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Development of innovative and reliable technical products: The impact of historical, educational, and social interaction aspects on reliability and safety engineering

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The industrialisation process has led to the development of innovative and reliable complex technical products, while also shaping different national approaches to reliability and safety engineering. In Europe, countries such as Germany and France exhibit distinct product characteristics and reliability philosophies. At the same time, Asian industrial nations like Japan and Taiwan have developed alternative approaches to reliability, influenced by different industrial structures and practices. As a result, highly developed industrial nations have followed divergent paths, leading to varying goals and philosophies in product design, process development, and efficiency during the use phase. This paper highlights key differences in product emergence processes and reliability engineering between selected European and Asian countries. German engineering is often characterised by high functionality and innovation based on bottom-up approaches, while French engineering tends to follow system-oriented, top-down strategies. Japanese engineering frequently results in highly optimised functional solutions. These differences arise from historical, social, cultural, educational, and work-environment factors, leading to distinct reliability and safety solutions. Results are illustrated using long-distance rail transport systems in Germany, France, Japan, and Taiwan.

Keywords: Product emergence process, reliability engineering, Europe, Asia, railway systems

1. Introduction

The industrialization process has produced innovative and reliable complex technical products, while different industrial nations have pursued distinct development paths. In Europe, Germany and France show clear differences in reliability and safety design, while in Asia, Japan and Taiwan established alternative engineering and reliability approaches. These variations lead to different goals and strategies in product development, process design, and efficiency during the use phase. German engineering is often associated with high functionality and innovative bottom-up approaches, whereas French engineering typically follows system-oriented, top-down strategies. Japanese engineering focuses on highly optimized and efficient solutions. These differences are shaped by historical, cultural, social, and educational influences, among other factors. The paper analyzes these varying reliability and safety engineering philosophies and illustrates them using long-distance railway systems in Germany, France, Japan, and Taiwan.

2. Goal of research study

The underlying question of the research study is to work out differences between highly developed industrialized nations of Germany, France, Japan and Taiwan regarding product development and product operation. The following perspectives and questions take center stage:

(i) Product development: How do the procedures for developing technically complex products differ?
(ii) What are the advantages of various product development strategies?

(iii) What influence have country-specific factors like history, education system, society on product operation in the context of reliability engineering?

In this paper, these three questions are examined and the differences between the mentioned industrialized nations are highlighted using examples from long distance railway systems.

3. Product Development Process

3.1. *Germany*

3.1.1. *Fundamentals: Phases, Activities*

The product life cycle consists of several phases with distinct objectives. In the development of complex technical products, many phases are executed in parallel across different specialist disciplines, such as vehicle, body, chassis, powertrain, electrics/electronics, and software in automotive engineering. The concept phase includes pre-development, product definition, and concept confirmation, aiming to define product structure, styling, performance specifications, and make decisions on in-house development or outsourcing. The series development phase comprises design and prototypes as well as series preparation, focusing on the development of all systems, assemblies, and components and the preparation of series production. Simulation, testing, and prototypes with increasing maturity are used to verify functionality and reliability. During series preparation, production facilities are implemented and product and process capabilities are confirmed, especially for safety- and function-critical features. After the Start of Production (SOP), the production phase begins with a ramp-up period that leads to full series production at the operation line. Reliability is ensured through inline, final, and external testing, with intensive inspection of critical features. The production phase ends with the End of Production (EOP), followed by continued spare parts manufacturing. The sales and field support phase covers product distribution, use, and long-term support beyond EOP; cf. (Bracke 2024), (DIN 2017), (Braess and Seiffert. 2013:1133).

3.1.2. *Reliability engineering Principles*

The frontloading approach emphasizes the early use of resources for reliability planning and technical reliability methods during the concept and series development phases, as a significant share of product costs is determined at this stage.

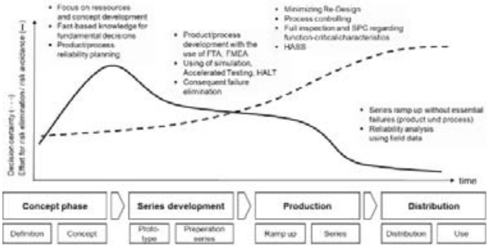

Fig. 1. Efforts for risk avoidance as well as decision certainty in the product emergence process with reliability planning in concept phase (Bracke 2024)

By focusing on concept development and systematic reliability planning, efforts for risk avoidance and elimination are intentionally increased early in the process. During series development, this approach is supported by the consistent application of reliability methods such as Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), simulation, accelerated testing, and Highly Accelerated Life Testing (HALT). As a result, the need for later redesign is reduced, early process control and capability at the SOP are enabled, and a low-defect production start can be achieved. Additionally, decision reliability is significantly improved in the early phases of product development.

