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Function-oriented system design for resilience and sustainability

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ABSTRACT: The main objective of this paper is the investigation of possibilities to enhance the resilience and sustainability of technical systems by means of function-oriented system design. Design for Resilience aims at creating technical systems capable of withstanding and adapting to internal and external changes. Design for Sustainability has the objective to create solutions that meet present needs without compromising future generations, for instance by means of avoiding environmental destruction, improving resource efficiency, and achieving a long-term ecological balance. Function-oriented design is the most abstract form of solution generation. This paper presents arguments to verify the hypothesis that function-oriented system design is a prerequisite for both Design for Resilience and Design for Sustainability, discusses connections between both aspects, and proposes a common process.

KEYWORDS: functional modelling, sustainability, design to x, sustainable design, resilient design

1. Introduction

Due to technological progress, increasing customer demands, and global competition, technical systems are getting more and more complex and are, mainly due to changing environmental conditions, exposed to more challenging operation conditions. Simultaneously, the demand for technical systems which benefit customers without e.g. exploiting natural resources or emitting toxic substances is intensified. In order to address the challenge of increased inner and outer complexity, a system should be able to absorb certain disturbances, to handle potentially destructive influences, to restore performance, and to continue functioning satisfactorily and safely in the face of changes in the operation environment (Moskalenko et al. 2023) – the technical systems need to be resilient. At the same time, the global society must meet the needs of a growing population and respond to the emerging climate crisis in conjunction with an ongoing loss of biodiversity (Hauschild et al. 2020). Manufacturing companies need to offer products and services which add positive value to society, but do not result in harm, either directly or indirectly (Acevedo et al. 2024) – the technical systems need to be sustainable. In recent years, science is proposing guidelines and strategies both for improving the resilience and sustainability. However, these guidelines and strategies are mostly focused on late stages of the design cycle. Today, first manufacturing companies try to integrate sustainability into the early stages of design and innovation but are challenged by the fact that multiple criteria cannot be satisfied simultaneously (Parolin et al. 2024). This paper focuses on the function-oriented stage, within which the most important decisions concerning the system functionality and architecture are made. Additionally, this paper proposes not to address these two objectives individually but by means of an integrated approach. Negri et al. (2020) were able to present empirical evidence which shows that sustainability and resilience influence each other; an example for a conflict situation might be that a company with a smaller stock may be more efficient and sustainable but less resilient; on the other hand, strategies aimed at consuming less rare elements from nature may increase both sustainability and resilience. The close connection of both concepts is visible in many areas. For instance in supply chain network design, resilience and sustainability are simultaneously addressed (compare e. g. Lotfi et al. 2020). Consequently, the following research question can be formulated:

> *Which guidelines, strategies, and methods can enable an integrated approach to increase the resilience and sustainability of technical systems simultaneously and already in the functional domain?*

The employed research method is an in-depth exploration of the function development of multi-domain systems and a main source of insight is the reflective experience of the authors; these insights are embedded in a four-stage research framework (Stetter and Pulm 2024). In order to address the research question, the paper starts with a recapitulation of the state of the art (Section 2) and continues with a discussion of possibilities to add and improve functions (Section 3), the presentation of an approach to integrate both aspects (Section 4), a process for a simultaneous approach (Section 5), as well as a conclusion and outlook (Section 6).

2. State of the art

This section summarises the state of the art in the fields Design for Resilience and Design for Sustainability as well as function-oriented system development.

