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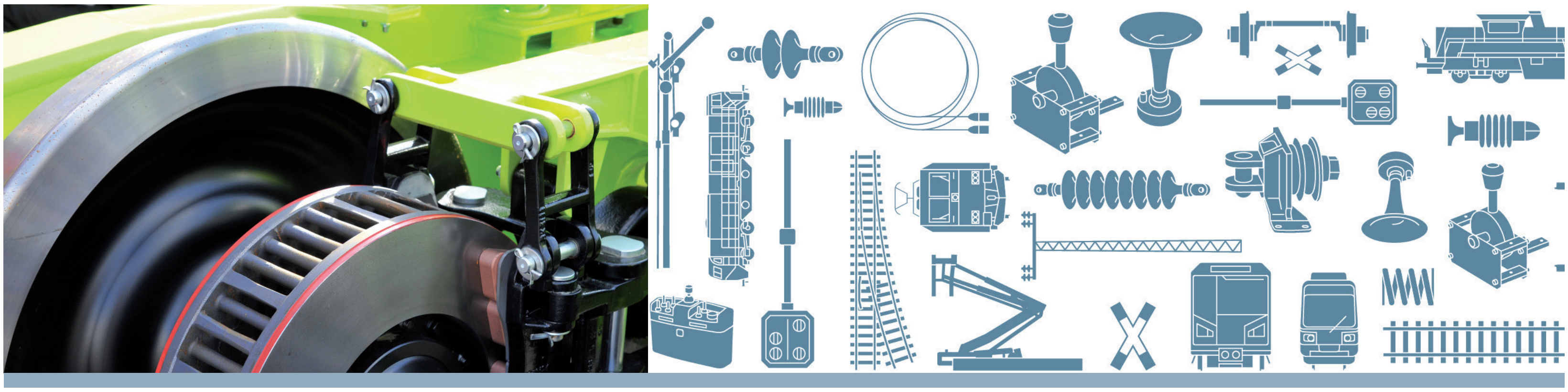
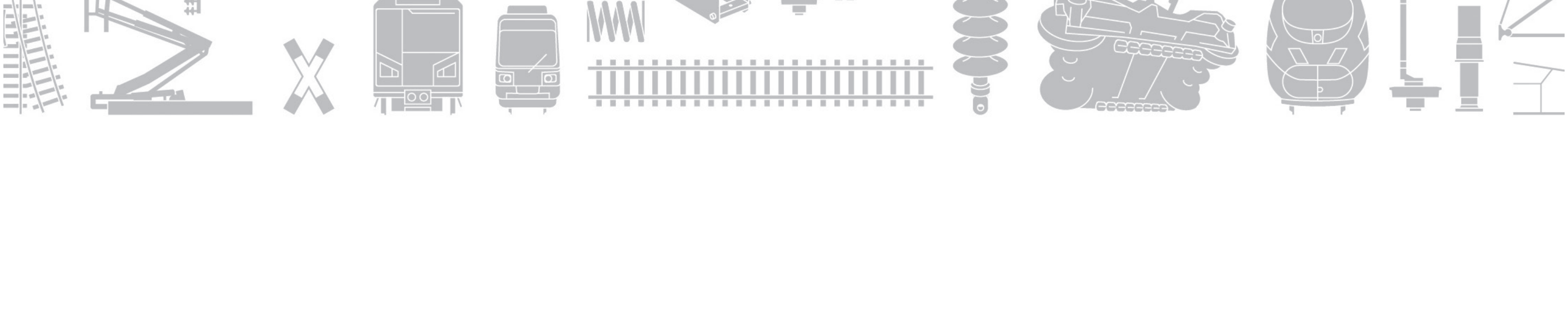


Verband der Bahnindustrie in Deutschland (VDB) e.V.

VDB-Guideline

Quality Engineering during Design phase of Rail Vehicles and Rail Vehicle Systems



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Preamble

The rail industry and the rail operators have the common goal of commissioning rail vehicles of high quality and on agreed terms and conditions. One key role is their **development** in the appropriate quality – because increasing performance requirements placed on the **products** and ever stricter laws and approval regulations (e.g. relating to the environment or European harmonisation) demand adaptations in the product design of rail vehicles.

Terms shown in bold type are explained in the glossary

To this end, the German Railway Industry Association (VDB) and Deutsche Bahn AG (DB AG) issued a memorandum of understanding on their decision to launch a quality partnership for the development of rail vehicles. It is intended to bundle the knowledge, experience and competencies of the rail industry and the operators. This guideline represents an important element in the quality partnership.

This guideline describes a process model using methods from **Quality Engineering** (QE process model). Due to this model, the parties involved in the manufacturing process are able to recognise risks already at the early stages of design and thus avoid them. The described actions for quality assurance place the main emphasis on trustful co-operation by the players in the development of rail vehicles and their subordinate **systems** (**sub-systems**).

This guideline is recognised by the VDB's member companies as the "industry standard". In the future it will be taken into account during the design/engineering of rail vehicles and their systems. It aims to advance the engineering in companies in the rail industry through the application of quality management methods, to minimise risks and to improve the transparency of the supply chain. The guideline indicates the options for achieving this. The companies themselves are responsible for implementing the resulting requirements for the engineering in a suitable manner. However, the minimum standard achieved should be that set forth in the guideline:

- Establishing structured product design processes, taking technology readiness and **integration readiness levels** into account;
- Evaluating the system through systematic analysis of **functional and non-functional requirements** (checklists) and review them after changes have been made;
- Demonstrating specific actions for assuring the quality of the design process right at the outset based on a quality plan and their consistent implementation with documentary evidence;
- Assessing the **readiness levels** using the QE process model upon completion of each phase (and communicating the results to the client).

The QE process model is intended for introduction throughout the rail industry and should be applied during the entire development process of a product. To avoid influencing competition, the guideline will initially apply only after the tender phase. However, it is expedient to apply the process model also during elaboration of the offer.

The increased transparency, the identification of a system's critical elements, and the actions to be derived therefrom are all of great importance for the offer.

Application of the methods and processes should concentrate on early error prevention. The associated systematic assurance of results reduces the effort needed for and the costs of subsequent corrective actions. A gradual introduction can compensate the initial temporary extra effort.

Furthermore, the rail industry expects a reduced effort due to the optimised monitoring of development projects by applying this guideline. Quality Gate Reviews should be streamlined and the results of the QE process model should feed into them. Evidence of the readiness levels which is of equivalent quality and quantity should be recognised during this process.

This guideline was developed jointly by the major market participants. It is planned that its contents will be incorporated into the ongoing development of the International Railway Industry Standard (IRIS). The guideline is not restricted to companies engaged in development activities in Germany, but should also be applied and implemented in the international context.

In addition, this guideline will help in generating the requirements more functional and in limiting detailed descriptions to those elements which need standardisation across multiple projects, e.g. for **integration** into an existing infrastructure or in the case of standard solutions.

Thanks to all these aspects, manufacturers and operators alike can achieve the desired results and thus contribute to the continuing partnership-based development of the rail sector.

1| Objectives of the guideline

Enhanced co-operation and communication

Even closer co-operation between manufacturers of rail vehicles and their suppliers is one aspect of the future viability of the railway industry. One of the things needed for achieving it is a common understanding of the requirements and the path towards qualitative assurance of results and deadlines, intensive and frank communication about the necessary actions, and transparency concerning these topics between all those involved along the entire supply chain.

This guideline is intended to contribute this process by providing assistance in deriving preventive actions for the assurance of development projects in the railway industry, which take the development status of the overall system and those of the sub-systems into consideration. This will markedly reduce the development risks.

Accomplish a common understanding of Quality Engineering

Furthermore, the guideline should achieve a common understanding of quality engineering and the use of quality engineering methods (QE methods) within the supply chain. It also describes how critical elements can be systematically identified at an early stage. At the same time it outlines approaches for value-based and targeted deployment of preventive QE actions in the development of complete rail vehicles and their subordinate systems and/or components. The guideline enables the manufacturers to concentrate on those actions that have been identified as relevant and effective.

Commissioning of rail vehicles on the agreed terms and conditions

This guideline is intended to assist in achieving the common objective of operators and manufacturers: commissioning high quality rail vehicles on the agreed terms and conditions – for example those applying to technical properties, deadlines and costs.

Establish transparency and comparability

Application of the guideline enables:

- the comparability of the development statuses of the individual systems from which a rail vehicle is constructed;
- the realistic, comparable description and assessment of the quality assurance actions and inputs required for the development goals to be achieved with certainty.

These objectives are achieved through application of the QE process model. It uses readiness models as a basis for focusing on identifying the development statuses of the superior and subordinate systems within a vehicle project. It also makes it possible to track the progress of development by means of comparison with a product design process as a reference and using defined items of evidence throughout the development process.
This comparison is based on a systematic, standardised analysis of the complete superior system and the subordinatesub-systems of the rail vehicle.

The analysis takes account of the **function view** and the component view, and enables identification of those elements in a system that exhibit the lowest level of readiness. The necessary QE actions are derived based on the **deviations** from the target statuses of the product design process (PDP). This guideline proposes QE methods depending on the degree and the type of deviation and the time of its occurrence. It is then up to the manufacturer or developer to draw up a QE action plan for each system.

Assuring innovation

The railway industry works on advancing the technology in rail vehicles with the aim of long-term success on the market. In this process, readiness models can be used to describe the statuses of systems, in order to pinpoint risks and obtain a transparent view of the quality assurance needed for innovations. For the analysis, a system with a low level of readiness in combination with a plausible action plan for assuring the objectives within a defined time frame is regarded as equivalent to a system that already exhibits a higher level of readiness.

Minimising efforts

At the beginning of a project, the QE process model requires a certain amount of initial efforts, but gains in the later phases compensate for this. All the analyses are conducted on the basis of standard checklists with questions about defined topic areas – so relevant topic areas and their status are systematically recorded. As the QE process model is applied more frequently, learning effects become apparent which decreases the initial amount of efforts. This guideline recommends the manufacturers to integrate the processes of the QE process model into their corporate processes, in order to avoid duplicated effort that could arise due to inadequate synchronisation of the contents of their development and quality processes with the QE process model. This applies in particular given that the functional description of systems by the clients is becoming ever more important. This have to be taken into consideration equally by the manufacturers and the suppliers of sub-systems in their development processes.
The analyses of the development statuses of systems also build on the function view.

2| QE process model

There are two basic approaches for developing rail vehicles (Figure 1):

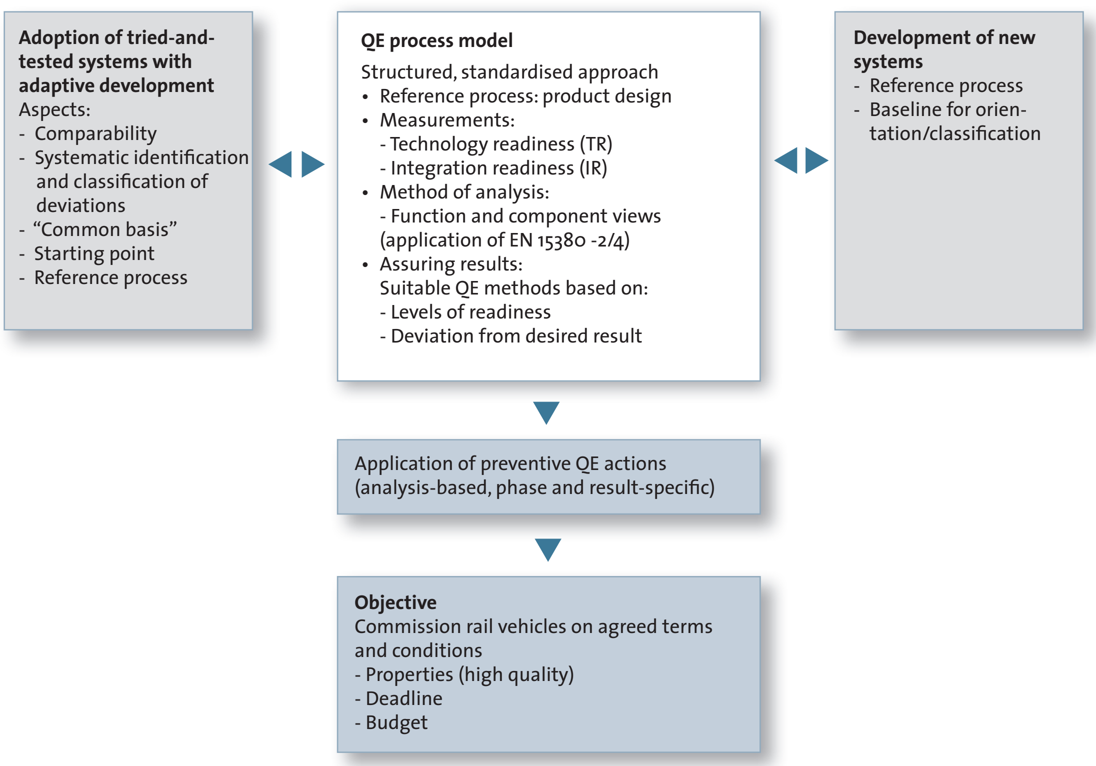
1. Adoption of tried-and-tested systems with adaptive development: the manufacturers construct new rail vehicles by evolving them out of tried-and-tested systems.

   This approach focuses principally on integrating the subordinate systems into the new, superior overall system. Another major focus is the analysis of the **boundary conditions** – for example amended licensing regulations and laws, other use profiles or changing installation conditions. Other factors include changing performance requirements placed on the systems.