3.2. *France*

In France, the development of complex technical products is historically and culturally shaped by the concept of *sûreté de fonctionnement*, which provides a unified framework integrating reliability, availability, maintainability and safety (RAMS). Unlike approaches that treat reliability mainly as a statistical property of components, the French tradition considers reliability as a system-level, lifecycle-dependent attribute, closely linked to safety justification and societal acceptability of risk. This approach has been strongly influenced by high-risk industrial sectors such as nuclear energy, railways, aerospace and defense, and has been formalised through academic contributions, national standards (AFNOR), and institutional methodologies (CEA, CNES, DGA). Foundational works such as Villemeur's *Sûreté de fonctionnement des systèmes industriels* (1988) have played a central role in structuring both education and engineering practice.

3.2.1. *Fundamentals: Phases, Activities*

The French product development process is characterized by a lifecycle-oriented, system-engineering approach that integrates reliability and safety from the earliest design stages. It typically extends from concept definition to operation and feedback and is closely aligned with RAMS standards such as IEC 60300 and sector-specific frameworks like EN 50126. The concept and preliminary design phase is particularly important, as system functions and architectures are defined and reliability and safety objectives are allocated at system, subsystem, and component levels. Functional decomposition and qualitative methods such as Functional Analysis, Preliminary Hazard Analysis (PHA), and FMECA support early identification of critical functions and failure modes. During detailed design, model-based analyses, reliability models, FTA, and stochastic methods are used to justify design decisions, with approaches such as FIDES widely applied (FIDES, 2004).

3.2.2. *Reliability engineering Principles* French reliability engineering places strong emphasis on probabilistic safety assessment and model-based analysis, known as *Évaluation Probabiliste de Sûreté* (EPS). Reliability and safety are evaluated using formal models that explicitly address uncertainty, rare events, and complex system interactions. Mathematical modelling based on stochastic processes, particularly Markov models (Cocozza, 1997), as well as emerging agent-based and networked system models (Zio, 2016), plays a central role. A key principle is the top-down construction of system reliability, beginning with system-level hazards and decomposing them into contributing functions and component failures using fault trees, event trees, and state-space models. This approach is especially suited to complex, safety-critical systems where empirical data may be limited and rigorous justification under uncertainty is required. It supports traceability, safety arguments, and certification processes, which are essential in highly regulated industries. French approach main advantages:

- early integration of reliability and safety into design decisions,
- strong coherence between engineering, regulation and certification,
- robustness in contexts with limited operational data,
- clear linkage between reliability, risk and societal safety objectives.

However, this approach also has limitations. Model-based EPS methods are resource-intensive and require advanced expertise in systems engineering. The strong focus on formal justification can reduce flexibility and slow development in fast-paced industrial contexts. In addition, compared to data-driven approaches, less emphasis may be placed on large-scale learning from operational data, although hybrid methods are increasingly being adopted.

3.3. *Japan*

In general, the product development process in Japan differs markedly from those in other countries. In Euro-American product development, the design phases are clearly divided: the initial design phase and the detail design phase. Engineers' responsibilities are also clearly divided. In the initial design phase, the concept of a product can be allocated to the requirements of each part. Design environment does not often change at the detail design phase. Therefore, designers can handle parts under their own responsibilities at the detail design phase.

3.3.1. *Fundamentals: Phases, Activities*

Japanese product development differs from European approaches in that initial and detailed design phases are not clearly separated. A central characteristic is *Suriawase*, a collaborative negotiation process involving design teams, production units, and suppliers from early design through detailed development as shown in the Fig. 4. This concurrent coordination supports product integrity and enables satisfactory multi-objective solutions despite significant uncertainty in early phases. Design requirements for individual components are often only tentatively defined and continuously refined through *Suriawase*, allowing development to proceed without interruption and helping to reduce overall development time. Japanese design environments are also marked by frequent changes, even during detailed design, to reflect customer and market demands, particularly in highly competitive industries such as automotive engineering. While *Suriawase* allows flexible adaptation to changing or additional requirements, it can delay final decisions and requires intensive communication and negotiation, creating a high workload. As a result, effective design support methods are needed to manage uncertainty, reduce coordination effort, and guide robust design decisions within the *Suriawase* process (Inoue et al., 2011).