2.1. Design for Resilience

Resilience of technical systems implies the ability to sense and respond to changes in the systems health conditions, to repel, resist, or absorb faults, and to recover from the effects of these faults (Yodo and Wang 2016). Resilience can be understood as a very far-reaching concept that ensures that products and systems prove themselves even under changing boundary conditions. A comparatively small number of publications is explicitly focused on Design for Resilience. El-Halwagi et al. (2020) present a review of initial research. Kusiak (2020) investigates Design for Resilience in the scope of open manufacturing. Goa et al. (2021) seek to explore Design for Resilience of supply chains. The central hypothesis investigated by Weisz (2018) is that systems thinking is a central component of Design for Resilience. Several researchers emphasise the connection with Design for Sustainability, e. g. Haug (2018), and perceive a prolongation of the useful life as central objective of Design for Resilience.
A sensible general procedure for Design for Resilience can be based on the spiral model of resilience engineering (Figure 1 – adapted from Häring 2021 and Stetter and Till 2023). This approach is similar to the Design Thinking approach of Plattner et al. 2009. The major aspects of these approaches are:

- An early identification with and a good understanding of the problem by observing the user and emphasising with him.
- The use of various prototypes to foster a profound analysis of the problem.
- An iterative rather than a sequential proceeding in order to continuously improve the product.
- An increase of concretion (from abstract requirements and functions to more concrete effects and physical design) through these iterations.

The original Design Thinking approach aims at user focus and innovation and by that tries to achieve and realise disruptive ideas. In resilient design, it is important to focus on risks and disturbance factors and to prevent a static design that is endangered by disruptive events.
So, Design for Resilience has a strong connection with resilience engineering, which now aims at developing the capability of technical systems to prevent unexpected, disruptive events (UDEs), to be protected from UDEs, to be able to respond to UDEs, and to be able to recover from UDEs (Häring 2021). Design for Resilience and resilience engineering are also connected with fault-tolerant design (Stetter und Till 2023). The central elements of resilience engineering cover hazard analysis methods (e. g. Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA)) as well as system modelling methods (often based on the Unified Modelling Language (UML) or the System Modelling Language (SysML)). The starting point of the procedure represented in Figure 1 are the initial requirements in the origin. From this point, the design process continues covering three stages of risk analysis and leading to release of the technical system for production.

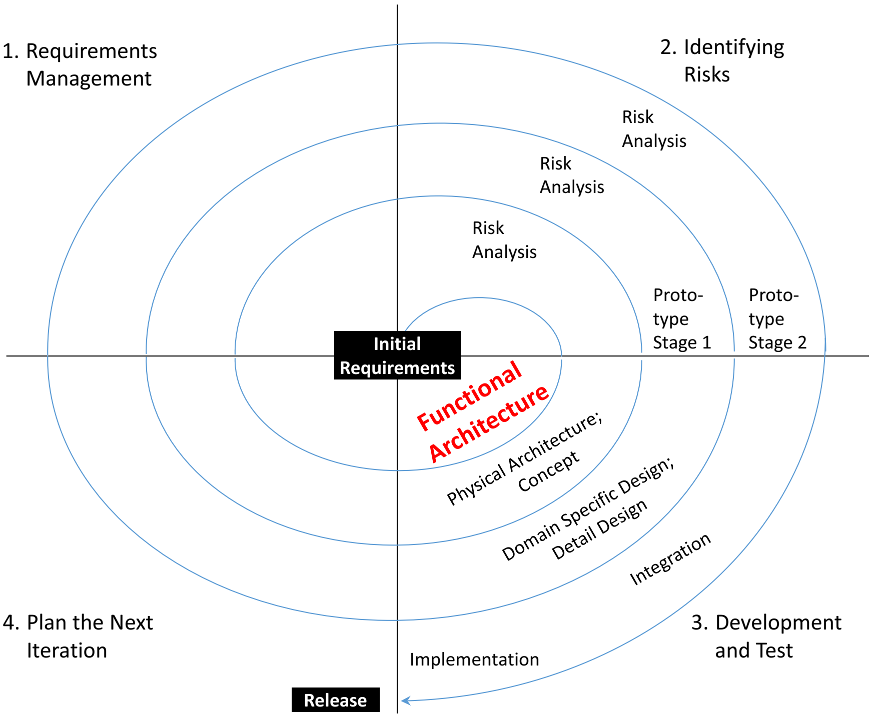

Figure 1. Main procedure in Design for Resilience

A central element of the risk analyses are resilience indicators which can be an effective tool to compute the resilience of technical systems (Kammouh et al. 2020). In all risk analyses, different sources for risks have to be considered – faults, disturbances, tolerances, ageing and wear, attacks, altered customer behaviour, resource scarcity, and changing operation conditions (Figure 2 – adapted from Stetter 2023).