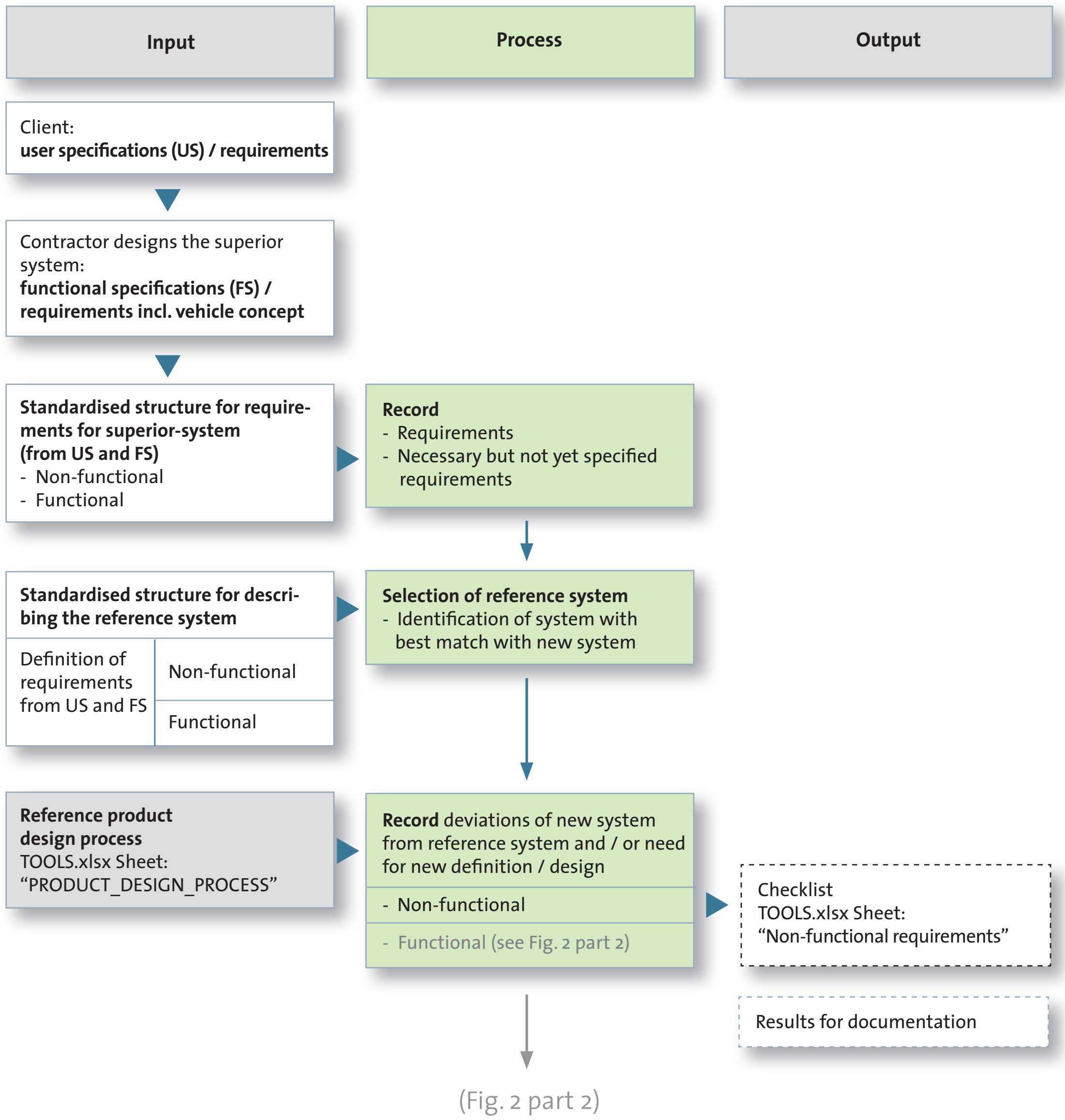
   The developers must identify how the requirements of the existing system differ from those of the new system, and use this information to derive the necessary actions. This procedure is applied in most rail vehicle projects.

2. Developing new systems and new sub-systems: a high degree of innovation is required to develop new rail vehicles or sub-systems.

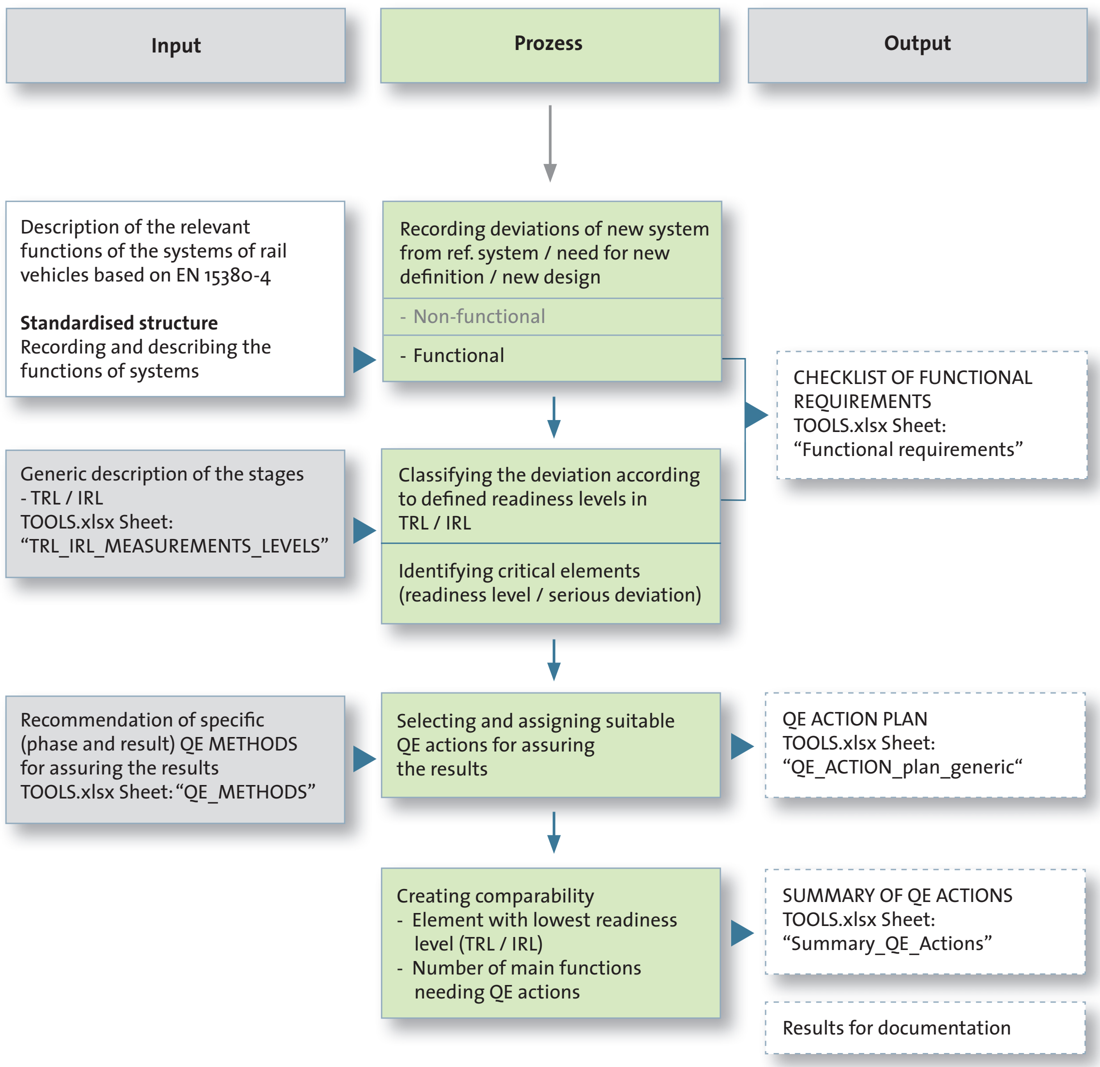
QE process model (Fig. 1)



Process steps in the QE process model (Fig. 2 part 1)



Process steps in the QE process model (Fig. 2 part 2)



In this approach, actions for assuring the necessary results are of great importance in every phase of product development.

In both approaches, the developers should assure their results by means of progress checks. The generic product design process (PDP) provides orientation; this process assigns specific development goals to the individual phases. Development risks can also be reduced by recommendation of preventive QE methods specific to the phase and the result.

The QE process model is based on the following elements:

- Product design process (PDP) with defined objectives for the phases as the reference process;
- Measurements for determining the development status: technology readiness level (in TRL) and integration readiness level (in IRL);
- Analytical methods for evaluating the status of systems and their deviations from comparator systems, from the function and component views;
- Assuring results by recommending appropriate QE methods based on the levels of readiness and the deviations from the desired result.

Figure 2 (parts 1 and 2) describes the steps in the QE process model and the relevant inputs and outputs. A structured and comparable approach is possible due to checklists for the inputs, the generic product design process, the stages in determining the levels of readiness and the recommendation of QE methods for assuring phase-specific results. The QE process model provides output in the form of systems' development status. Uniformly structured checklists and action plans ensure that the status is transparent and comparable.

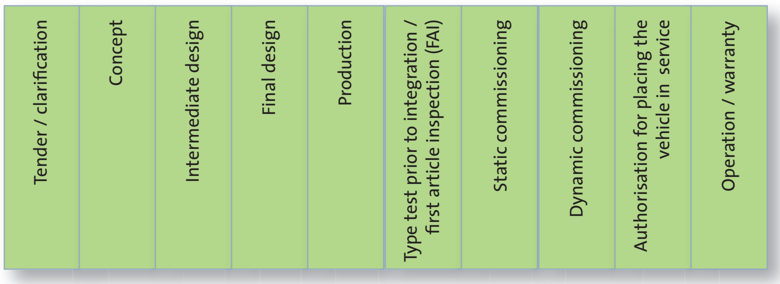
3| Elements of the guideline

3.1 Product design process (PDP) for rail vehicles

This guideline describes the procedure within the product design process (PDP) for rail vehicles, from the "Tender" phase all the way to the "Operation/warranty" phase (Figure 3). The development methodology is function-based: the starting point for the design process is the functions that a system has to fulfil. The required construction elements are also derived from these functions.

The PDP therefore describes the results of every design phase from the function and component views. The desired results for each phase and the standard structure of the PDP allow different systems to be compared. When existing solutions are transferred to a new project, the PDP makes it possible to allocate a system to a design phase on the foundation of objectively verifiable results.

Generic reference process: product development process (Fig. 3)



The PDP of the QE process model represents a generic process with specific quality assurance actions defined for each development phase. In addition, the results that have to be achieved in each phase are defined, along with the evidence required to show that they have been achieved. The PDP is therefore a product-oriented process. By contrast, the specific development processes of the manufacturers are frequently oriented on the workflows in development. The manufacturer has the task of transferring the requirements for development phases to its own development process.

The PDP is divided into generic phases, the first of which is the tender phase and the last is the warranty phase. The PDP includes the engineering phases "Tender", "Concept", "Intermediate design" and "Final design". These phases are structured in line with the procedure set out in the VDI guidelines 2206 (Design methodology for mechatronic systems) [VDI 2206] and 2221 (Systematic approach to the design of technical systems and products) [VDI 2221]. The other phases are oriented on the railway vehicle handbook "Handbuch Eisenbahnfahrzeuge" [BUN 2010] and on the established practice for commissioning rail vehicles.

Milestones describe the results that have to be achieved upon completion of the individual phases. It can thus be ascertained whether the respective objectives have been reached. Readiness models add more precise detail to this classification: they use systematic, standardised questions about predetermined categories in defined stages to present the status of development projects in a comprehensible and transparent manner. The readiness models and the stages are described in detail in section 3.2.

The milestones also provide the basis for co-ordination and synchronisation within the supply chain. Here the developers do not have to adhere exactly to the **reference process**, but instead it serves to indicate which results in the individual phases are helpful for achieving the objectives. The developers of the systems are responsible for taking these results into consideration during their work.

Figure 4 shows the phases of the PDP and the categories of results, which allow systematic, phase-specific evaluation of the phase-specific results. It also describes the phase-specific results of project management and quality management. They determine such things as the content and timing of communication in the supply chain and the preparation of quality engineering action plans (QE plan).

Schematic diagram of the product design process (PDP) (Fig. 4)

	Project phases	Tender / clarification	Concept	Intermediate design	Final design	Production
	TR-levels	3.1	3.2	3.3	3.4	
	IR-levels	I	II.I	II.II	II.III	
Product development	**Development phase**	Planning - requirements for information - Compilation - Recognition of gaps	Conceptual design - Functional structures - Basic solutions	Drafting and designing modular structures Elaborating solutions/ functional structures	Overall draft design	
	Function view	Specifying and describing main functions	Specifying and describing overall function and major sub-functions Specifying how functions are fulfilled (draft system design) by functional structures (incl. sub-functions) and operating principles and/or functional architecture control)	Division of elements for control (hard-wired/software; superior/subordinate)		
	Component view	General arrangement of structure/space is determined (black box)	General arrangement of structure/space is determined (black box)	Design of key modules (sub-systems and system elements, e.g. assemblies, individual parts), including linkages (interfaces) / programming the software modules (control)	All major design decisions have been made, Completion of design and linkage of all components / software modules (control) of the system	
PM - superior/subordinatesystem		Agreeing project communication / status / duty to provide or collect information / format of communication (e.g. VDB Requirement Interchange Format / RIF) with the aim of exchanging as much concrete information as possible Schedule with fixed co-ordination times for interfaces	Procedural strategy for the co-ordinating with the operator (final customer) and for the support of the system supplier by the sub-system supplier; Project-related exchange of information between superior/ subordinatesystems, e.g. change management, regular co-ordination after each phase; Step-by-step approach for synchronising the entire supply chain	Entire supply chain is synchronised Project-related exchange of information between superior/ subordinatesystems, Active life of change management (bilateral) for all co-ordinated topics - regular co-ordination after each phase Ongoing documented progress tracking	Project-related exchange of information between system and sub-system, Active life of change management (bilateral) for all co-ordinated topics - regular co-ordination after each phase	
Q management / QE plan		QE plan for systems based on readiness level analysis (TRL /IRL) Plan for elements not yet taken into account	Updated analysis-based QE plan - evaluation of the elements on the critical path - review after each phase Action plan for elements not yet taken into account			

Reference product design process: determination of desired results for each phase
- Provides orientation
- Deviations indicate a need for further analysis