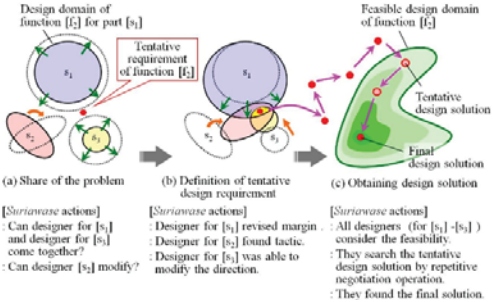

Fig. 4. Present situation of product development process based on *Suriawase*.

3.3.2. ***Reliability engineering principles***

Japanese companies have had their engineers trained for multiple tasks and skills (called "*Tanoko*" in Japanese) based on long-term employment and long-term trading with suppliers because of the labor shortage after World War II. That is why Japanese engineers are good at works of many different teams and can find an optimum design solution faster than other countries through a trial-and-error processes among several teams. Therefore, the product development based on *Suriawase* takes root in Japanese culture. The *Suriawase* development has an advantage in a product with integral architecture which individual parts of a structure are complexly intertwined with related functions such as automobiles, or light nimble home electrical appliances (Takeishi and Fujimoto, 2001).

3.4. Taiwan

Taiwan's industrial practice shows close collaboration among firms and strong links between design, manufacturing, and operation. Development does not strictly follow clearly separated phases, but instead progresses through iterative coordination among multiple actors, incl. manufacturers and system integrators. As a result, product specifications and performance attributes may continue to be refined during later stages of development and early operation.

3.4.1. ***Fundamentals: Phases, Activities***

Product development in Taiwan is characterized by strong collaboration across organizational boundaries and close integration of design, manufacturing, and implementation activities. Rather than strictly separating and fixing design phases early, development evolves through iterative coordination among system integrators, manufacturers, and specialized suppliers. Empirical studies show that development activities are often conducted in parallel, with design decisions continuously refined based on manufacturing and service feedback, particularly in industries with extensive OEM and ODM experience (Chu and Cheng, 2007). As a result, the boundaries between conceptual design, detailed design, and implementation are less rigid than in classical phase-based models. Specifications are gradually stabilized through ongoing coordination and feedback, even in later development stages. This approach enables flexible responses to uncertainty but leaves some performance attributes intentionally open until later phases. This collaborative and adaptive development style has important implications for reliability engineering. Since product characteristics evolve during implementation and operation, reliability is not viewed solely as a design-time attribute but is closely linked to production, operation, and maintenance phases: A basis for operation-oriented reliability engineering approach.

3.4.2. ***Reliability engineering principles***

In Taiwan, reliability engineering is mainly established and managed during the operation and maintenance (O&M) phase rather than being fully defined at the design stage. Reliability is regarded as a dynamic system property that evolves over the product lifecycle and is continuously evaluated using operational data, maintenance actions, and feedback from real environmental conditions. Although reliability-oriented design and component qualification are important, they do not solely determine overall system reliability.

This operation-oriented approach is especially evident in large-scale infrastructure and energy systems exposed to harsh environments, such as offshore wind farms and high-speed rail systems. In these applications, reliability is treated as a time-dependent property that is updated based on observed failures, degradation behaviour, and environmental loads. Recent studies on offshore wind farms in Taiwan illustrate this reliability-based O&M optimization models that incorporate local environmental conditions, including extreme typhoon events. Overall, Taiwan's reliability engineering emphasizes adaptive, data-driven O&M strategies supported by close industrial collaboration and continuous operational feedback (Liao, et al., 2026).

4. Country-specific influencing factors on reliability and safety engineering

4.1. *Historical impact: Industrialization*

4.1.1. *Germany*

In Europe, industrialization began in the second half of the eighteenth century in England (Griffin 2010) and later spread to Germany, where it accelerated significantly during the period of the German Empire. The development of the railway system illustrates this process well: starting with the first steam locomotive in 1804 and the opening of the first public railway line in 1825, railways enabled the fast transport of people and goods. This strongly supported the Industrial Revolution and gained additional importance through military logistics, particularly during Franco-German War of 1870–1871. Today, the ICE high-speed train is a key component of German transport infrastructure; (Jehle et al. 2006) and (Pollard 1981).