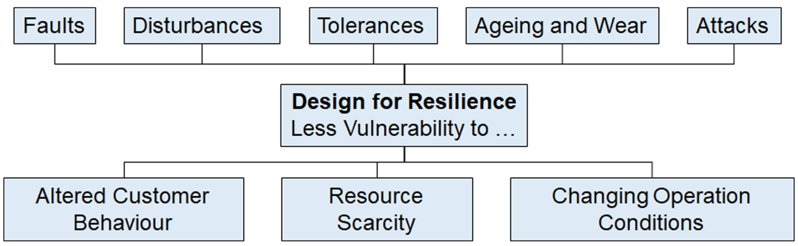

Figure 2. Main aspects of Design for Resilience

All these different sources can deploy risks on the technical systems having the potential to decrease the longevity, performance, and sustainability, or to result in systems which are dangerous to themselves, their environment, and to humans. Several possibilities to increase the resilience of technical systems can be found in literature such as redundancy, robustness, high-quality materials, simplicity, and proactive maintenance. However, most of them focus on later stages of the design process.

2.2. Design for Sustainability

Design for Sustainability focuses on creating technical systems which meet current needs of customers, the producing company, and society in general without compromising the environment or future generations. Today, Design for Sustainability is understood in a very broad scope – ranging from maximising efficiency in the consumption of energy, materials, and other resources as well as reducing the environmental impact of technical systems across their life cycle to designing technical systems which generate economic growth, avoid harm to people and environment, as well as provide positive opportunities for society (Acevedo et al. 2024). Sustainability thus covers ecological, economical, and social aspects. Approaches such as eco-design are part of Design for Sustainability, but do not cover all aspects. The current emphasis on sustainability also starts to include the early stages of design including function development, technology development, conceptual design, and architecture development (Parolin et al. 2024). A strong focus on intended functions of a technical system can contribute to minimising material consumption and to producing systems which are easier to assemble and disassemble, leading to a more sustainable environment (Sareh 2024).

One may ask, why designers are currently not designing the most sustainable technical systems. The main causes for this are probably not the unlikely circumstance that design engineers are not aware of the necessities and possibilities of sustainable design, but three additional aspects (Glönkler et al. 2023):

- A multitude of competing objectives must be considered, especially cost and global competitiveness, and the current economic system fosters short-term and local thinking.
- Nearly all design decisions concern more than one domain.
- Operation conditions can be continuously changing, and their change can be difficult or even impossible to predict.

These aspects lead to enormous challenges for design engineers and a structured approach towards Design for Sustainability is mandatory. This approach has to be integrated in current product development processes in industry. Today, in most cases, a Model-Based Systems Engineering (MBSE) approach is applied, putting the models of the technical system in the centre of the procedure. Product and process models are interconnected and enable continuous digital processes (Eckert at al. 2015). In many cases, the well-known V-model serves for the representation of the global logical structure and may include the aspects of sustainability (Figure 3 – adapted from Glönkler et al. 2023).