Separate detailed presentation available at www.bahnindustrie.info

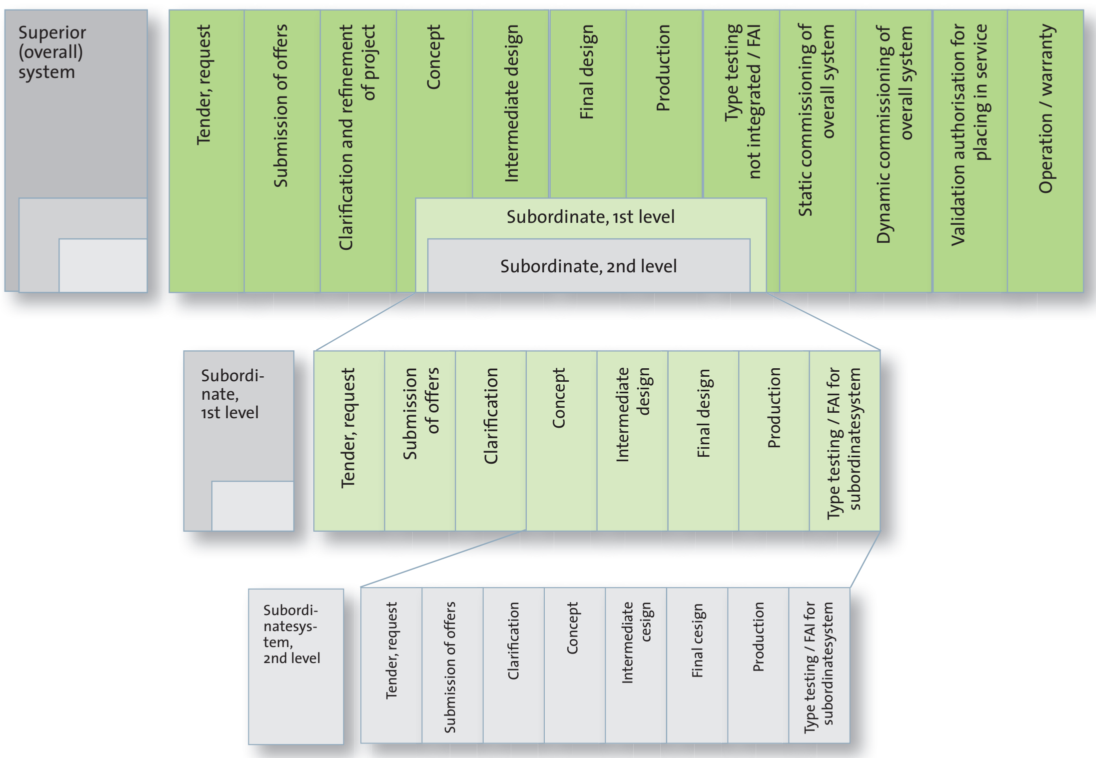
Production	Type test prior to integration / first sample test (FST)	Static commissioning	Dynamic commissioning	Authorisation for placing the vehicle in service	Operation / warranty	
	4	5	6 / 7	8	9	
	III	IV.I	IV.II	IV.III	V	
	Assurance of properties through verification / validation					Product development
	Experimental vehicle Near-series product First sample	First sample / series element integrated into superior system	First sample / series element integrated into superior system, Adaptation / programming of integrative part (higher / subordinate system) of software (control) as far as dynamic commissioning	Series element integrated into superior system	Series element integrated into superior system	
	Project-related information exchange between system and sub-system Actively living the change management (bilateral) for all co-ordinated topics - regular co-ordination after each phase					PM - superior/subordinatesystem
	Updated, analysis-based QE plan - assessment of the elements in the critical pathway - review after each phase Plan of action for elements not yet taken into consideration					Q management / QE plan

Integration of the supply chain during the development of rail vehicles is a major factor affecting success – because the overall systems are built up from sub-systems, and the majority of them have to be either adapted and/or developed specifically for each project. The current state of the art is modular solutions and platform solutions. The systems are developed in advance for specified use cases. However, the manufacturers have to ensure that the original requirements placed on the systems correspond to the requirements of the new system. Here, too, the QE process model helps developers by enabling them to conduct a systematic analysis for identifying deviations. In some cases the requirements placed on the subordinate systems cannot be specified until the concept phase for the superior system, since prior to this not all the required information is available. For this reason, these systems can only be developed after this point. As a rule this reduces the time available for developing the subordinate ssystems. The risk of this happening can be minimised using the simultaneous/concurrent engineering procedure. To incorporate the subordinate systems into the superior system, they have to be physically integrated into the overall system following the type testing and first article inspection and at the latest at the time of static commissioning. However, it is possible that the integration has to take place much earlier in the assembly process, depending on the individual project. In such cases the design process for the subordinatesubordinate systems starts after that of the overall system, although it ends before that of the overall system. The development period for the sub-systems has to be shorter than that for the overall system. The cascade relationship between the partners in the supply chain is shown in Figure 5.

The cascade within the supply chain (Fig. 5)

Cascading the PDP from the overall system to the supply chain: superior (overall) system manufacturer > subordinatesystem manufacturer > subordinate(component) system manufacturer

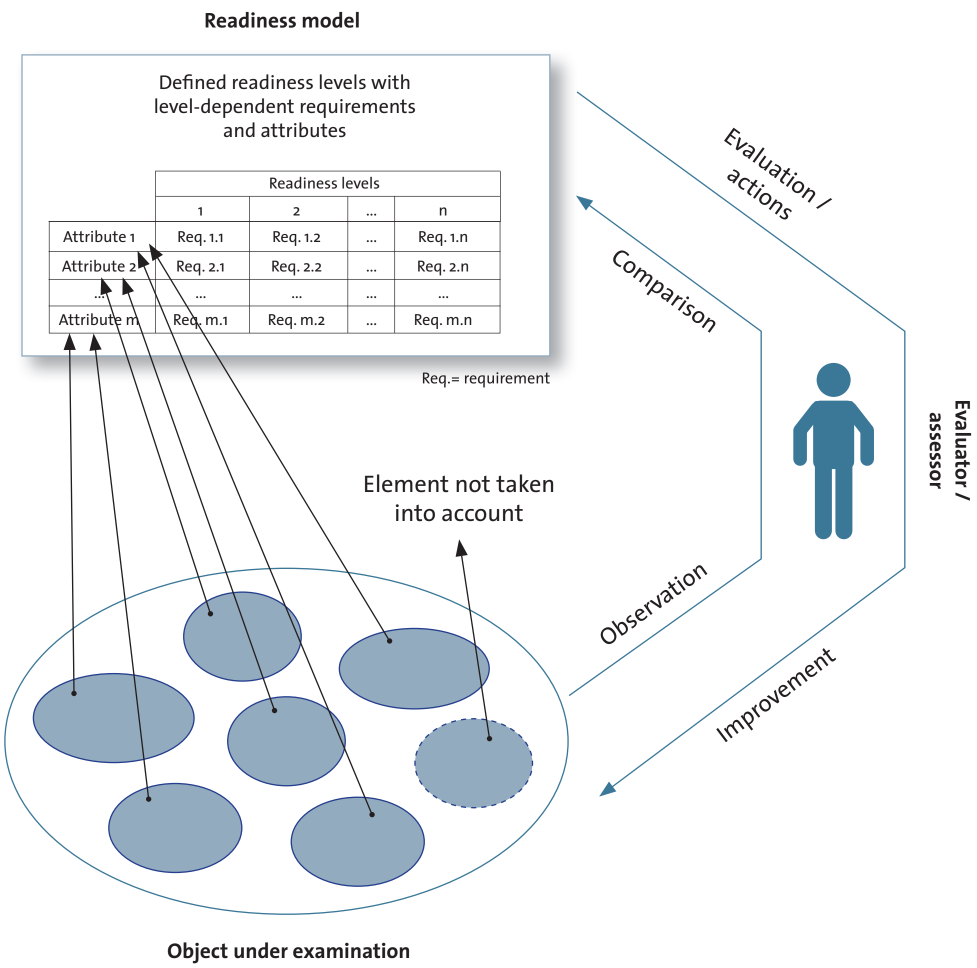
The PDPs of the superior and subordinatesystems (supply chain) have the same structure. The PDP of the subordinatesystems / supply chain is compressed and starts with a time lag



3.2 The models for technology readiness level (TRL) and integration readiness level (IRL)

Readiness models make it possible to determine the development status of complex systems in a transparent and comprehensible way. The level of readiness is evaluated on the basis of specifically defined attributes, to which various requirements are assigned stage by stage. The degree to which these requirement stages are fulfilled determines the system's level of readiness. Readiness models thus make the progress of complex systems transparent during the process of product development. Not only the defined attributes play a key role here, but so do regular evaluations of the system in a predetermined schedule – frequently during each phase. Figure 6 illustrates the basic structure of readiness models.

Principle of readiness models [AKK2013] (Fig. 6)



A level of readiness is regarded as reached only when not only the local criteria for that particular level have been met, but also those described at the previous stage (so each level of readiness builds on the previous ones [AHL 2005]). If this is not the case, the level of readiness of the system is reset to the level that has already been fulfilled. A system reaches a higher readiness level only if it fulfils all the criteria defined for the higher level – the level of readiness is always determined by the weakest part of the system.

Readiness models have already been successfully established in other sectors, too, e.g. the aerospace industry, which applies levels of technological maturity (Technology Readiness Levels). These do not differ in their fundamental logic, but this guideline for rail vehicles considers technological readiness and integration readiness separately and then combines them, because here as a rule established sub-systems are linked with innovations.

Following on NASA's maturity model, the technology readiness model for rail vehicles consists of nine levels, whereby the engineering phase is divided into the four sub-levels TRL 3.1 to TRL 3.4. They represent development progress in this phase of the process – which is crucial to project success. The underlying phases are derived from the generic development phases in the VDI design guidelines 2206 and 2221 [VDI 2206, VDI 2221].

The phases in the assurance of properties are oriented on the established verification and validation processes for rail vehicles.

The integration readiness model (IRL) consists of five levels and here, too, the engineering phase is divided into sub-levels. The levels IRL II.I to II.III cover the step-by-step co-ordination process of interfaces between the superior/subordinatesystems. Step-by-step co-ordination is generally indispensable here, as short project duration usually demands that the systems are developed simultaneously. The assurance of properties is also sub-divided into the phases IRL IV.I to IV.III, to make the progress during commissioning measurable here as well.

Figure 7 describes briefly what the TRL and IRL readiness levels contain.

Brief description of technology and integration readiness levels (Fig. 7)

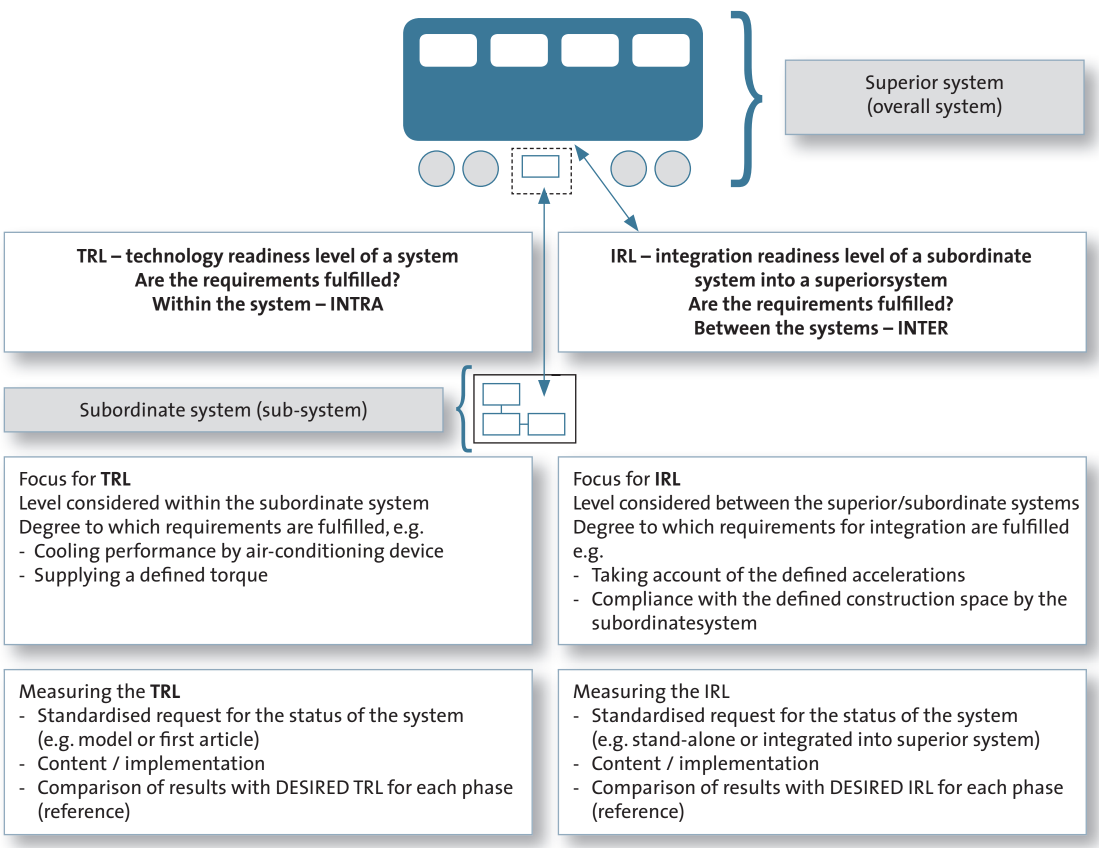
	Brief description of IR levels	Major IRL-TRL interaction	Brief description of TRL levels
Definition/ clarification	IRL I Main functions are defined and divided between systems (model) Interfaces and interaction are determined (model)	Superiorsystem defines subordinate system's boundary conditions and functions →	TRL 3.1 Requirements and boundary conditions are described Main functions are defined
Design	IRL II.I Determination of all cross-system functions (incl. ancillary and derived functions; functional architecture), Functional structures and operating principles (model); generation of complete information for subordinate system (functional, non-functional) (model)		TRL 3.2 Product (model) conceptual design is complete Association of function<->operating principle<->construction element
	IRL II.II Detailed determination of interfaces for elements of the specific phase (model), Description of data interface for sub-systems that are characterised by complex software and have feedback loops to the circuit diagram of the train and/or between the systems (model)		TRL 3.3 Construction elements (model) of a functional structure fulfil requirements placed on this functional structure Determination of assurance of properties (verification / validation principle)
	IRL II.III All overarching functions are fulfilled (model) Detailed determination of all interfaces (model)		TRL 3.4 Design of all construction elements is complete (model) All construction elements are integrated into the system (model) Interacting elements fulfil the requirements (model)
Assurance of properties isolated	IRL III Defined input from superior system fulfils / triggers defined function in non-integrated subordinate system From viewpoint of subordinate system, testing of connection to superior system and other systems	Subordinate system fulfils boundary conditions and functions ←	TRL 4 Evidence that all requirements are fulfilled by the first sample that is not integrated into the superior/subordinate system (experimental set-up with system qualification brought forward) to the extent defined and verifiable for the type test and first sample test (FST)
Assurance of properties integrated	IRL IV.I Defined interaction fulfils / triggers defined function / feedback on the initial sample integrated into the superiorsystem under static conditions		TRL 5 Evidence that all requirements are fulfilled by the first sample that is integrated into the superior system under static conditions
	IRL IV.II Defined interaction fulfils / triggers defined function / feedback on the initial sample integrated into the superiorsystem during test or trial operation	↔ Assurance of properties through integration of superior/ subordinatesystems	TRL >= 6 Evidence that all requirements are fulfilled by the first sample that is integrated into the superior system under simulated use conditions (test operation) TRL >= 7 .... under realistic conditions (trial operation)
	IRL IV.III Defined interaction fulfils / triggers defined function / feedback on the series product integrated into the superiorsystem under approval and acceptance conditions		TRL 8 Evidence that all requirements are fulfilled by the series product that is integrated into the superior system under approval and acceptance conditions
	IRL V Defined interaction fulfils / triggers defined function / feedback on the series product integrated into the superiorsystem under operating conditions	↔	TRL 9 Evidence that all requirements are fulfilled by the series product that is integrated into the superior system under operating conditions

The TRL evaluates the degree to which a separate system achieves a certain functional capability. It focuses on the fulfilment of the requirements placed on the system: it describes the performance of this system.

