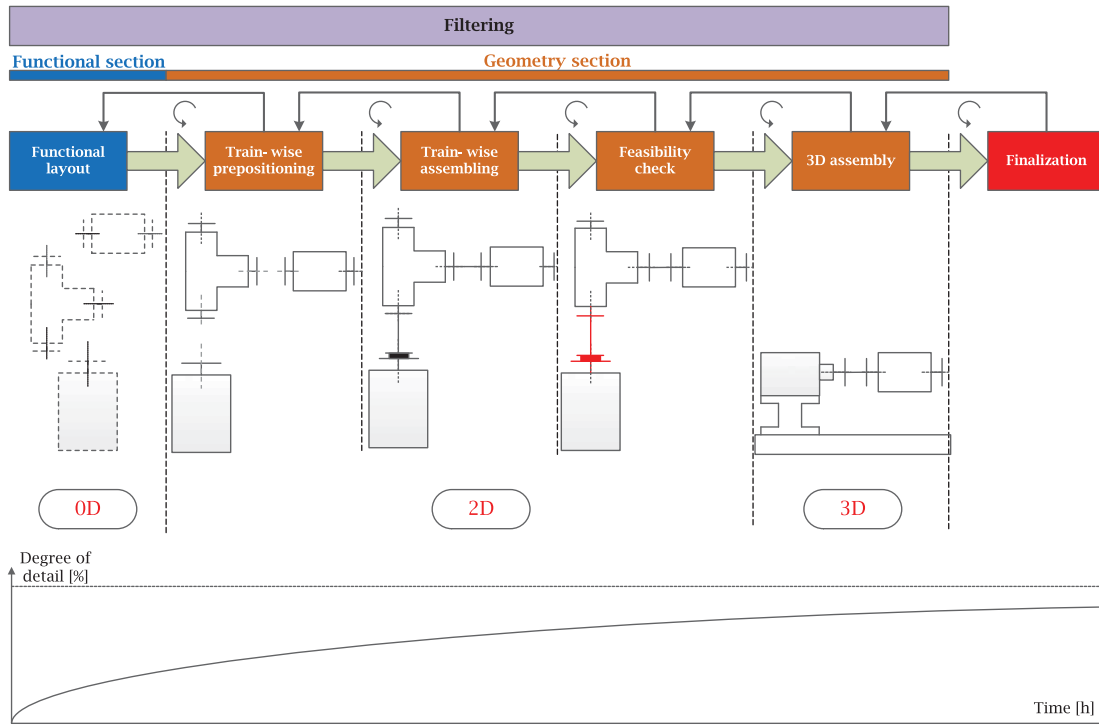
Fig. 6:   Principle workflow of the semi-automated test bench assembly method.
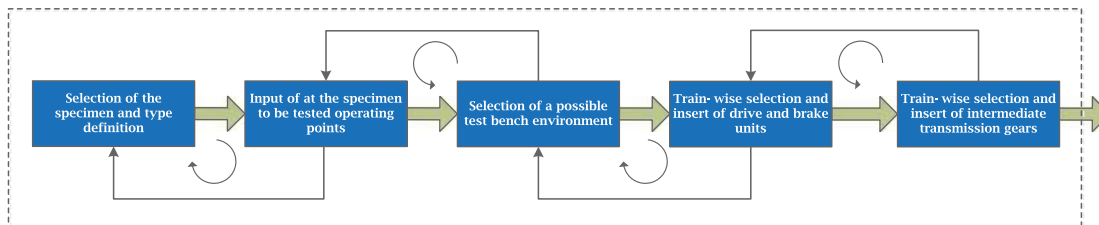

Fig. 7:   Workflow of the functional layout design process.

user has to select the participating parts. The tool then automatically detects all pre-defined reference elements within these parts and gives the user the possibility to select them. The user-selected elements are directly displayed in the CAD environment. When the desired elements have been chosen, they are automatically aligned by the tool. As the height differences of trains in a powertrain test bench are normally small in comparison to their longitudinal and lateral dimensions, a two-dimensional bird's-eye view within the 3D-CAD environment is applicable during the positioning processes. Nevertheless, the user always has the possibility to apply interactive changes within the general 3D model.