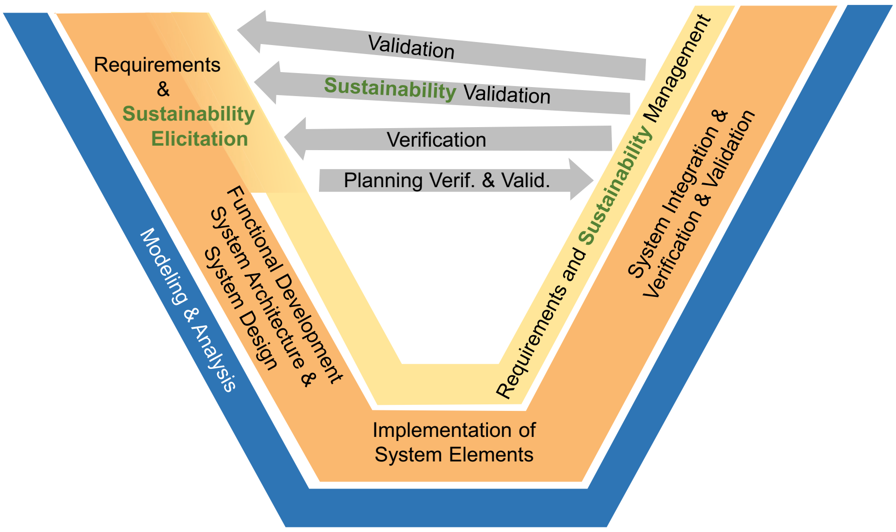

Figure 3. Main procedure in Design for Sustainability

The logical representation in Figure 3 emphasises an explicitly performed sustainability elicitation and a sustainability management, as the issues and challenges need to be monitored, reflected, updated, revisited, validated, and controlled throughout the design processes (Glönkler et al. 2023). Several possibilities to increase the sustainability of technical systems can be found in literature such as energy and resource efficiency, waste minimisation, carbon footprint reduction, longevity, as well as biodiversity protection. However, again, most of them focus on later stages of the design process.

2.3. Function-oriented system design

In design science and industrial practice, the function domain is understood as the link between the requirements (what a technical system should do) and the physical realisation (how the goals are achieved). Innovative systems contain a rising number of functions, and companies need to search for new technologies, new ways to apply existing technologies, and to combine technical systems with services which support function fulfilment (Eisenbart et al. 2017). The development processes in this domain are frequently carried out by a “system architecture” or a “function development team” and aim at generating – from a customer point of view – functional representations of mechanical and electrical components as well as software functions (Pulm and Stetter 2021). In systems engineering, the function-oriented analysis needs to be carried out as an ongoing, iterative process to ensure that all elements of engineering design, production, operation, as well disposal and service are covered (Haskins and Fet 2023). In function-oriented system design, the responsible teams need to determine how to fulfil the implicit and explicit demands and wishes of customers and society through mechanical and electronic components as well software functions. This is strongly connected with the system architecture. Fundamental properties of technical systems which increase resilience and sustainability have to be implemented already in this stage, because the main design decisions are taken here (Eisenbart et al. 2012).

3. Addition and improvement of functions

The focus of this section is both the addition and improvement of functions in order to enhance resilience (Section 3.1) or sustainability (Section 3.2). The overlap and integration potential are addressed in Section 4. The presented approaches in the function domain were gathered in numerous engineering design projects in practice and academia.

3.1. Resilient functions

As mentioned before, the functionality of technical systems can be endangered by several risks – faults, disturbances, tolerances, ageing and wear, attacks, altered customer behaviour, resource scarcity, and changing operation conditions. This section aims to propose approaches in the function domain which allow technical systems to fulfil their purpose efficiently and safely in spite of these risks and lists potential functions.

Functional redundancy: Redundancy per se is one of the main aspects of Design for Resilience. In the domain of concrete geometry and material, redundancy can be realised through providing several entities (sensors, actors, computation units, etc.) for the same function. A more abstract and fundamental redundancy can be achieved if the added parallel entities rely on different physical phenomena, e. g. a combination of electric and hydraulic actuators. Functional redundancy can become even more fundamental by replacing one parallel entity by a software function entity, e. g. a virtual sensor or a virtual actuator including artificial intelligence (AI) functions.