The integration readiness evaluates the degree of fulfilment of the functional capability of the combination of several systems. It indicates the status of the system as compared with the superior system: does it meet all the requirements for being integrated into a superior system and satisfying its requirements in this environment?

Technology readiness and integration readiness are compared and contrasted in Figure 8.

Comparison of technology readiness and integration readiness (TRL/IRL) (Fig. 8)



- Superior system defines the requirements placed on integration (functional / non-functional)
- IRL can be applied between all superior/subordinate systems in the supply chain
- Subordinatesystem reports degree of IRL fulfilment to superior system
- Independent view of TRL / IRL is possible only with identical requirements / framework conditions (platform solutions must be validated for all requirements of a new application project)
- Changes to the boundary conditions generally lead to changes to systems => new analysis / classification

When the degree of fulfilment is measured, all requirements have to be taken into consideration – the non-functional requirements and the functional ones alike. The requirements for integration are largely defined by the superior system: the subordinate system must satisfy both these requirements and its own, and report the degree of fulfilment to the superior system. The requirements arising from the integration have a crucial influence on the development of a subordinate system – its realisation is, for example, greatly affected by the construction space available and the regulations that have to be satisfied.

The requirements placed on the subordinate systems to be integrated must therefore be known at the start of their development. If that is not the case, assumptions are frequently used in practice. If the assumptions are not correct, a large number of decisions have to be revised – which as a rule results in duplicated work and extra time. Innovations and/or components at **technology readiness levels** 1 and 2 generally do not come into question for the realisation of specific rail vehicle projects, but instead are developed independently in advance.

For a system to be allocated to a readiness level it is necessary to analyse the systems according to their properties (e.g. physical state of the product, function, **component**) and to determine levels of fulfilment of the requirements. The desired parameters for the levels are given in Figure 9. The levels are oriented on the generic product development process. For this reason, the phases of the PDP and those of the readiness levels are identical. The function view is of special importance: although the development processes of systems are mostly based on the functional requirements, when they are analysed the emphasis is frequently on the component view. However, the readiness levels will be comparable only if consideration is given both to the function view and to the component view.

Specific classification in the different levels in the TRL and the IRL is carried out based on achievement of the desired results and/or the evidence for the process phases to which they are allocated (see Figure 9). The desired results of the process phases are divided into the categories of the system's status (e.g. model, first sample), the function view and component view. The table also specifies evidence of achievement of the desired results.

Figure 9 shows the table for determining the readiness levels.

Prinzipdarstellung zur Bestimmung der Reifegradstufen (Abb. 9) Teil 1

	Project phases	Tender / clarification	Concept	Intermediate design	Final design	Production
	PDP development phase	Planning - Requirements for information - Compiling - Identifying gaps	Conceptualisation - Functional structures - Basic solutions	Drafting and design of modular structures Elaborating solutions / functional structures	Complete draft design	
	Physical state / conditions for testing	Model Simulation / description				
TRL	**Level of technology readiness**	3.1	3.2	3.3	3.4	
	Function view	Complete information on interaction (physical, process technology, information, etc.) with other systems (integration), e.g. which accelerations must be taken into consideration Solutions for critical requirements Main (i.e. crucial) functions are defined	Functional structures and principles for all functional requirements Assignment of function/principles of action to construction element Product's conceptual design is complete - System draft (multi-domain solution concept)	Definition of assurance of properties (validation principle)		
	Component view	Complete information and description of system attributes Laws, regulations, standards Use profile, vehicle config. Customer's special requirements Interfaces (material, energy, information) to the construction components to be designed, e.g. structure/space for construction, climate, dynamic, etc.		Construction elements of a functional structure fulfil requirements placed on this functional structure Definition of assurance of properties (verification / validation principle)	Design of all construction elements is completed All construction elements are integrated into the system Interacting elements fulfil requirements	
	Evidence for TRL	- Basic vehicle structure („PowerPoint design") - Clause-by-clause commentary on the requirements of the functional specifications - Designation of the relevant main and sub-functions based on EN 15380-4, second level - Description of the deviations pursuant to checklists for „non-functional requirements" and „functional requirements"	- Conceptual specifications - Overall layout (elaborated vehicle structure) - Installation spaces - Draft total weight - Interface description is available	3-D model (preliminary)	- Transfer of all production documents - Approval of circuit diagrams - Approved validation plan incl. rough definition of evidence required (type tests)	
IRL	**Level of integration** readiness	I	II.I	II.II	II.III	

Please note: The second part of the table is shown on the next two pages.

Separate detailed view available at www.bahnindustrie.info

Production	Type test prior to integration / first article inspection (FAI)	Static commissioning	Dynamic commissioning	Issue of commissioning approval	Operation / warranty
	Assurance of properties through verification and validation (scope for stand-alone systems)	Assurance of properties through verification / validation			
	First sample (experimental set-up if system qualification is brought forward) is not integrated into superior system Test is not integrated into superior system (stand-alone)	First sample (experimental set-up if system qualification is brought forward) is integrated into superior system); Test of the system is integrated into standing (static) superior system	First sample (near-series product if system qualification is brought forward) is integrated into superior system; Testing under test conditions (TRL 6) or trial operation (TRL 7) conditions	Series product is integrated into superior system; Testing under conditions for approval or acceptance operation	Series product is integrated into superior system; Deployment under conditions of specific operation
	4	5	6 / 7	8	9
	Evidence of fulfilment of all functional requirements to the extent defined and verifiable for type test and first article inspection (FAI)	Evidence of fulfilment of all functional requirements (static)	Evidence of fulfilment of all functional requirements (dynamic)	Evidence of fulfilment of all functional requirements (approval / acceptance)	Evidence of fulfilment of all functional requirements (operational deployment)
	Evidence of fulfilment of all requirements placed on construction elements to the extent defined and verifiable for type test and first article inspection (FAI)	Evidence of fulfilment of all requirements placed on construction elements (static)	Evidence of fulfilment of all requirements placed on construction elements (dynamic)	Evidence of fulfilment of all requirements placed on construction elements (approval / acceptance)	Evidence of fulfilment of all requirements placed on construction elements (operational deployment)
	Evidence of fulfilment of requirements placed on sub-ordinate system (FAI report) Type test reports (prior to integration)	Type test reports (integration - static)	Type test reports (integration - dynamic)	Commissioning approval Approval certificate Acceptance reports	No reports of necessary design modifications within one annual cycle
	III	IV.I	IV.II	IV.III	V

Schematic diagramof determination of readiness levels (Fig. 9) Part 2

	Project phases	Tender / clarification	Concept	Intermediate design	Final design	Production
	PDP development phase	Planning - Requirements for information - Compiling - Identifying gaps	Conceptualisation - Functional structures - Basic solutions	Drafting and design of modular structures Elaborating solutions / functional structures	Complete draft design	
	Physical state / conditions for testing	Model Simulation / description				
TRL	**Level of technology readiness**	3.1	3.2	3.3	3.4	
IRL	**Level of integration readiness**	I	II.I	II.II	II.III	
	Function view	Multi-system functions are defined and main functions are distributed (which system does what?)	Multi-system functions are defined and main functions are distributed (which system does what?)		All overarching functions are fulfilled	
	Component view (interface - material energy information)	Determination of interfaces (material, energy, information) and interaction (physical, process technology, etc.)	Generation of complete information for subordinate system functional requirements; non-functional requirements and attributes: laws, regulations, standards, use profile, vehicle config. Customer's special requirements for interfaces (material, energy, information) placed on the construction components to be designed, e.g. construction concept/space, climate, dynamic, etc.	Detailed definition of interfaces for elements of the specific phase; Description of the data interfaces for sub-systems characterised by complex software and feedback loops to circuit diagram of train and/or between the systems. Software (Train Control Monitoring System, TCMS) can be implemented later in a separate cycle	Detailed definition of all interfaces	
	Evidence for IRL	Description of deviations pursuant to checklists „non-functional / functional requirements“	Tech. Specifications available for procuring elements and subordinate system (incl. interface description)	Approval of interfaces (protocols)	Approval of data interfaces (reports)	

Production	Type test prior to integration / first article inspection (FAI)	Static commissioning	Dynamic commissioning	Issue of commissioning approval	Operation / warranty
	Assurance of properties through verification and validation (scope for stand-alone systems)	Assurance of properties through verification / validation			
	First sample (experimental set-up if system qualification is brought forward) is not integrated into superior system Test is not integrated into superior system (stand-alone)	First sample (experimental set-up if system qualification is brought forward) is integrated into superior system); Test of the system is integrated into standing (static) superior system	First sample (near-series product if system qualification is brought forward) is integrated into superior system; Testing under test conditions (TRL 6) or trial operation (TRL 7) conditions	Series product is integrated into superior system; Testing under conditions for approval or acceptance operation	Series product is integrated into superior system; Deployment under conditions of specific operation
	4	5	6 / 7	8	9
	III	IV.I	IV.II	IV.III	V
	Defined input from superior system triggers defined function in non-integrated subordinate system (test environment, e.g. signal on pin x triggers door opening)		Defined interaction fulfils / triggers defined function / feedback from the subordinate system		
	From the viewpoint of subordinate system, test of connection to superior system and other systems	Fulfilment of requirements placed on interaction			
	Report (FAI)	Type test report (static)	Type test report (dynamic)	Commissioning approval Approval certificate Acceptance report	No reports of necessary design modifications within one annual cycle

3.3 Phase assignment for desired results and readiness levels of the reference process (PDP)

Simplifications were made during definition of the desired phase-specific results of the reference process. They relate to assignment of the desired development content, the desired levels of technology readiness and the desired levels of integration readiness to the individual phases.

For the phases, the reference process determines the desired results in the categories and the levels of desired technology and integration readiness. The readiness levels of the TRL and the IRL are synchronised with the individual phases, even though the analyses differ, as do the classifications in levels. The boundary conditions for integration – such as the determination of construction spaces – are an important input for the development of a subordinate system and have to be available when its development commences.

The degrees of fulfilment of the desired results of technology and integration readiness are examined during the clarification phase, and form the basis for assignment to the relevant IRL or TRL levels. For example, if a system does not achieve the desired result for a TRL level, it does not reach the respective readiness level in the TRL. TRL analysis is independent of assignment to the IRL. If the desired results for the IRL are achieved, the system analysed reaches the respective readiness level in the IRL. The need for action – for instance selecting the required QE actions – is oriented on the lowest level of readiness in each case.

Comparison of the development process status with the reference process allows those elements to be identified that exhibit the lowest level of readiness. This enables targeted QE actions to be taken that assure the achievement of higher levels of readiness.

It should be noted that a low level of readiness is not necessarily associated with a high risk to the achievement of goals: the risk is derived from the effort needed in each case for implementing the necessary quality engineering actions (quantity, type, scope). The difficulty, the complexity and the risk of the necessary QE actions are determined by the specific content that is necessary for attaining the goal of the higher level of readiness.

If the requirements change during the development process, the same procedure should be applied as for the analysis. In this case, those elements of a system have to be identified which have been altered and/or are influenced by the change. Assignment to the relevant process phases or TRL/IRL levels uses the same criteria as in the original analysis. Changes to the concept usually lead to re-classification at a lower TRL or IRL. Re-classification is carried out in those levels where the changes were made.

3.4 Analysis of systems for creating comparability

The analysis of the non-functional requirements aims to identify any relevant special attributes and deviations by means of systematic query and thus to ensure that these points are taken into consideration in the design process.

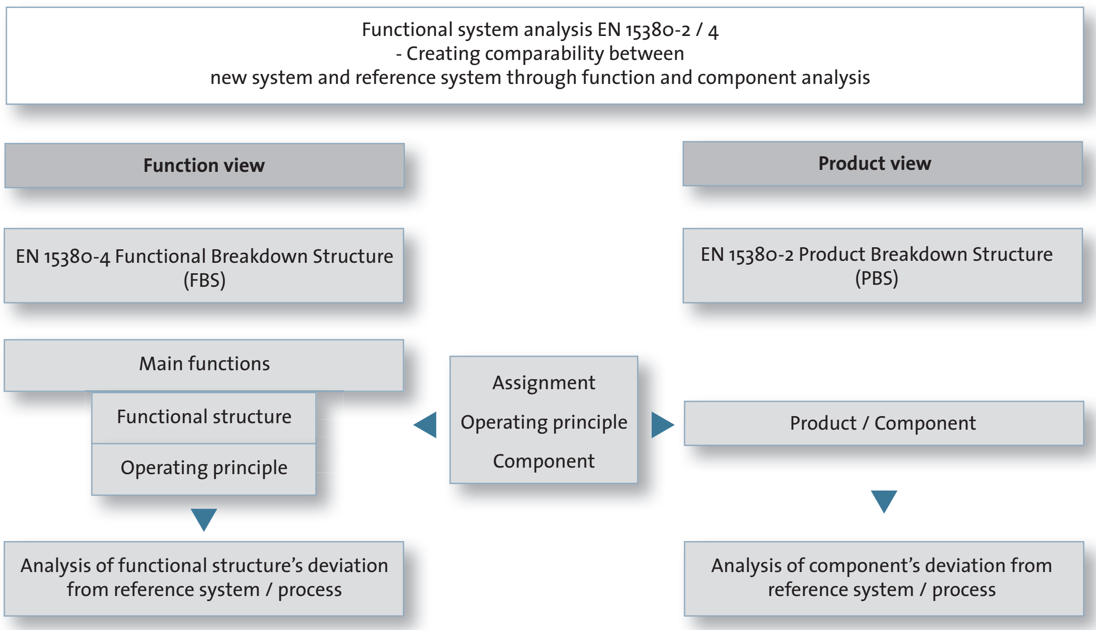
The degree of fulfilment of the criteria for the individual levels is determined by analysis of the systems' development status. The basis for this is the function view and component view of the respective system. This procedure corresponds to EN 15380-2 (component view) and EN 15380-4 (function view).

Different analyses require different views of the systems – their reliability can only be calculated theoretically, for example, using elements from both views: the linkages between the components are derived from the functional structure, whereas the reliability of the individual components is determined by the components themselves. Systems constructed from identical components that are linked with one another in different ways will exhibit different reliability values. Components with redundant links generally have greater reliability than components connected in series.

Similar considerations are required for the comparability of systems. The functional structure of a system is of major importance for its transferability to a new system as a **reference system**. If the functional structure of a system is changed while the components remain identical, the empirical values from operational deployment can be transferred to the new system only to a limited degree.