4.1.2. *Japan*

In Japan, industrialization began at the end of the nineteenth century as a result of external pressure from the United States. During the Edo period, Japan pursued a strict isolation policy, which ended after the arrival of U.S. warships in 1853. This event triggered the transition to the Meiji era in 1868, marked by political reforms and rapid industrial and technological development (Kajima 1976). The evolution of the Japanese railway system reflects this progress: early limitations in track gauge restricted speed, but major advances occurred from the 1960s onward. With the introduction of Shinkansen high-speed trains, Japan developed one of the most reliable and punctual railway systems worldwide (Givoni 2006). Another important influence on Japanese product development was the post–World War II period. Due to labor shortages, engineers were trained for multiple skills and worked in long-term, cross-functional teams (Bracke and Inoue, 2018). Close cooperation between design, production, and suppliers, known as "*Suriawase*," enabled efficient optimization of products and processes (Inoue et al., 2011).

4.1.3. *France*

Industrialization in France developed more gradually than in Germany or England and was strongly shaped by the central role of the state in economic and technological development. Beginning in the late eighteenth century, early industrial growth was supported by major infrastructure projects, particularly canals and railways, which became key instruments for territorial integration and economic modernisation. The expansion of the railway network during the nineteenth century, notably under the Second Empire, facilitated industrial production, military logistics, and administrative control, establishing rail transport as a strategic national asset. In contrast to market-driven models, French industrialisation relied heavily on state-led planning, regulation, and technical administration, a tradition that continued throughout the twentieth century in sectors such as energy, transport, aerospace, and defense. Large national programmes - such as nuclear power development and high-speed rail (TGV) - illustrates combination of advanced engineering with strong safety and reliability requirements. This historical context fostered a distinctive engineering culture emphasizing system-level thinking, formal justification, and risk control, which later crystallized in the concept of *sûreté de fonctionnement* and continues to influence French product development and reliability engineering practices today.

4.1.4. *Taiwan*

Taiwan's industrialization has been driven by export-oriented manufacturing and close integration into global supply chains. After the post-war period, Taiwan first developed labor-intensive industries and later shifted toward technology-intensive sectors such as electronics and semiconductors. Dense industrial clusters were formed at an early stage, enabling close interaction among firms and rapid accumulation of manufacturing know-how. A key characteristic of Taiwan's industrialization is the strong linkage between the early design stage, manufacturing, and implementation. Rather than relying solely on formalization in the early design phases, industrial capabilities were developed through production experience, incremental improvement, and feedback from operation. OEM and ODM business models further reinforced this approach by requiring close coordination with overseas partners. As a result, reliability has historically been strengthened through manufacturing, operation, and maintenance experience (Liao, et al. 2026).

4.2. *Education and work environment impact*

4.2.1. *Germany*

German society is shaped by a hierarchical structure combined with a social market economy. The German education system, based on the Humboldtian model, emphasizes comprehensive education that integrates research, arts, and sciences (Baumgart 1990). This model fosters broad cultural knowledge and creative, innovative thinking and remains a foundation of the German education system today. The social market economy, established after 1949, supports entrepreneurial freedom while providing social security, creating an environment that encourages independent thinking and innovation.

4.2.2. *Japan*

In contrast, Japanese society is characterized by a strong hierarchical structure, discipline, and a high value placed on education. The traditional principle of lifelong employment and strong loyalty to employers has led to a close connection between work and personal life. As a result, Japanese employees tend to strongly identify with their work, which is among other things reflected in low absenteeism rates (Bracke and Inoue, 2018).

4.2.3. *France*

Education and work culture in France are shaped by a strong tradition of state-led education, intellectual rigor, and formal qualification. Engineering education, particularly through the grandes écoles, places high emphasis on mathematics, theoretical modelling, and system-level abstraction, fostering engineers trained to reason analytically about complex technical systems. In the professional environment, work is structured around clear institutional frameworks and defined responsibilities. Hierarchical organisation coexists with a strong sense of public responsibility, especially in safety-critical sectors.

4.2.4. *Taiwan*

Taiwan’s education system and work environment strongly influence its industrial practices. Engineering education emphasizes practical skills and problem-solving, supported by close cooperation between universities, research institutes, and industry. Engineers often gain early experience through applied projects and direct interaction with manufacturing and production environments. In the workplace, engineers typically work in cross-functional teams involving design, manufacturing, and supply-chain partners. This setting promotes frequent communication, rapid feedback, and flexible responses to changing technical and operational conditions. Instead of strict role separation, competence is developed through hands-on experience and iterative improvement, reinforcing an engineering approach in which system performance and reliability are continuously strengthened during production, operation, and maintenance (Chu and Cheng, 2007).