Diagnosis on several levels: Diagnosis is the process of estimating the condition of certain entities of the system itself or its surroundings. In general, diagnosis functions may detect any of the risks visible in Figure 2. Added diagnosis functions can detect the presence of risks, estimate the risks quantity, and recommend accommodation actions, e. g. through active fault-tolerant control (Witczak 2014). It is possible to apply diagnosis on several levels recursively; one lower diagnosis level can only concern a small sub-section of the system, while higher diagnosis levels may estimate conditions of large system sections or the complete technical system.

Adaptation and adaptive control: Certain conditions of hardware (mechanics, sensors, and actuators) such as production tolerances and wear can be compensated by means of software and parameter adaptation, e. g. through learning sensor and actuator limits. One example could be to measure the degradation of a catalytic converter and to adapt the motor control in a combustion engine vehicle.

Integration of information sources: Car navigation systems can provide curve radii which the electronic stability program (ESP) can compare with radial acceleration information from accelerometers in order to make accurate decisions concerning the driving situation and to initiate preventive actions such as increased damping or brake actuation.

Fall-back solutions: Risks may lead to the failure of certain sensors or actuators and can make certain control loops infeasible. If this it is detected, a simplified control loop may be activated, which may lead to certain compromises, for instance concerning efficiency, but may still ensure safe functionality and operation until a service convenience.

Functional robustness: The conventional understanding of robustness is closely connected to measurements and interoperability of detailed part geometries. It is also possible to formulate the basic idea of functional robustness – a robust function should be as independent as possible from certain conditions of the system itself and its environment. In a nutshell: a function which requires many conditions to be performed is not robust. A certain kind of function model – as proposed e. g. by Ehrlenspiel and Meerkamm (2017) – allows the representation of so-called conditions states for operation of functions. It can be concluded that a reduction of condition states will lead to more functional robustness and more resilient product functions.

Replaceability: In the same scope of independent functions, functions should be replaceable by other functions. Though this measure mainly applies to the physical level of the product, it might also be applied to the functional domain, if functions are not dependent on other functions and can be easily integrated in the overall processing flow of the machine.

Application of artificial intelligence (AI): Currently, numerous research initiatives investigate the application in product design and operation (compare e. g. Rudolph 2014). Pattern recognition, for instance, can greatly enhance diagnosis functions and can help to detect risks earlier and ease control and accommodation activities. Statistical analysis – alone or again in conjunction with pattern recognition – can be applied to specify the user behaviour and focus on realistic operating conditions. Additionally, prognosis functions may be realised using AI. Together, AI can work on different levels, as there are

- Control by some kind of intelligence (e. g. engine control unit),
- Connection of otherwise not related parts of the machine (e. g. engine control unit with navigation system),
- Data analysis (e. g. statistics on the use of the product).

This might be applied to e. g. optimisation of energy consumption, wear detection, of the user behaviour. The addition and improvement of resilience functions is sensibly realised as a process which is initiated with an evaluation of current and future risks. The design team needs to decide possibilities in the solution domains (function, abstract physics, geometry and material). Solutions on the function domain can be represented with different kinds of function models, e. g. relation-oriented function models as applied in the TRIZ/TIPS methodology or flow-oriented function models (compare Ehrlenspiel and Meerkamm (2017)).

3.2. Sustainable functions

The main goal of Design for Sustainability is the creation of products which fulfil customer requirements and meet internal demands of the producing company and society in general without compromising future generations. One typical example of Design for Sustainability could be the replacement of a toxic material by a non-toxic material with similar properties. In the function domain, several prominent possibilities can be identified which can improve sustainability, too.

A number of possibilities are directly or indirectly related to the design paradigm for optimal systems (Ponn and Lindemann 2008):

Avoidance of irreversibility: This design paradigm for optimal systems (Ponn and Lindemann 2008) can also require added or improved functions. The most prominent example is the function “store energy”, for instance in a spring. One example from biology for this function is insect flight storing energy in the chitin body. In technology, one prominent example are the valve springs in a combustion engine. The avoidance of irreversibility can avoid the waste of energy, can greatly enhance the efficiency of technical systems, and thus contribute to sustainability.