When a tried-and-tested system (reference system) is adopted as the basis for a new system whose requirements have been altered, the effects of these changes have to be subjected to a structured analysis. The empirical values from operation of the reference system can be compared with and transferred to the new system only after the analysis has been carried out. The process steps in the functional system analysis according to EN 15380-2 and EN 15380-4 are shown in Figure 10. The functional structures and the mechanisms of operation of the **main functions** are analysed and presented starting from the function view. The main functions of a system are the crucial functions. The functions of rail vehicles are structured and defined in EN 15380-4. On the basis of the analysis, the existing system is compared with the new system. If differences are found in the functional structure and the mechanisms of operation, further analyses are required.

Analysis from the function and component views. The product structure results from the physical implementation of the functional structure (Fig. 10)



Based on the functional analyses, the **elements**/components can be assigned to the mechanisms of action – this is the point where the function view and the product view are linked together.

The functional structure is a major foundation for the methodological design and the value analysis of systems. The VDI guidelines 2206 and 2221, which describe the design process for systems, are also based on functional structures.

3.4.1 Structuring requirements – functional and non-functional

Structuring according to functional and non-functional requirements facilitates the analysis of systems. Systems theory provides the following definition: the function of systems consists of transforming the input quantities (material, energy, information) into the new output quantities (material, energy, information), taking into account state variables. The main functions (the essential functions according to EN 15380) are used for comparing systems. They serve as the starting point when systems are being developed.

Beside the functional requirements, every product have to fulfil non-functional requirements as well. They describe the boundary conditions under which a function is performed and which properties the system has to have.

Railway vehicle systems can be compared according to the following scheme in relation to how the non-functional requirements are organised:

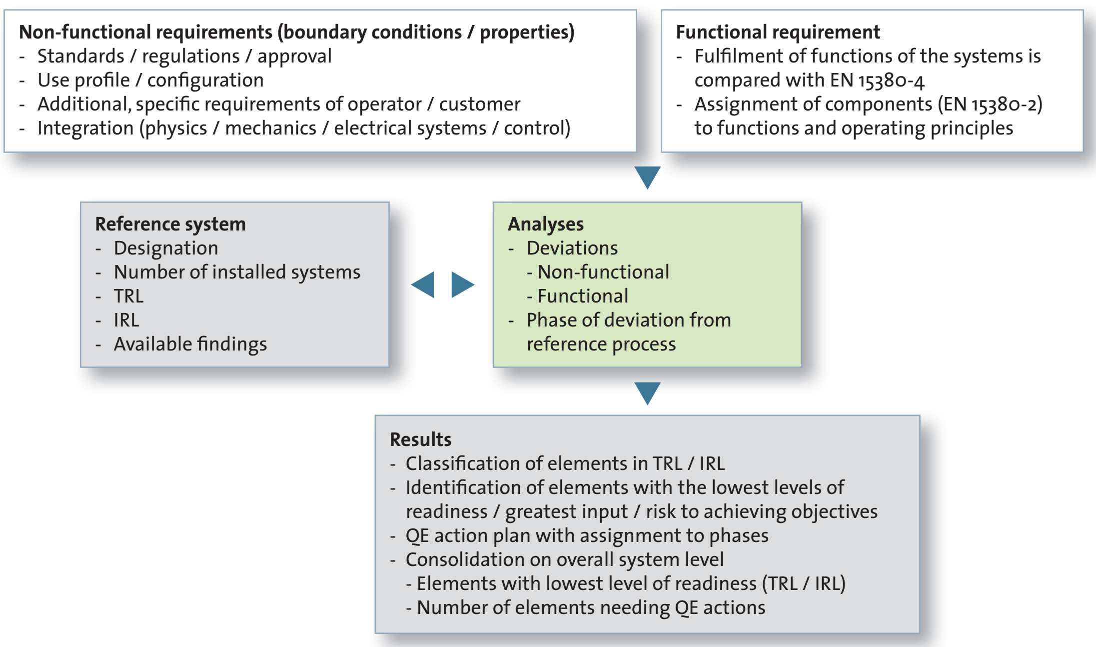
- Standards, regulations, approval
- Use profile, configuration
- Additional specific requirements of the operators or customers
- Provisions for integration (mechanics, physics, electrical systems, control)

3.4.2 Structure and types of checklists

Checklists allow systems to be analysed according to pre-set categories. The pre-defined structure of the checklists ensures that the manufacturers have to respond on all the relevant aspects. This means the systems can be made comparable. Furthermore, checklists encourage the teams to tackle the topics actively.
The checklists are filled out by the respective manufacturers or developers of the systems who are also responsible for forwarding the information to the superior system.
The structure of the checklists corresponds to the functional and non-functional analysis. It is shown in Figure 11.

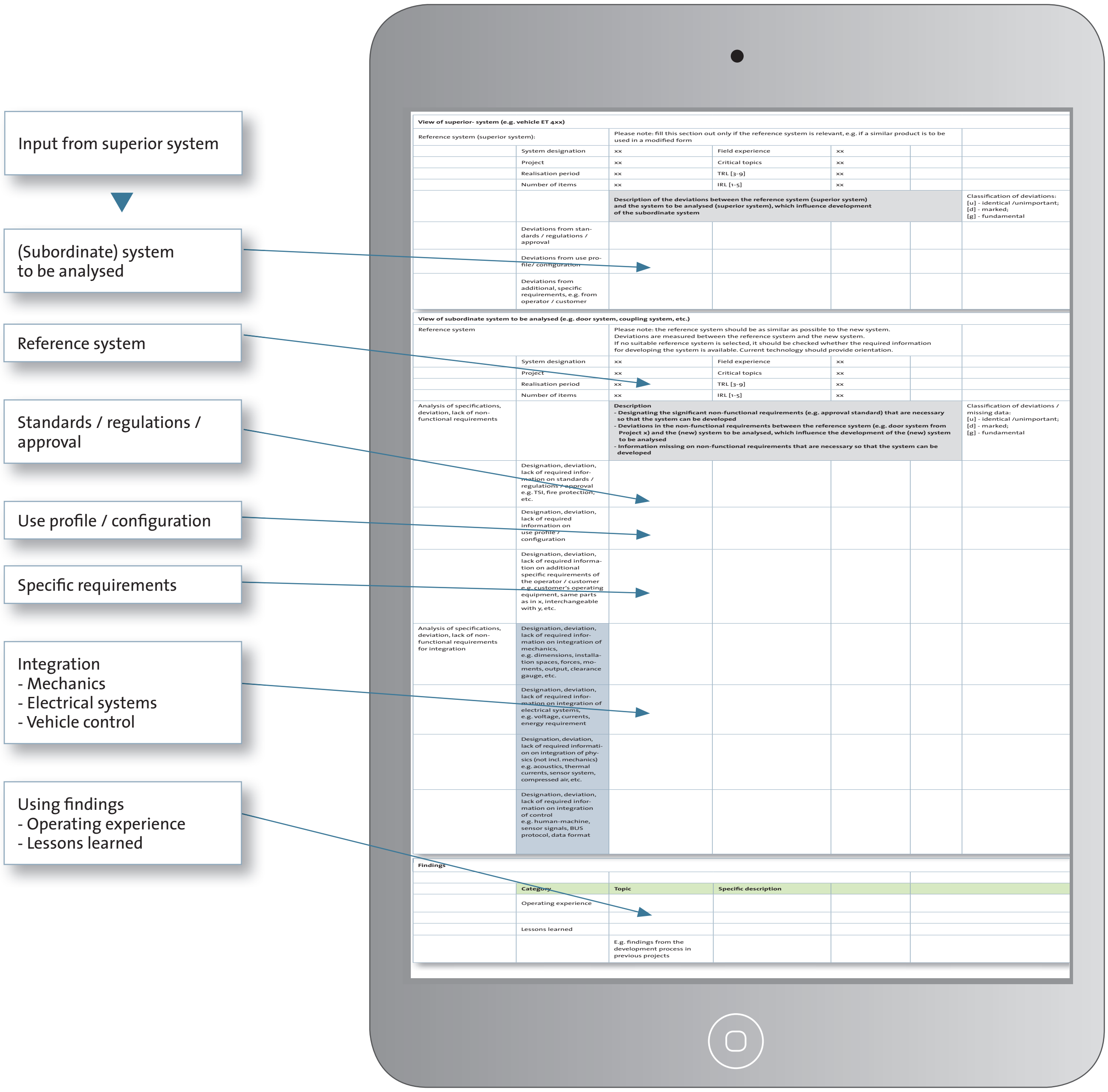
This structured analysis of systems allows deviations to be identified and described – it forms the basis for classification to the levels of readiness. Actions for assuring the objectives are derived from the analysis and are assigned to the phases of the product design process (PDP).

Structure of the checklists (Fig. 11)



3.4.2.1 Non-functional checklist

Schematic diagram of non-functional checklist (Fig. 12)



Separate detailed view available at www.bahnindustrie.info

The non-functional checklist (Figure 12) is divided into three sections ("Superior system", "Subordinate system" and "Findings"). In the first section the superior system is analysed. The first check is whether a reference system for it exists, which exhibits a high level of agreement with the new superior system. If such a reference system can be identified, its essential data are to be recorded. The second check is on whether deviations in the areas of standards, regulations and approval exist in the use profile and the configuration, or in additional specific requirements of the operator or the customers. This is necessary, for example, when an entire rail vehicle is to be adopted for use in a new system.

Changes to the non-functional requirements – for instance in the approval regulations or the region of deployment – may render it impossible to transfer the readiness levels of the reference system to the new system. The deviations should therefore be recorded and analysed.

The second section of the checklist considers the new subordinate system that is to be analysed. Here, too, a check is run on whether a reference system for it exists which has a high level of agreement. This is often the predecessor system that is intended either to be used or to undergo evolutionary development in the new system. The decision to use a reference system is of far-reaching importance and has to take the manufacturer's product strategy into account. Once the reference system has been selected, the relevant information should be entered in the checklist.

In the next step the significant non-functional requirements (e.g. approval standards) are set forth, which are required for development of the system. This is followed by an analysis of the deviations between the new system and the reference system. However, one may discover that some information about the non-functional requirements placed on the system is missing. The structured query is carried out in line with the above-mentioned topics:

- Standards, regulations, approval
- Use profile / configuration
- Additional, specific requirements of the operator or the customers
- Integration:
  - o Mechanics
  - o Electrical systems
  - o Physics (not including mechanics)
  - o Control

If no reference system is selected, it should be checked whether the most important information for development of the new system is available. The checklist have to contain descriptions both of this information and of missing information. The items to be included in the checklist are selected based on current technology: those items should be described that deviate from the state of the art. Apart from the description of the deviations and/or the missing information about the non-functional requirements, each of the deviations should be classified as "identical/unimportant", "marked" or "fundamental".

The available findings are recorded in the third section. The query is divided into the topics of "Error events" and "Lessons learned". The lessons learned are generally based on company-specific know-how that the companies wish to protect – for this reason these findings are recorded in the system-specific checklist. It is intended to help in using the available findings during development of the system.

Using findings

The purpose of checklists is to systematically record experiences from projects and to feed it into the development process while giving consideration to competition-related aspects (e.g. protection of know-how, location of the competition) and sensitive data handling. It is insufficient to limit this to the pure engineering phases as far as completion of the "Final design" process phase, because some key findings concerning the effectiveness of the engineering are only made during verification, when approval is issued, or as a result of experience in continuous operation.

3.4.2.2 Functional checklist

The functional analysis of systems is a key element in the QE process model and forms, among other things, the foundation for comparing various system concepts. In order to create comparability and conduct a functional analysis, all the main functions of the relevant systems have to be taken into consideration – even if some questions remain unanswered. Application of EN 15380-4 ensures that this is the case. It lists those functions that should be fulfilled for each of the relevant rail vehicle systems.

The main functions are determined in a first step. Based on the functional structures of the systems, the main functions are then compared with the defined functions taken from the standard. It should be ensured that all the relevant functions of each system, which are listed in the standard, are fulfilled by the designated functions or functional structures of the system. This procedure also allows systems with different approaches to finding solutions to be compared in terms of their fulfilment of functions and their levels of readiness.

The VDI guidelines 2206, 2221 and 2803 also describe how functions are fulfilled by several functions and sub-functions. They represent the functional structures. These functional structures are realised by active structures – that is, by physical, chemical or other effects and their structures. The active structures determine the elements, parts or components which can be used to realise the active structures and the functional structures. Several elements taken together can be regarded as element structures. Functions are realised either by elements or by element structures.

The functional analysis of the systems follows the methodology described in the guidelines and is reflected in the functional checklist (Figure 13). Comparison of the systems – that is, of the new system with the reference system – is carried out on this basis: first of all there is a check on whether the functions from the standard are fulfilled for the specific system and whether the functional structures match. This is done in the system's function view. Any deviations should be detailed in the checklist. Then the components that realise the functional structures are compared. This is done in the component view of the system.
The next step consists of an evaluation of the deviations from the function and component views. The deviations are classified in the specified levels "identical/unimportant", "marked" or "fundamental". Assignment to the TRL or IRL readiness levels follows the procedure described in section 3.2.

Schematic diagram of functional checklist – example (Fig. 13)

Functional analysis of door system based on EN 15380-4		Identification and designation of main functions Criterion for main function: crucial to fulfilling purpose	Identification and designation of relevant sub-functions Criterion for relevance: necessary for fulfilling main function	Functional structure and operating principle	Construction elements realising the functional structure	Deviation between reference system and (new) system to be analysed (function and construction element)	Deviation category - Functional structure, operating principle Deviation measurement - Identical / unimportant [u] - Marked [d] - Fundamental [g]	Deviation category - Construction element Deviation measurement - Identical / unimportant [u] - Marked [d] - Fundamental [g]	TRL classification (at which level are decisions made about the object of deviation)	IRL classification (at which level are decisions made about the object of deviation)
E	(Operate door system)	x	...	...	...	...	...	...		
F	(Bolt outside door)	x	...	...	...	...	...	...		
G	Unbolt outside door	x	...	...	...	...	...	...		
H	Enable outside door opening	x	...	...	...	...	...	...		
J	Plan entrance illumination	x	...	Permanent electrical contact "1" to control	Electromechanical switch - Electric part	Electric switch from door system x with TRL 9 and IRL 5	Functional structure [u]	Part [u]	4	III
K	Block outside doors	x	Block door	Central rotary switch - transferred by Bowden cable to bolting articulation	Electromechanical switch - Mechanical part Bowden cable Kinematics Integration into bolting articulation	New part	Functional structure [u]	Part [g]	3.1	I
			Bolt door securely	Central rotary switch - transferred by Bowden cable to bolting point on lower part of door leaf	Electromechanical switch - Mechanical part Bowden cable Kinematics Integration into bolting point	New part	Functional structure [u]	Part [g]	3.1	I

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The analysis makes it possible to assign levels of readiness to the elements of a system and on this basis to assure actions for achieving objectives. It is also possible to compare systems based on the levels of readiness. The procedure for this is described in section 3.7.