4.3. *Society and social interaction impact*

4.3.1. *Germany*

German society places strong emphasis on discipline, punctuality, and reliability. Adhering to rules, contracts, and agreements is seen as a moral obligation and a foundation of trust. At the same time, tolerance and acceptance of diversity play an important role in Germany’s multicultural society. Cleanliness, order, and consideration in public spaces are regarded as expressions of mutual respect. Privacy is another key aspect of social interaction, with clear boundaries between private and professional life. Civic participation, democratic co-determination, and a strong culture of discussion reflect Germany’s commitment to democratic values. A high awareness of rules and structured procedures contributes to a predictable and organised society. Combined with a strong sense of solidarity and welfare-state orientation, these characteristics create a balance between individual freedom and collective responsibility, supporting innovation and problem-solving in engineering and industrial contexts.

4.3.2. *Japan*

Social interaction in Japan is strongly influenced by values such as respect, harmony, and consideration for others. Cultural principles like

Omotenashi (hospitality), *Wa* (harmony), *Reigi* (politeness), and *Ken* (self-restraint) shape behaviour in daily life (Nussbaum and Roth, 2005). Japanese hospitality emphasizes sincere, proactive care for others without seeking recognition, while harmony and group orientation encourage conflict avoidance and decisions that prioritise collective well-being. Politeness, respect for hierarchy, adherence to etiquette, and self-discipline are reflected in orderly public behaviour, strong rule compliance, and a pronounced apology culture. Loyalty, teamwork, modesty, and restraint further strengthen social cohesion, supporting efficiency and reliability in industrial and engineering contexts. In contrast, social interaction in Germany is characterised by individuality, openness, and direct communication. Personal freedom and self-responsibility are highly valued, and directness is seen as honest and respectful. Open criticism is widely accepted as constructive for improvement in both social and professional environments.

4.3.3. *France*

Social interaction in France is characterised by a strong emphasis on individual expression, intellectual debate, and respect for institutional frameworks. Open discussion and critical argumentation are culturally accepted and often valued, even in hierarchical contexts, fostering a tradition of rational justification and collective deliberation. At the same time, social cohesion is supported by a strong role of the state and shared public services, reinforcing a sense of collective responsibility. Rules and procedures are respected, though often interpreted flexibly through negotiation and dialogue. In professional and engineering environments, this combination encourages analytical reasoning, formal decision-making, and a critical examination of risks, contributing to system-oriented and safety-conscious approaches to technical development.

4.3.4. Taiwan

Social interaction in Taiwan's industrial context is strongly shaped by dense inter-firm networks and frequent collaboration across organizational boundaries. Long-standing experience with OEM and ODM business models has created a working environment in which coordination, negotiation, and joint problem-solving are integral to everyday engineering practice. Studies on collaborative product development emphasize the importance of continuous communication between design, manufacturing, and service actors, rather than strict reliance on formalized procedures. Within this setting, social interaction supports pragmatic decision-making and rapid feedback throughout development and operation. Trust is built through repeated cooperation and shared operational experience, enabling flexible and efficient responses to technical challenges. As a result, engineering performance and system reliability are enhanced through collective, experience-based practices across the entire product lifecycle.

5. Example railway system: Comparison of GER-, FR-, JP-, and TW-engineering

This chapter provides an overview of the comparison of technically highly complex products from industrialized nations, using rail transport as an example. Figure 3 shows the rail network expansion (long-distance transport) in the countries analyzed here - Germany, France, Japan and Taiwan - in an international context.

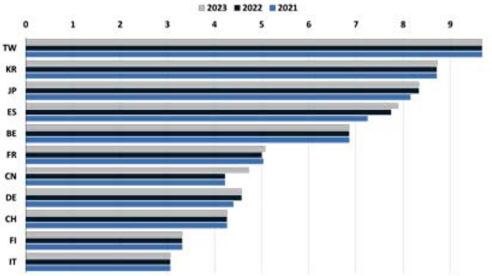

Fig. 3: Kilometer related to area of Germany (DE), Japan (JP), France (FR), Taiwan (TW); (Statista 2023)

5.1. *Comparison parameter punctuality*

One of the most important overarching variables when comparing the effectiveness of long-distance rail transport is punctuality; see Fig. 4 - 7. Japan shows the highest punctuality compared to France, Taiwan (data diffuse) and Germany.