Cascading: This design paradigm for optimal systems (Ponn and Lindemann 2008) is often used with concrete geometry, e. g. in bridge design to avoid single areas with high load. In the function domain, cascading might be applied to energy sources as well as energy users, e.g. intelligent energy grids (compare redundancy) or different engines vs. a central power supply as well as e. g. a distribution of lights in order to only switch them on where they are needed compared to a central light source. Another form of cascading might be nesting as proposed in TRIZ/TIPS with the example of a telescopic shaft and the aim of reducing necessary space or other resources.

Functional integration (and separation): Though functional integration mainly refers to the physical domain, whereas one component takes over two or more functions (which in itself might be sustainable), it is also possible to combine functions on the abstract level – whether it be identical or diverse functions. An example might be the guidance of different flows such as force, electricity, information, and material, which might be integrated into one function. While functional integration aims mainly at a reduction of used material and resources, functional separation aims at maintenance and replaceability.

Further possibilities concern the integration of new functions, amplifications and systematic variation:

Integration of separation functions: Separation functions can remove certain toxic or otherwise dangerous substances from the matter flows of a technical system. One example can be an oil separator in a sewage system. Another form of separation might be the shielding of functions or subsystems of the regarded product.

Integration of conversion functions: Certain functions can lead to the conversion of a toxic or otherwise dangerous substance into a less dangerous or even harmless substance. One example is a catalytic converter for a combustion engine, which can be understood as a prominent example for sustainability. Integration of statistical functions: In technical systems, functions can be added that monitor the user operations and the results can be used for a better dimensioning of components, are better planning of maintenance and an optimised utilization of replacement parts. One example could be a profound knowledge how often the first gear of a gear system of a car is really used and for many operation hours it has to be dimensioned. A further example for sustainability could be a brake pad that it is replaced when it is really worn and not before.

Integration of documentation functions: Especially for a circular economy, persons who should service or disassemble a technical system, should easily get information concerning materials and appropriate disassembly processes. A vision could be a QR code visible on a technical product which would lead to a detailed material description and suggestions and explanations of a disassembly and service process.

Amplification of effects or functions: Again, on the physical level, the strength of effects is important when choosing how to realise a certain function. Yet, a weak effect that is strengthened by additional measures might be advantageous for sustainability. This strengthening might be already considered on the functional level. A similar strategy would be the limitation of functions.

Variation of structure: Though variation of build clearly refers to the physical form of the product, certain principles might be transferred to the functional domain. These might be (among others):

- Variation of connection structure: Is another order and sequence of functions more sustainable?
- Variation of reference system: Is a change of main and subsidiary flow possibly and more sustainable?
- Variation of chronological sequence: Can a function flow be in one or both directions, is it possible continuously or with breaks, etc.?
- Variation of set-up: Can sequential, parallel, or circular set-ups be exchanged?
- Reversion or negation: Can a function be eliminated or added, can it be extended or minimised, can it be exchanged in any form?

Further possibilities focus on force and matter flows:

Circulation of matter flows: In same cases it may be sensible to recirculate matter flows, because a second "run" through the same processes may lead to certain advantages. One example is the exhaust gas recirculation – a recirculation of exhaust gases to the intake of a combustion engine for increased efficiency and lower emissions.

Circulation of force flows in the meaning of force and load compensation: A recirculation of force in subsidiary flows might reduce load and thus lead to a reduction of resources needed. The principle of self-help might also increase robustness and thus resilience.

Avoidance of matter flows: Especially in older computers, entertainment and photography systems, the information flow was connected to a matter flow, for instance in a tape recorder or a conventional camera. The energy necessary for the transport of the matter can be avoided if the information flow is decoupled such as in modern MP3-players or digital cameras.