3.5 QE methods for assuring specific phase results

A core element in the quality partnership for developing rail vehicles is the process model for determining the need for quality assurance – always taking the state of development into account – so that its application can be concentrated on the relevant parts of development.

Figure 15 indicates suitable methods for preventive action to assure the desired results, based on the deviations of the system to be analysed from the reference process or the reference system in the relevant categories of the phase and of the TRL/IRL. The recommended methods are quality engineering methods that have already been put into practice. They are therefore not described in detail in this guideline.
The categories, phases and deviations correspond to the classification of the readiness levels in Figure 9 in section 3.2, which facilitates navigation within the table.

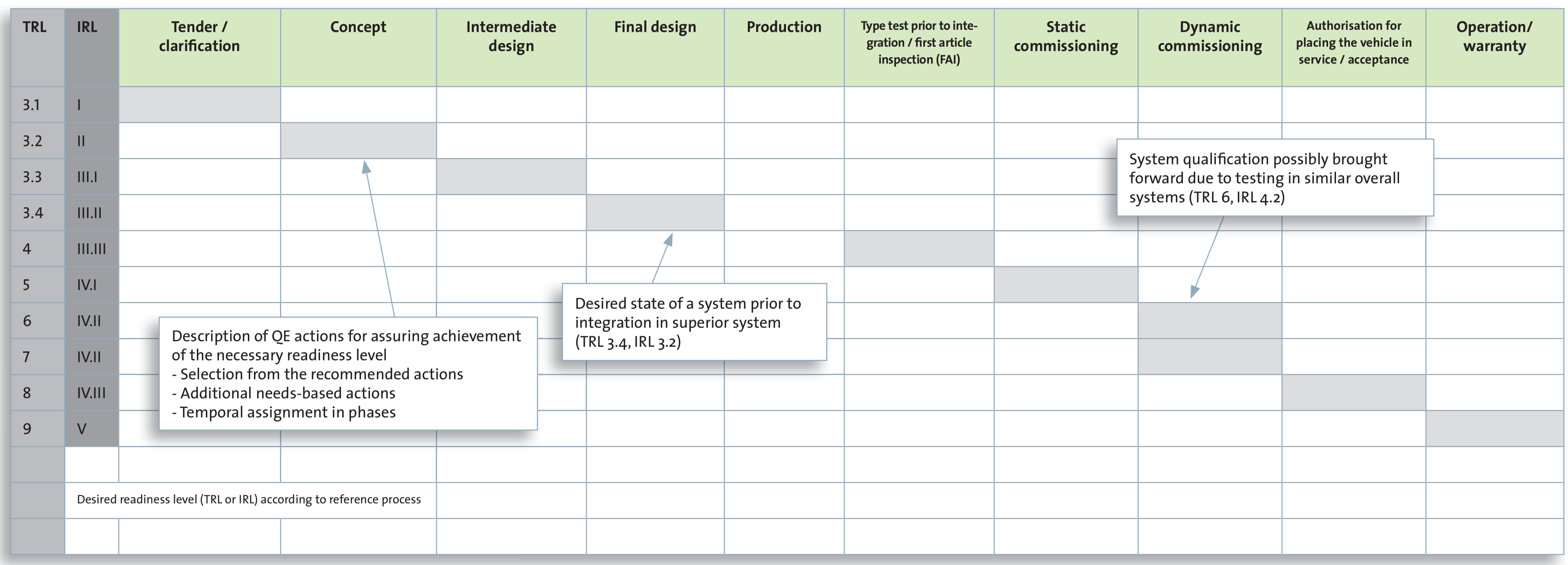
3.6 QE action plan: determining actions for assuring results

The QE process model concentrates on assuring the achievement of objectives during the product design of rail vehicles and/or their sub-systems and components. This is done by determining specific QE actions on the basis of the phase-specific deviation of a system from the reference process. Section 3.4 sets out the necessary analyses from the function and component views.

The recommendation of QE methods for assuring specific phase results is given in section 3.5. The manufacturers/developers of a system use this as a foundation for determining the actions to assure the results. Selection of the methods is their responsibility and the QE action plan indicates the method selection for each phase.

The QE action plan shows the need for QE actions and the associated risks for a system all the way to its final completion. It forms the basis for reporting the status of a subordinate system to the superior system. Progress is tracked upon completion of every phase between the superior and the subordinate systems. The subordinate system is responsible for providing the information. Figure 14 shows the generic structure of the QE action plan.

Determination of QE actions depending on deviation (phase and category) (Fig. 14)



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Recommendation of suitable QE methods (Fig. 15)

Phase	Tender / clarification	
TRL	3.1	
IRL		
Function / component view	TRL function view	TRL component view
Specific deviation	Complete information on interaction (physical, process technology, information, etc.) with other systems (integration) Solutions for critical requirements Main functions are defined	Complete information: laws, regulations, standards, use profile, vehicle configuration customer's special requirements for interfaces (material, energy, information) placed on the parts to be designed, e.g. construction space, environment, dynamic, etc.
Suitable QE methods		
Requirements engineering	x	x
Checklists Non-functional requirements Functional requirements	x	x
Use case	x	x
Systematic description of functions and system (e.g. Unified Modeling Language, UML)	x	x
Quality Function Deployment (QFD)	x	x
Modelling and analysis of the system in relation to: - Dynamics - Warming up - Stray fields - EMC - Vibration noise, etc.		
FMEA		
Virtual prototyping / 3-D model		
Software in the loop simulation		
Hardware in the loop simulation / Iron Bird		
Special tests: sturdiness, rigidity, endurance strength, pressure, tight-ness, emissions (liquid, gas, waves/ vibrations, e.g. sound, EMC, etc.)		

Separate detailed view available at www.bahnindustrie.info

Categories of specific deviations of the system to be analysed from reference process / reference system
- Phase of deviation
- Type of deviation (technology readiness / integration readiness)

Tender / clarification		Concept	
		3.2	
I			II.I
IRL function view	**IRL component view**	**TRL function view**	**IRL function view**
Multi-system functions: Dividing up main functions (which system does what?)	Definition of interfaces (material, energy, information) and interaction (physical, chemical, process technology, etc.)	Functional structures and operating principles for all functional requirements Assignment of function/operating principle Part – Product's conceptual design is complete	Multi-system functions: Definition of all functions (incl. ancillary and derived functions), functional structures and operating principles
x	x	x	x
x	x	x	x
		x	x
		x	x
x		x	x
		x	x
		x	x

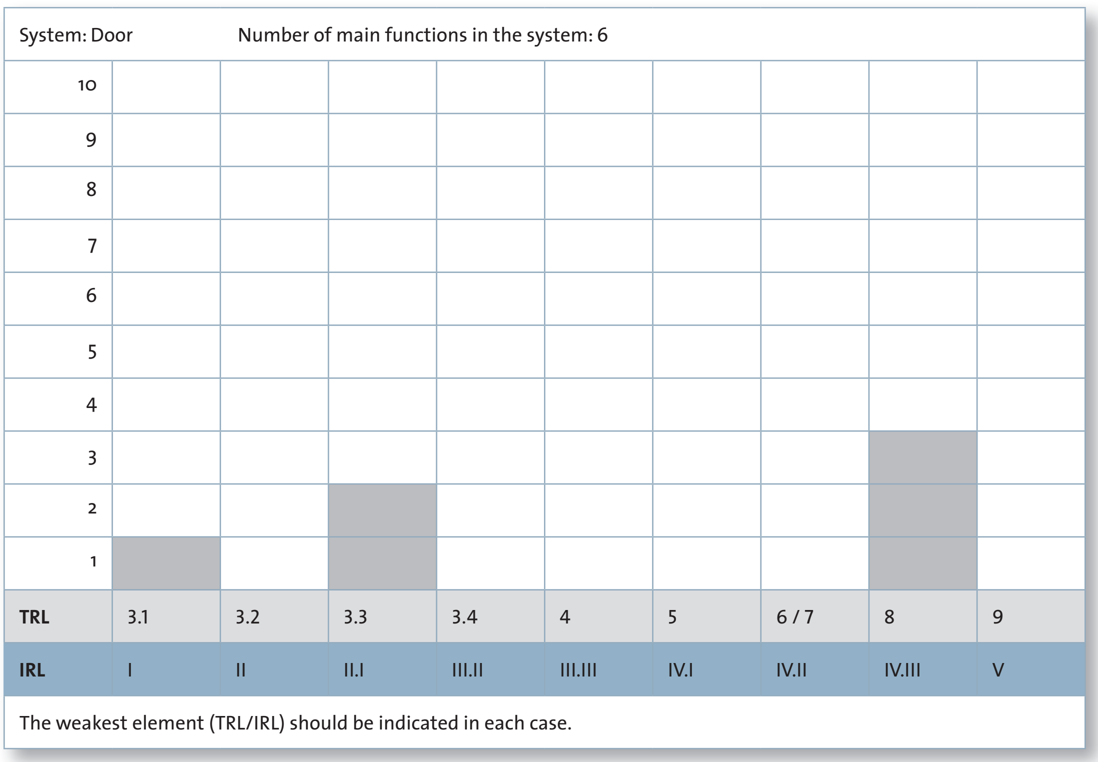
3.7 Presentation of systems' status based on readiness levels

As a rule, the elements with the lowest level of readiness and requiring the most effort for achieving the objectives also represent the highest risks (critical path of a development). The number of elements with a low level of readiness and a high level of development effort is also of particular significance when it comes to estimating the total risk. For instance, two systems are compared, which have to fulfil eight main functions pursuant to EN 15380-4. One construction element structure in one system exhibits a low level of readiness for one main function. In the other system, six element structures exhibit a low level of readiness for the main functions and each one requires a high degree of effort. The effort for realising the element structures with the lowest levels of readiness is the same for both systems. Yet the risk to achieving realisation is higher for the system with several element structures with low levels of readiness.

The QE process model takes this situation into account. It indicates not only the component structures with the lowest level of readiness but also the number and levels of readiness of those component structures that realise the main functions of systems. The different systems are comparable because the number of main functions is specified in EN 15380-4. The status of systems is shown in Figure 16.

Readiness levels in realisation of main functions by element structures (Fig. 16)

Example with six main functions; indication of the weakest element in each case



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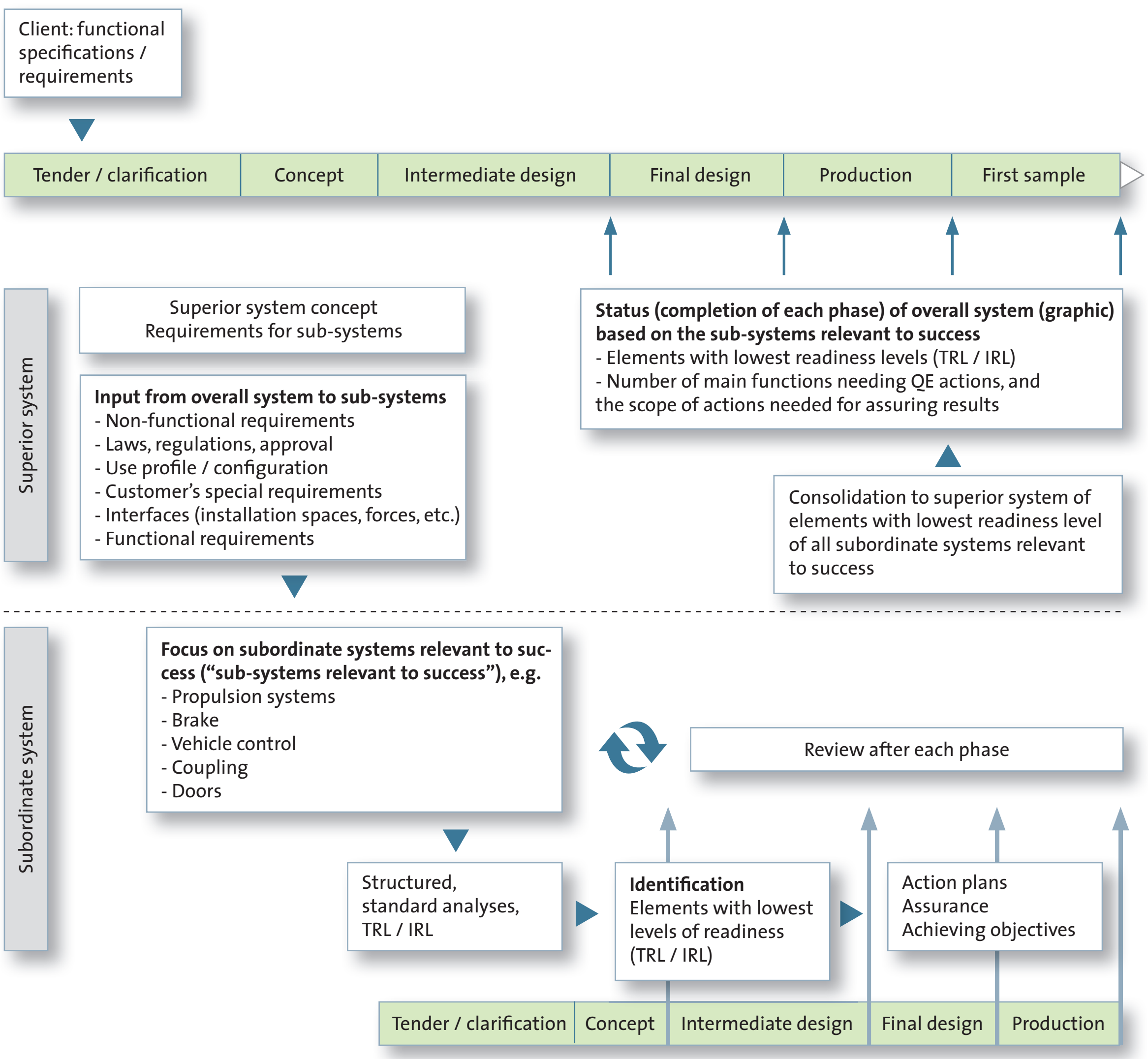
4| Application of the QE process model in a project