After the first prepositioning actions have been done, further components, like torque load cells, cardan or homokinetic shafts, can be inserted into the assembly. As discussed above, these torque transmitting components are normally coupled by different types of flanges. With the help of the filter tool, the database is searched for components, which

fulfill given coupling criterions. If a suitable component is found, it is inserted and coupled to the desired component. The coupling process within the assembly environment is performed automatically by use of the automated part coupling tool. Principally, the tool detects and couples flanges inside the respective components, which are (geometrically) free and fit together. The automated coupling process itself works similar to the automated prepositioning process. Pre-defined axes and planes inside parts, which define flanges, are detected and set coincident.

At this stage of the assembling process, frequently two parts have to be coupled with a specific distance by any or by a particular torque-transmitting component. In case that no suitable component can be found in the database, the automated part creation tool is started. Commonly used components, like shafts or flange adapters, can be created automatically out of templates and inserted in the desired type and in the required geometrical dimensions. Possible limiting
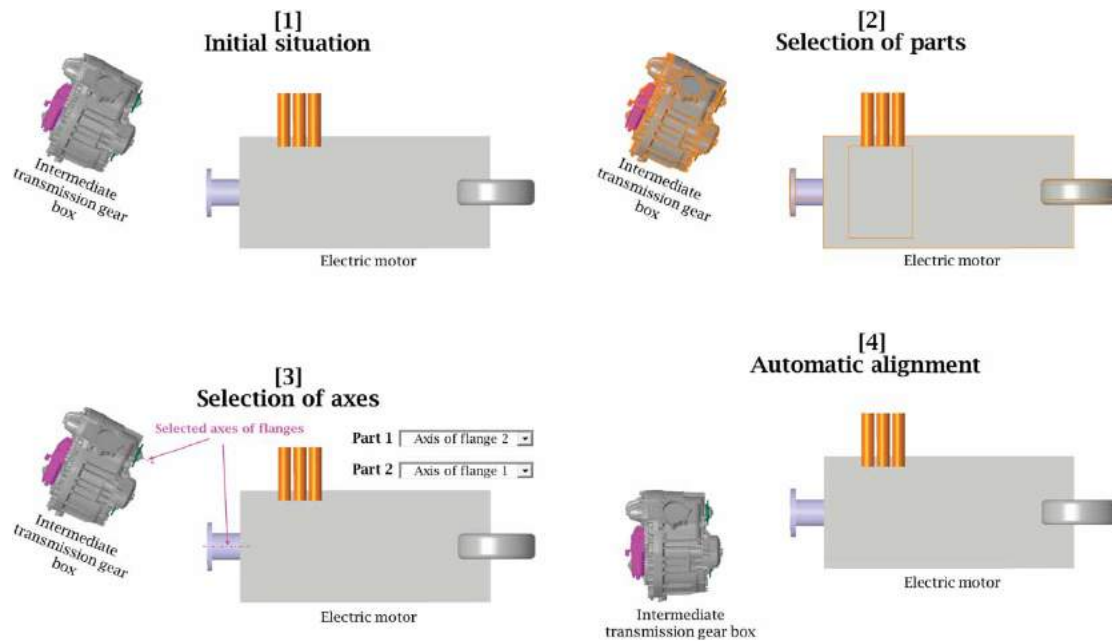
Fig. 8:   Exemplary prepositioning process in a two-dimensional view by the use of predefined axes.
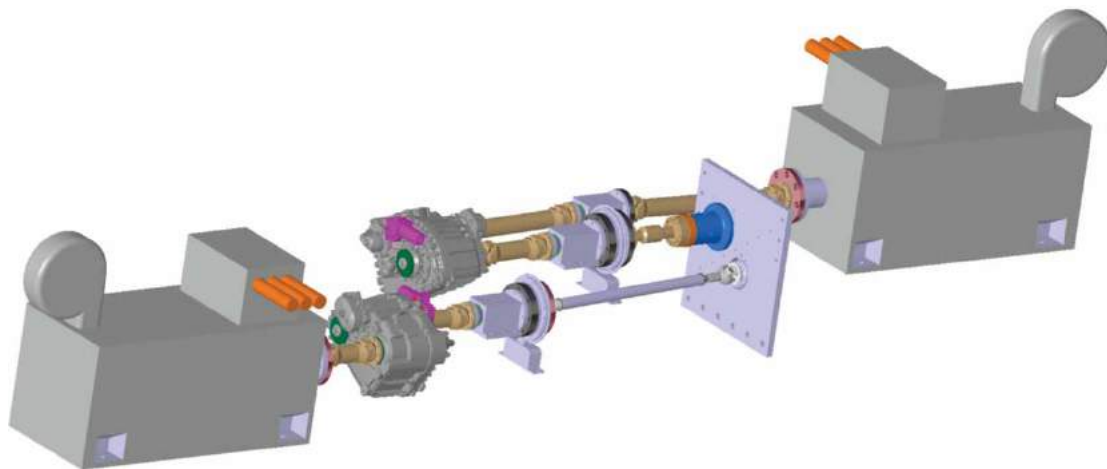