Finally, some possibilities add abstract levels to the system:

Control of technical processes: A control function can frequently be added and can lead to cleaner and more efficient processes. For instance, the control of the air-fuel ratio in a combustion engine can lead to better combustion and reduced emissions of carbon monoxides and nitrogen oxides.

Digitalisation/virtualisation of functions: Many operations in technical systems – usually functions which ultimately enable information flows – can be replaced by digital/virtual functions which can often save space and weight and are more efficient to be carried out.

Application of artificial intelligence (AI): AI can also be applied in added functions for the sake of sustainability. One example could be a neuronal network that estimates the composure of the exhaust gases and can assist the engine control unit for achieving lower emissions.

Obviously, central paradigms of Design for Sustainability are a life-cycle orientation and the consideration of circular economy potential. Thus, it is crucial to apply this functional orientation on all phases of the product life cycle, as there are sourcing (of raw materials and components), transportation, production, operation, service and maintenance, disposal, etc. Further advantages are possible by means of an integration with Design for Resilience (Section 4).

4. Integration of resilience and sustainability

Design for Resilience and Design for Sustainability have close and complex interdependencies, which need further investigation that can only be started here.
In certain aspects, there is a mutual support or a common goal from both approaches. On example for a mutual support is a knock control system in an internal combustion engine. On the one hand, it improves sustainability by allowing higher compression ratios and optimized ignition timing. On the other hand, it also increases resilience by protecting the engine from potential damage caused by knock-induced pressure spikes, for instance in the case of low-quality fuel. It is important to note that the operational life of resilient products can be considerably longer than that of conventional products. Especially in the case of changing external conditions, resilient systems may still be functional when conventional products cannot be used any more. It may not always be sensible to extend the lifetime, but in most cases, it will be sustainable to use technical systems for a longer time due to the savings of production resources. Further mutual support might be achieved by cascading and modularisation (i.e. an easy exchange of parts and an adaptation to the size needed) and the avoidance of matter flows (again by saving material resources).
Nevertheless, there are aspects which are contradictory, i.e. serving one approach but harm the other one. Resilience might be increased by a robust (materially strong) design, by fall-back solutions, and redundancy. All of those can undermine sustainability by the additional need for resources.
Aspects such as functional integration, avoidance of irreversibility, as well as simplicity in the design might increase sustainability in the first instance but will deteriorate the resilience of the product. It has to be investigated in each case, in how far the then reduced life time of the product can harm sustainability again.
It gets even more complex when regarding aspects such as control systems, diagnosis, artificial intelligence, and digitalisation in general. These approaches help being more efficient and thus be more sustainable during the operation. They enable a reaction to changing environmental conditions as well as changing customer demands, and by that establish a customer focus leading to a longer operational life. On the other hand, these approaches have an extremely high energy consumption, they lead to a product complexity that is often hard to handle, they consume a lot of natural resources such as noble earths with respective negative side effects (e.g. land consumption), and they lead to a strong dependence on working infrastructure and logistics, both during production and during the operational usage.
These complex and often not clear interdependencies and contradictions make it necessary to consider Design for Resilience and Design for Sustainability together. This demands for a combined process, which is discussed in the following chapter.

5. Process

A combined consideration requires synchronised processes. A first outline of this kind of process was developed based on analyses of industrial engineering design processes (compare Stetter&Pulm 2024); it is oriented on well-known systematic design procedures and seeks to enable an early addressing of possible contradictions. The process for the simultaneous approach of Design for Resilience and Design for Sustainability on the functional level – together with applicable methods – is depicted in Figure 4.