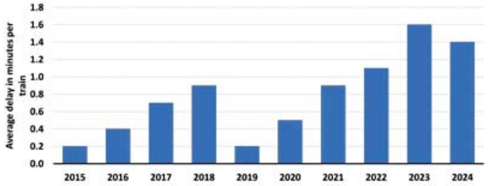

Fig. 4. Average delay of JR Central Tokaido Shinkansen in Japan FY 2015-2023 (Statista 2023). Note: Japan; fiscal years 2015 to 2023

Fig. 5. Punctuality of Deutsche Bahn long-distance trains (EC, IC, ICE (Jehle et al. 2006)) until 09.2024 (Statista 2023).

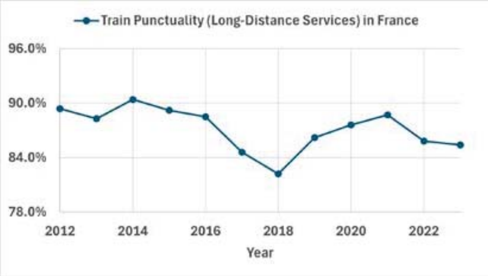

Fig. 6. Proportion of punctual TGV trains on the French rail network from 2012 to 2023 (AQST, 2024).

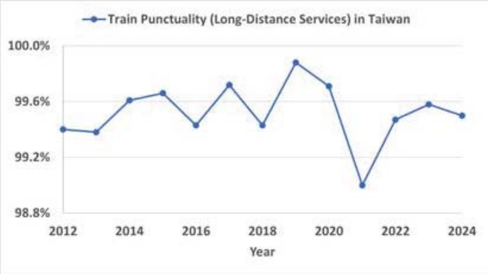

Fig. 7. Average delay regarding Taiwan High Speed Rail (THSR), long-distance passenger transport.

5.2. *Comparison based on criteria catalogue*

The comparison of long-distance rail transport in the following discussion is largely carried out qualitatively using defined criteria. The comparison provides an initial impression of how a highly complex system is realized based on different product development strategies.

Criterion Rail network(s): Long-distance, regional, freight
GER: Common rail network, partially segmented
FR: Integrated but strong segmented
JP: Clearly separated networks
TW: Clearly separated networks

Criterion: Use of rail network(s)
GER: Several train operators on one rail network
FR: Dominant national operator
JP: One train operator per network
TW: One dominant operator per network

Criterion: standardisation
GER: high standardisation
FR: High (state-driven, RAMS-oriented)
JP: very high standardisation
TW: High (imported and adapted)

Criterion: Railway station (Long Distance train system)
GER: Terminal station / Through station
FR: Predominantly terminal stations (Paris-centric)
JP: Through station
TW: Predominantly terminal-oriented stations

Criterion: Pacing
GER: approx. 10 min
FR: approx. 3 - 5 min on high-speed lines)
JP: approx. 1.6 min
TW: Moderate (≈ 5 - 10 min)

Criterion: Boarding of passengers
GER: Moderately structured
F: Moderately structured
JP: high structured
TW: Moderately structured

Criterion: Response capability to malfunctions
GER: Ø 30 min – XXX min respectively days
FR: Structured but moderate (Ø 15–45 min)
JP: Ø 5 – 30 min
TW: Moderate, recovery-oriented (Ø 15–60 min)

Criterion: Tolerance of malfunction (operator)
GER: Medium
FR: Medium
JP: low
TW: Medium to high

Criterion: Investment (Estimation)
GER: ~ 7,6 bn Euro/year
FR: 4-5 bn Euro/year (infrastructure investment)
JP: ~ 10,5 bn Euro/year
TW: ~1–2 bn Euro/year (operation & infrastructure combined)

6. Summary

This paper demonstrates that reliability and safety engineering practices in highly industrialized countries are systematically shaped by national product development structures and socio-technical contexts. By comparing Germany, France, Japan, and Taiwan, the study shows that reliability is embedded at different stages of the product lifecycle: early design frontloading in Germany, system-level RAMS justification in France, iterative optimization through *Suriawase* in Japan, and operation-oriented, data-driven adaptation in Taiwan. These approaches lead to distinct decision-making logics, risk management strategies, and trade-offs between flexibility, formal justification, and operational performance. The comparative analysis of long-distance railway systems confirms that no single reliability strategy is universally superior. Instead, each approach achieves robustness and safety through internally consistent combinations of development processes, organizational structures, and social interaction patterns. The results highlight that effective reliability engineering cannot be separated from its historical, educational, and institutional context and that transferring reliability methods across countries requires careful adaptation rather than direct replication.

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