Fig. 9:   Build-up of an entire train system by use of the semi-automated test bench assembly method.

factors from suppliers are considered, as they can be retrieved from the supplier database.

After the entire train system has been created, the test bench feasibility check tool is applied. A configuration of a train system by use of the presented method is shown in Fig. 9 exemplarily. As the layout and the loading conditions of each component in every train are known, automated checks regarding strength, power flow or connectivity of individual components are performed without any user-oriented effort. In case, that these checks have a positive outcome, the design of a powertrain test bench configuration is finalized. Substructures, fixations or miscellaneous components can then be efficiently filtered and inserted by the filter and insert tool. These parts are positioned by conventional available positioning

tools within the 3D-CAD environment. Finally, the presented method enables the automatic creation of bills of materials, orders for suppliers and shop drawings for the actual test bench.

During the entire process of assembly, data exchange between the semi-automated layout creation tool and the layout database takes place. In the layout database, layout metadata of the present test bench configuration is stored. It represents a multidimensional database, which consists of several lists. Thereby, a list in the database itself can represent a complete train of a test bench configuration. Every time a new part is inserted into the assembly, the part is inserted in the database as well. When a part gets coupled to another part, a respective entry is done in the database again. Therewith,

a complete representation of the present test bench layout is possible. A database-based representation of a powertrain test bench offers several advantages and possibilities:

- Feasibility checks, like strength analyses of used shafts, can be efficiently performed by the system, as the loading conditions of the individual components are known.
- It can be easily checked, if the present test bench is in compliance with the predefined functional layout.
- All trains of the test bench can be checked for completeness and consistency regarding part couplings.
- Former created test benches can be analyzed, modified and adapted efficiently.
- In automatable processes, like the generation of bills of material, additional relevant metadata can be added and stored.

4. CONCLUSIONS

The conventional design of a powertrain test bench is a rather time-consuming and expensive task, which needs to be done by experienced and involved engineers. With the presented method, a collaborative solution for several test benches has been introduced, which provides a user-friendly application and enables a significant reduction of time and costs in the design process of industrial applications. The design effort decreases significantly, because the semi-automated test bench assembly method considers all suitable, existing and currently available parts and allows a quick connection within the CAD-based assembly environment. Not existing, but frequently used components, like shafts or flange adapters, can be easily created and inserted automatically in required dimensions. The implemented coupling and positioning tools accelerate the assembling process significantly, but require a manual pre-definition of reference elements inside the individual parts before. An implemented feasibility check tool examines the train system for its accordance with geometric and functional boundary conditions. It does not analyze or optimize the test bench functionality or components in detail, but checks general

limiting factors, like clashes or sufficient dimensioning. The necessary metadata for that is stored in the respective databases.

In general, the design of a powertrain test bench represents a very challenging task, where many engineering skills are needed and influencing factors have to be considered. Therefore, it is not possible to design a complete test bench at the press of a button. Thus, the user is supported by the method as far as possible but always has the opportunity to take its own interactive decisions. For this reason, the full potential of the semi-automated method may be limited to the design of rather usual types of powertrain test benches. Otherwise, it is always possible to work in an advanced manual mode, where specific components can be filtered, inserted or created in a very effective way. By integration of knowledge-based CAD, computation processes for functional layouts and a comprehensive database structure, the presented method is able to support test bench configuration in a broad field of applications.

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