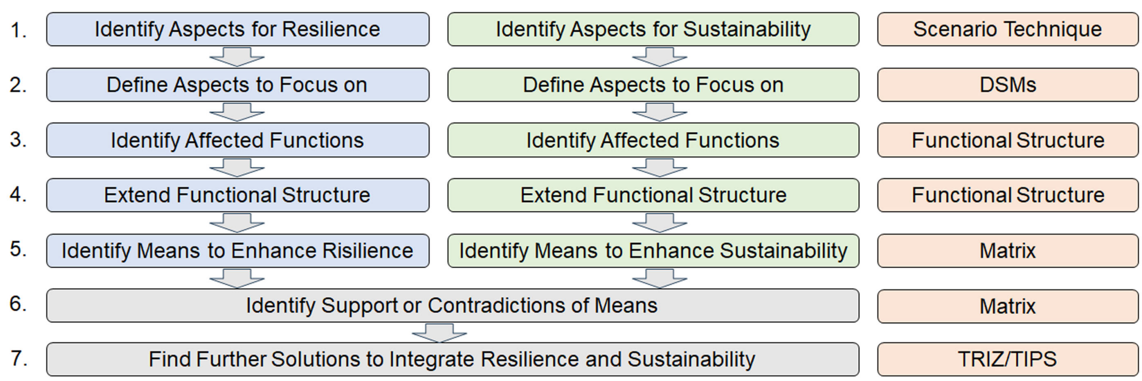

Figure 4. Process for Design for Resilience and Sustainability

A first step is to identify relevant and crucial aspects demanding a Design for Resilience, as there are changing customer requirements, changing operation conditions, ageing and wear, etc. (s. chapter 2.1). In the same way, critical aspects regarding sustainability have to be collected; these might be, amongst others, longevity, replaceability, repairability, resources, emissions, social factors such as working conditions or the use of the product, economics, etc. A scenario technique might help describing possible and probable scenarios and derive these aspects from them.
Also, as part of scenario technique, the most important key aspects both for resilience and sustainability have to be identified, which can be supported by a Design Structure Matrix (DSM). These are the aspects the following functional considerations.
Next, the aspects are linked to the functions of the product. It is possible to just list the affected functions (step 3) or to understand the aspects as harmful functions in terms of TRIZ/TIPS and graphically connect them to the functional structure by other useful or harmful functions (step 4).
Then, means to enhance resilience or sustainability as described in chapters 3.1 and 3.2 can be determined. These might be linked to the regarded function or alter the functional structure itself. Matrices connecting the aspects with the respective means might help in this step (s. Figure 5 left for resilience, similar for sustainability). These matrices have to be enhanced and are part of future research.

Resilience Measure	Resilience Factors	Faults	Disturbances	Tolerances	Aging and Wear	...
Functional Redundancy		x	x		x	
Diagnosis		x	x	x	x	
Adaptation and Adaptive Control			x	x	x	
Integration of Information Sources			x	x		
Fall-Back Solutions		x	x	x	x	
...						

Resilience Measure	Sustainability Measures	Avoid. of Irreversibility	Cascading	Functional Integration	...
Functional Redundancy		o	+	-	
Diagnosis		o	-	-	
Adaptation and Adaptive Control		o	+	-	
Integration of Information Sources		o	o	o	
Fall-Back Solutions		o	+	+	
...					

Figure 5. Connection of aspects and measures for Design for Resilience (left) and interdependence between measures for resilience and sustainability (right) – extract

For each function or functional area, the mutual interaction of the measures has to be analysed (step 6 in Figure 4). They might be neutral to each other, supporting each other, or contradicting each other. Here, another matrix showing these interactions might help (Figure 5 right). Examples for this have been named in chapter 4. If there is a contradiction between measures for resilience and sustainability, the use of TRIZ/TIPS might help identifying new solutions to overcome these contradictions.

6. Conclusion and outlook

The main aim of this paper was the investigation of possibilities to improve the resilience and sustainability of technical systems by means of function-oriented system design – a Design for Resilience and a Design for Sustainability respectively. For this reason, the addition and improvement of functions for both aspects as well as their integration was discussed. An initial description of a process for a simultaneous approach was also presented. Interesting fields for future research work are a widening of the empirical basis and a collection of optimised function models for complex systems.

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