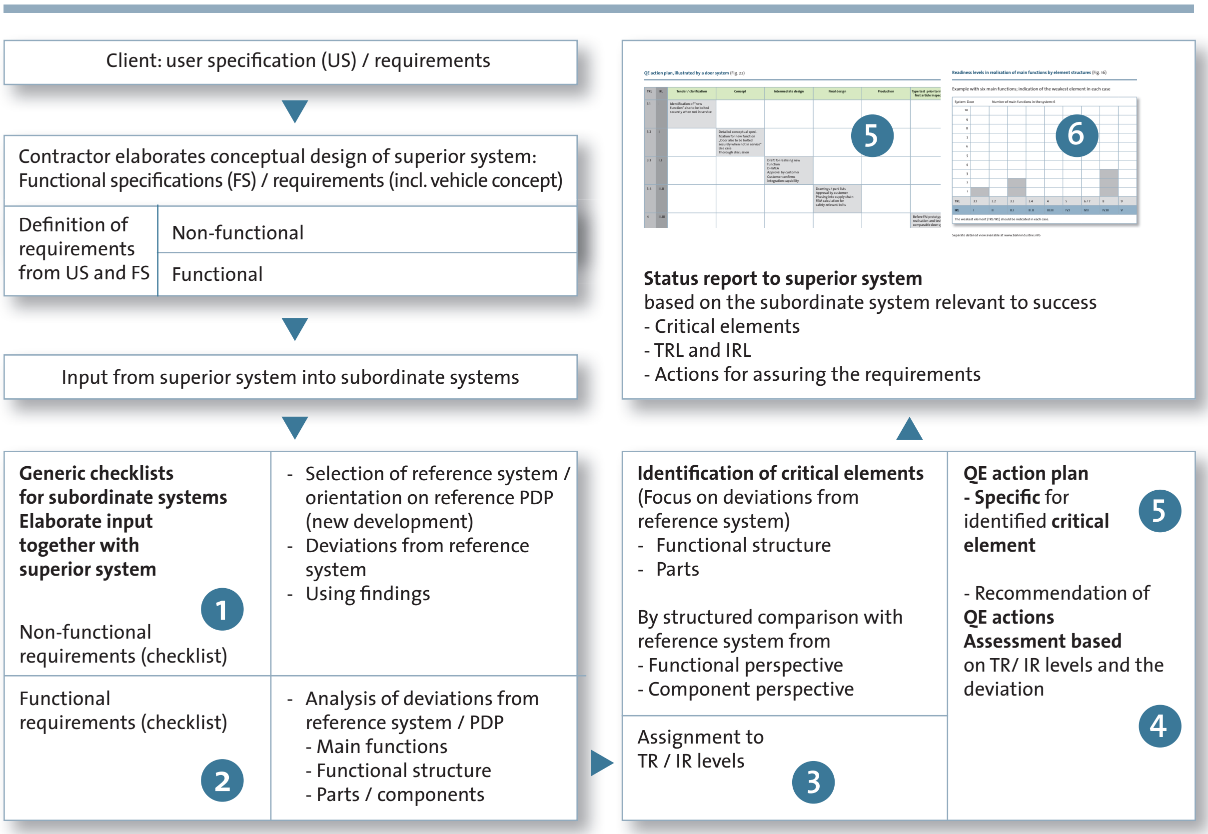
The steps in applying the QE process model are shown in Figures 2 and 3 in section 2. Figure 17 illustrates the phase assignment to the superior and subordinate systems.

Figure 18 presents the content and the sequence of the checklists for applying the QE process model in a customer project, and is oriented on the flow diagram from Figure 17. This means that the checklists reflect the QE process model.

Flow diagram for applying the QE process model, illustrated with a customer project
(Fig. 17)



Flow diagram and application of checklists during application of the QE process model to a customer project (Fig. 18)



The following steps are necessary when applying the process model:

(1) Recording and determining fulfilment of the non-functional requirements (identification of deviations from the reference system)
- Based on the checklist “Non-functional requirements”

(2) Recording and determining fulfilment of the functional requirements (analysis of deviations of main functions, functional structure, parts/components from the reference system)
- Based on the checklist “Functional requirements”
- Based on the table “Product design process”

(3) Classification in readiness levels (TRL/IRL)
- Based on the table “TRL_IRL_MEASUREMENTS_LEVELS”

(4) Selection of appropriate QE methods (on the basis of TRL/IRL and the deviation)
- Based on the table “QE_methods”

(5) Preparation of the QE action plan
- Based on the table “QE_ACTION_plan_generic”

(6) Presentation of the status report
- Based on the table “Summary_QE_actions”

These steps are described in more detail below:

Step (1) – Recording the non-functional requirements

First of all the non-functional requirements are analysed. It should be checked whether all the necessary information is available. If reference systems exist, it should be clarified whether the non-functional requirements (boundary conditions and stipulated properties) can be transferred to the new system. The foundation for this analysis is the non-functional checklist shown in Figure 12 in section 3.4.2.1.
The approach for determining the deviations between the new system to be analysed and the tried-and-tested reference system is shown in Figure 19.
The system manufacturer have to fill out the non-functional checklist and document the result. The input from the superior system should be co-ordinated in dialogue between the manufacturers/developers of the subordinate system and those of the superior system.
The manufacturer of the superior system and the manufacturer of the subordinate system may have to co-ordinate on the completed checklist.

Step (2) – Recording the functional requirements

In the next step the functional requirements are analysed pursuant to EN 15380-2 and EN 15380-4. Starting from the functional structures, the systems are analysed in the function view and in the component view. The analysis have to identify those elements where deviations from the selected reference system occur. If no reference system has been defined, the deviations from the reference process should be determined. The analysis follows the approach described in Figure 13 in section 3.4.2.2.
Figure 20 shows the determination and comparison of the functional structures with the functions described in EN 15380-4 for each system. Manufacturers/developers have to determine the functions of the specific systems on the basis of the standard. They are also responsible for conducting and documenting the comparison of the functions with the requirements of the standard. The manufacturer of the superior system and the manufacturer of the subordinate system may have to co-ordinate on the comparison that is carried out.

Step (3) – Classification in readiness levels (TRL/IRL)

The deviations identified serve as initial values for determining the levels of readiness. The foundation for this is the evaluation of the matrix for determining the levels of readiness as shown in Figure 21. It should be borne in mind that the attribute "Physical state of the system / conditions for test" (upper rows of the matrix) have to be taken into account for all such queries. The test conditions during the phase of property fulfilment are of crucial importance when the levels of readiness are increased (such as whether the test was carried out under static or operating conditions).
The elements with the lowest TR and IR levels have to be given particular consideration, since low levels of readiness are an indicator for additional input and risk. The documentation of the analysis – i.e. setting the levels of readiness (TRL and IRL) – corresponds to the approach set out in Figure 13 (functional checklist) in section 3.4.2.2.
Manufacturers/developers must work through and document the functional and non-functional checklists of the specific system. The manufacturer of the superior system and the manufacturer of the subordinate system may have to co-ordinate on the completed checklist.

Step (4) – Selection of appropriate QE methods
Starting from this analysis, the manufacturers select needs-based QE actions, which result from the process model, depending on the category and phase of the deviation (see Figure 15 in section 3.5).

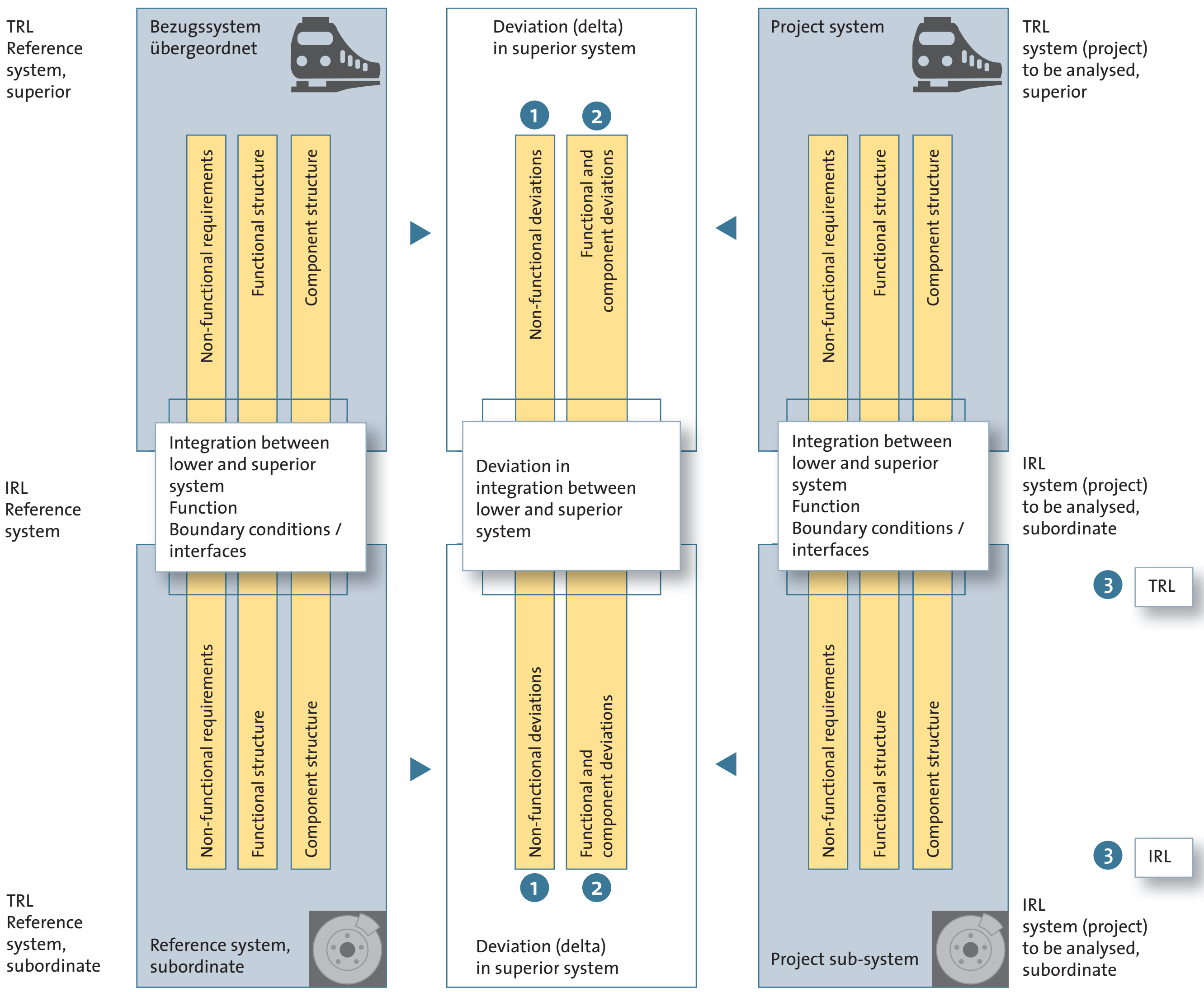
Step (5) – Preparation of the QE action plan
The QE action plan assigns the selected actions to individual phases. They are intended to ensure that the desired results (desired TRL or desired IRL) are in fact achieved at the appropriate time. Assignment of the actions to the target TRL or IRL over the individual phases enables the status to be represented graphically. The form for this presentation is shown in Figure 14 in section 3.6. A review should be conducted to complete each phase, involving a check on whether the actions selected have been implemented.
In addition, it should be clarified whether – for example – changes have resulted in new critical situations that have to be analysed according to the QE process model.

Figure 22 shows a specimen QE action plan for a door system.

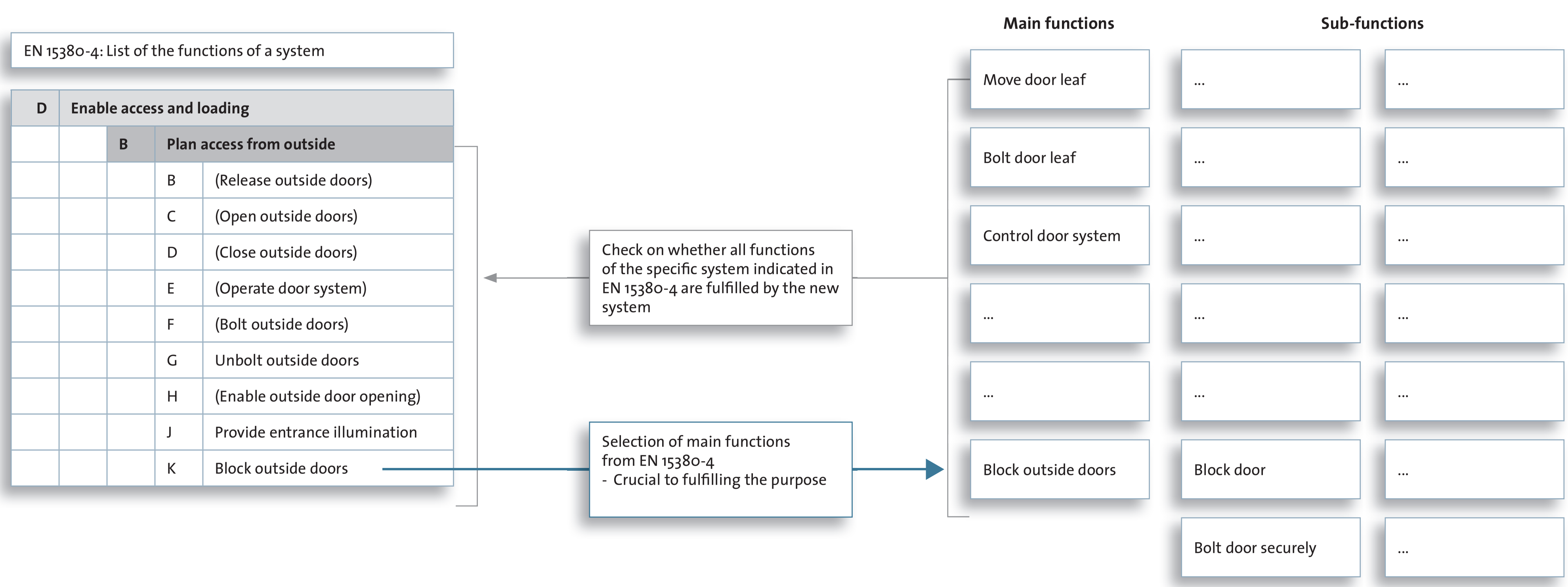
Step (6) – Presentation of the status report
In order to show the status of the overall project, in each case the element with the lowest level of readiness and the highest risk up to completion is represented graphically in accordance with Figure 14 in section 3.6. For all the subordinate systems relevant to success, this is done by their manufacturers or developers, who report the status to the superior systems. The project-specific definition of the systems relevant to success is a common task for the manufacturers/developers of the superior and subordinate systems.

The manufacturers/developers have to carry out and document presentation of the status of the specific system. Upon completion of each development phase, the manufacturer of the superior system should be notified of the status in the presentation prescribed in section 3.7 (status and number of element structures that realise the main functions of systems).

Approach for determining the deviation between a new system to be analysed and a tried-and-tested reference system (Fig. 19)



Determining and comparing the functional structures with the functions described in EN 15380-4 for specific systems (Fig. 20)



Approach for determining levels of readiness based on the assessment matrix (Fig. 21)

	Project phases	Tender / clarification	Concept	Intermediate design	Final design	Production
	PDP development phase	Planning - Requirements for information - Compiling - Identifying gaps	Conceptualisation - Functional structures - Basic solutions	Drafting and design of modular structures Elaborating solutions / functional structures	Complete draft design	
	Physical state / test conditions		Model Simulation / description			
ERG	Technology readiness levels	3.1	3.2	3.3	3.4	
ERG	Function view	Complete information on interaction (physical, process technology, information, etc.) with other systems (integration), e.g. which accelerations must be taken into account Solutions for critical requirements, main (i.e. crucial) functions are defined	Functional structures and operating principles for all functional requirements Assignment of function / operating principle Construction element Product's conceptual design is complete - System draft (multi-domain solution concept)	Definition of assurance of properties (validation principle)		
ERG	Component view	Complete information and description of the attributes of the system: laws, regulations, standards use profile, vehicle configuration Customer's special requirements for interfaces (material, energy, information) placed on the construction elements to be designed, e.g. structure / construction space, environment, dynamic, etc.		Construction elements of a functional structure fulfil requirements placed on this functional structure Definition of assurance of properties (verification / validation principle)	Design of all construction elements is completed All construction elements are integrated into the system Interacting elements fulfil requirements	
ERG	Evidence for TRL	- Basic vehicle structure („PowerPoint design") - Clause-by-clause commentary on - Requirements of the functional … …nt to …onal requirements"	- Conceptual specifications - Overall arrangement (elaborated vehicle structure) - Installation spaces - Draft total weight - Interface description available	3-D model (preliminary)	- Transfer of all production documents - Approval of circuit diagrams - Approved validation plan incl. rough definition of evidence required (type tests)	
IRG	Integration readiness levels	I	II.I	II.II	II.III	
IRG	Function view	Multi-system functions are defined and main functions are distributed (which system does what?)	Determination of all multi-system functions (incl. ancillary and derived functions; functional architecture), functional structures and operating principles		All overarching functions are fulfilled	
IRG	Component view (interface - material, energy, information)	Definition of interfaces (material, energy, information) and interaction (physical, process technology, etc.)	Generation of complete information for subordinate system functional requirements; non-functional requirements and attributes: laws, regulations, standards, use profile, vehicle configuration Customer's special requirements for interfaces (material, energy, information) placed on the construction elements to be designed, e.g. construction concept/space, environment, dynamic, etc.	Detailed definition of interfaces for elements of the specific phase; Description of the data interfaces for sub-systems characterised by complex software and feedback loops to circuit diagram of train and/or between the systems. Software (Train Control Monitoring System, TCMS) can be implemented later in a separate cycle	Detailed definition of all interfaces	
IRG	Evidence for IRL	Description of deviations pursuant to checklists „non-functional / functional requirements"	Tech. specifications available for procuring elements and subordinate system (incl. interface description)	Approval of interfaces (protocols)	Approval of data interfaces (protocols)	

Determination of the TRL based on achievement of all desired results for the respective level

Production	Type test prior to integration / first article inspection (FAI)	Static commissioning	Dynamic commissioning	Authorisation for placing the vehicle in service	Operation / warranty
	Assurance of properties through verification and validation (scope for stand-alone systems)	Assurance of properties through verification and validation			
	First sample (experimental set-up if system qualification is brought forward) is not integrated into superior system, Test is not integrated into superior system (stand-alone)	First sample (experimental set-up if system qualification is brought forward) is integrated into superior system); Test of the system is integrated into standing (static) superior system	First sample (near-series product if system qualification is brought forward) is integrated into superior system; Testing under test conditions (TRL 6) or trial operation (TRL 7) conditions	Series product is integrated into superior system; Test under conditions for approval or acceptance operation	Series product is integrated into superior system; Deployment under conditions of specific operation
	4	5	6 / 7	8	9
	Evidence of fulfilment of all functional requirements to the extent defined and verifiable for type test and first article inspection (FAI)	Evidence of fulfilment of all functional requirements (static)	Evidence of fulfilment of all functional requirements (dynamic)	Evidence of fulfilment of all functional requirements (approval / acceptance)	Evidence of fulfilment of all functional requirements (operational deployment)
	Evidence of fulfilment of all requirements placed on construction elements to the extent defined and verifiable for type test and first article inspection (FAI)	Evidence of fulfilment of all requirements placed on construction elements (static)	Evidence of fulfilment of all requirements placed on construction elements (dynamic)	Evidence of fulfilment of all requirements placed on construction elements (approval / acceptance)	Evidence of fulfilment of all requirements placed on construction elements (operational deployment)
	Evidence of fulfilment of requirements placed on subordinate system (FAI report) Type test protocols (prior to integration)	Type test protocols (integration static)	Type test protocols (integration dynamic)	Commissioning approval Approval certificate Acceptance protocol	No reports of necessary design modifications within one annual cycle
	III	IV.I	IV.II	IV.III	V
	Defined input from superior system triggers defined function in non-integrated subordinate system (test environment, e.g. signal on pin x triggers door opening)	Defined interaction fulfils / triggers defined function / feedback from the subordinate system			
	From the viewpoint of the subordinate system, test of connection to superior system and other systems		Fulfilment of requirements placed on interaction		
	Protocol (FST)	Type test protocol (static)	Type test protocol (dynamic)	Authorisation of service Approval certificate Acceptance protocol	No reports of necessary design modifications within one annual cycle

Determination of the IRL based on achievement of all desired results for the respective level

QE action plan, illustrated by a door system (Fig. 22)

TRL	IRL	Tender / clarification	Concept	Intermediate design	Final design	Production
3.1	I	Identification of "new function" also to be bolted securely when not in service				
3.2	II		Detailed conceptual specification for new function „Door also to be bolted securely when not in service“ Use case Thorough discussion			
3.3	II.I			Draft for realising new function D-FMEA Approval by customer Customer confirms integration capability		
3.4	III.II				Drawings / part lists Approval by customer Phasing into supply chain FEM calculation for safety-relevant bolts	
4	III.III					
5	IV.I					
6	IV.II					
7	IV.II					
8	IV.III					
9	V					

Separate detailed view available at www.bahnindustrie.info

	Type test prior to integration / first article inspection (FAI)	Static commissioning	Dynamic commissioning	Authorisation for placing the vehicle in service	Warranty
	Before FAI prototype realisation and testing in comparable door system complete type test, in particular stress test with 2,500 Pa Tilting test Evidence of operating force Vibration test				
		Process steps Reference process			
			Process steps Reference process		
			Process steps Reference process		
				Process steps Reference process	
					Process steps Reference process

Glossary

Ancillary function
Function that is not the main function. A sub-function of a product may be an ancillary function in relation to the product. It may be the main function in relation to the part of the product in which this sub-function occurs [VDI 2221].

Assembly
A combination of element structures forming a unit that cannot yet be used independently [EN 15380-2].

Black box
Representation of a system that executes functions with only input and output.

Boundary condition
Uninfluenceable condition that must be taken into consideration as a predetermined property. [EN 15380-5].

Development
Analysis and processing of new findings and their application. Creation of new products through targeted and methodological considerations, experimentation and designs.

Deviation is fundamental: The deviation occurs at a fundamental level and has an impact on the object being examined; basic changes are required to handle the deviation in the object being examined.
Example: the energy is transmitted by a different operating principle (electric instead of pneumatic), and different parts must be used.

Deviation is identical/unimportant: The deviation is not crucial and/or is of secondary importance, and impact on the object being examined is negligible; no changes are required for handling the deviation in the object being examined. For example, the colour inside an equipment box is changed from light blue to light grey (there are no requirements relating to the colour).

Deviation is marked: The deviation is clear and crucial and there is an impact on the object being examined; no basic changes are required for handling the deviation in the object being examined.
For example, an energy absorption element is designed for a slightly higher energy absorption, and the operating principles remain as before; the part is modified.

Element
A unit comprised of several construction elements is an assembly [derived from EN 15380-2].

Element structure
Functional structures are implemented by active structures – that is, through physical, chemical or other effects – and their structure. The active structures determine the construction elements, parts or components with which the active and the functional structures can be

realised. Several elements can be combined as element structures. Functions are implemented by elements or element structures.

Function
There are several different definitions of this term. The following definition based on EN 15380-4 should be used for application of the QE guideline:

A function executed by technical means and/or humans transforms (viewed as a "black box") input parameters (material, energy, information) into target-oriented output parameters (material, energy, information). Functions can be described using a noun and a verb (e.g. convert energy, enable access). Questions such as "What is the purpose?" or "What does the system achieve?" lead to identification of the function.

Functional requirement
Expresses the special demand or ability of a function in the Functional Breakdown Structure (FBS).

Please note: functional requirements and use cases are generally initially derived from the passengers or freight/load to be transported and the wishes of the operators. Later in the development process, functional requirements of the fitters and suppliers are added. They express the requirements placed on a certain functionality described in the FBS – for example in relation to interoperability with other functions, safety, operation, function/behaviour or functional architecture/design restrictions. The functional designation is normally specified even more precisely in the details of the properties, which supply more information about reliability, availability, performance capability, quality, documentation, input and output data and behaviour in real time. These superior functional objectives, which are elaborated for environmental conditions, design characteristics and selected target groups and target objects, are "requirements placed on a function" [EN 15380-4].

Integration
Refers to the interaction between systems.

Integration readiness level
The integration readiness model evaluates the degree of fulfilment of the functionality of the interaction of several systems. It indicates the status of a system vis-à-vis the superior system: does it fulfil all the requirements for integration into a superior system and for fulfilling its requirements in this environment?

Level of readiness
A level of readiness describes the readiness of an observed field in relation to a certain method or a model for action or management. Different amounts of agreement – between the defined criteria (attributes relevant to decision-making) and a degree of fulfilment of the criteria – result in various levels of readiness. One or more requirements are assigned to each of these levels of readiness.
A level of readiness is regarded as attained only if the criteria described there and those described in the preceding stage are shown to be met. The levels of readiness accordingly build on one another [AHL2005].

Main function
Crucial function of a product or of an assembly [EN 15380-2]. Function that describes a main purpose of a product [VDI 2221].

New system
The new system is the result or product that is to be developed to fulfil the requirements.

Operating principle
The operating principle refers to the connection between the physical effect, geometrical features and material features (effective geometry, effective action and material). It allows recognition of the principle of the solution for fulfilling a sub-function [VDI 2206].

Overall function
Totality of all functions that a product realises or is intended to realise. The overall function can be divided into sub-functions. The overall function is derived from the task; it fulfils the overall task of the product [VDI 2221].

Part
A product that can be unequivocally identified, which is regarded as indivisible for a certain planning and control purpose, and/or cannot be taken apart without being destroyed [EN 15380-2].

Product
Planned or achieved result of work [EN 15380-5].
The product fulfils the function and is comprised of product groups [EN 15380-2].

Product group
A product group fulfils the function of an assembly or a component.

Product structure
The product structure results from the physical implementation of the functional structure.

Quality engineering
Quality techniques for qualitative assurance of a product development. Quality engineering methods are used for defining, monitoring and controlling conformity of the developed products with the requirements and for determining the need for quality assurance.

Reference process
The reference process represents the ideal process and provides a basis for comparisons.

Reference system
The reference system represents the system with which something else is to be compared. The new system is compared with the reference system.

Requirement
Qualitative and/or quantitative determination of properties or conditions for a product; the requirements may be given different weightings [VDI 2221].

Sub-function

Every function that can be identified by dividing up a superior function. Sub-functions can be main functions and ancillary functions. Sub-functions can be arranged in a hierarchy [VDI 2221].

Sub-system

A rail vehicle is built up of sub-systems.
Please note: EN 15380-5 defines ten main systems, also called 1st level systems. The main systems are comprised of 2nd level sub-systems. In this guideline, the term “sub-system” is regarded as equivalent to the term “main system/first-level system” as in EN 15380-5.

System

Systems execute functions [VDI 2221].
Set of interrelated objects considered in a certain context as a whole and regarded as separated from their environment [EN 15380-5].
Note 1 on the term: a system is generally defined with a view to achieve a given objective, e.g. by performing a definite function.
Note 2 on the term: examples of a system: a drive system, a water supply system, a stereo system, a computer.
Note 3 on the term: a system is considered to be separated from the environment and from other external systems by an imaginary surface, which cuts the links between them and the system.

System level

Level of grouped systems [EN 15380-5].

Technology readiness model

The technology readiness model evaluates the degree of fulfilment of the functional capability of a separated system. It focuses on fulfilment of the requirements placed on the system. It describes the performance of this system.

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Abbildungsverzeichnis

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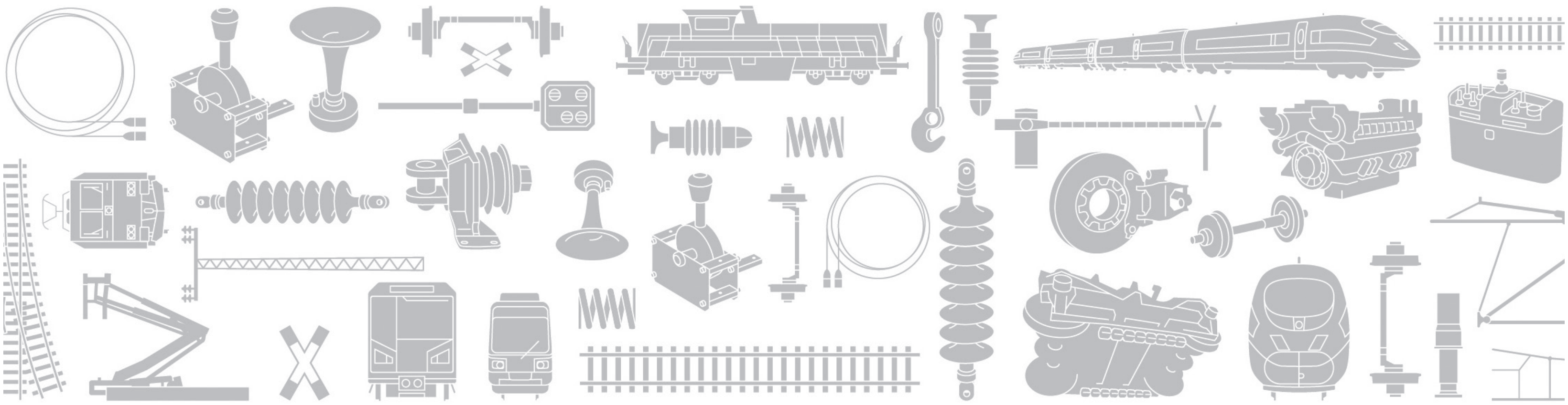

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