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Research paper

Resilience in supply systems – What the food industry can learn from energy sector

Fabian Ossevorth [a], Paul Seidel [b], Sebastian Krahmer [a], Joachim Seifert [b], Peter Schegner [a], Peter Lochmann [c], Lukas Oehm [d], Marc Mauermann [d]

[a] Technische Universität Dresden, Professur für Elektroenergieversorgung, 01069 Dresden, Germany
[b] Technische Universität Dresden, Professur für Gebäudeenergietechnik und Wärmeversorgung, 01069 Dresden, Germany
[c] Technische Universität Dresden, Professur für Verarbeitungsmaschinen/Verarbeitungstechnik, 01069 Dresden, Germany
[d] Fraunhofer-Institut for Process Engineering and Packaging IVV, Division Processing Technology Dresden, Germany

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ABSTRACT

Drastic events such as pandemics, earthquakes or other disasters threaten not only the immediate living conditions of people but also indirect circumstances such as energy supply, infrastructure and food production. To ensure that damage and failures in these areas do not lead to a disaster, special requirements are placed on this critical infrastructure. In this context resilience, which is defined as the resistance of a system to external effects, is required. A field that is indeed part of the critical infrastructure, but which has not been considered as intensively as the energy sector, is food production.

The investigation focuses on how fundamental principles of thermodynamics, system theory and reliability theory can be applied to the modelling of food production processes to obtain a measure of resilience. Using known state and process variables from thermodynamics and electrical power engineering, analogous variables are derived for the food industry. These variables serve as an evaluation standard for a quality measure Q. In addition to system-theoretical considerations, it is investigated how existing evaluation criteria of power engineering, such as System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Duration Index (CAIDI), can be transferred to food production.

Design: The investigation focuses on how fundamental principles of thermodynamics, system theory and reliability theory can be applied to the modelling of food production processes to obtain a measure of resilience. Using known state and process variables from thermodynamics and electrical power engineering, analogous variables are derived for the food industry.

Purpose: Drastic events such as pandemics, earthquakes or other disasters threaten not only the immediate living conditions of people but also indirect circumstances such as energy supply, infrastructure and food production. To ensure that damage and failures in these areas do not lead to a disaster, special requirements are placed on this critical infrastructure. In this context resilience is required.

Findings: The aforementioned state and process variables serve as an evaluation standard for a quality measure Q. In addition to system-theoretical considerations, it is investigated how existing evaluation criteria of power engineering, such as SAIDI and CAIDI, can be transferred to food production.

Originality: This paper fulfils an identified need to study a part of the critical infrastructure that has not been as extensively looked at as the energy sector, namely food production.

E-mail addresses: fabian.ossevorth@tu-dresden.de (F. Ossevorth), paul.seidel@tu-dresden.de (P. Seidel), sebastian.krahmer@tu-dresden.de (S. Krahmer), joachim.seifert@tu-dresden.de (J. Seifert), peter.schegner@tu-dresden.de (P. Schegner), peter.lochmann@tu-dresden.de (P. Lochmann), lukas.oehm@ivv-dd.fraunhofer.de (L. Oehm), marc.mauermann@ivv-dd.fraunhofer.de (M. Mauermann).

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1. Introduction

Undoubtedly, energy and food supply are among those sectors of economy, which are essential for providing daily necessities of life for the population. Regarding energy systems, the past years has brought great advances for ensuring the security of supply during critical situations. This progress of the energy system – including electrical, thermal and gas technology – is characterized by resilience[1] efforts. However, the states of the art of resilience science and engineering regarding energy and food systems are quite different. Energy system engineering faces urgent matters of security of supply under volatile energy production, since renewable energy sources have been launched in the 2000s. Additionally, many other sectors of economy are dependent on reliable energy supply [1]. In this context, methods, procedures and key figures for evaluating system resilience of critical infrastructure are already established, [2–6]. Food system engineering has not considered resilience of food supply, yet. Although many food producers count as critical infrastructure, which compromise security of food supply of the population in case of a failure, an approach for evaluating resilience of food supply systems is missing.

The following article attempts to transfer existing terms and criteria of resilience to the food supply system focusing on the commonality between the energy and food system.

The focus of this work is to apply generally applicable tools from the disciplines of electrical and mechanical engineering for the design of resilient systems. In particular, network theory, system theory and methods of reliability theory should be mentioned here.

The focus is on the approach of identifying physical quantities that describe the system. From these and from derived variables, signal flows, processes and complex models can be created, from which in turn a quality or loss function is developed. Based on this function, the system resilience can then be evaluated through an iterative process and the system can be designed accordingly.

At the present time of our research, we are not yet in a position to present a fully calculated example, but to show correlations and introduce individual procedures. In Section 2 we present physical quantity variables that can be identified as difference and flux variables and are thus suitable for a network description. Equivalent to flow and difference quantities are the distinction of variables into state and process variables, which will be used in the following chapters.

A compilation of known key figures that quantify reliability and resilience is given for the electrical energy supply in Section 3. For thermal and chemical supply systems, state and process variables as well as permissible limit values are mentioned. The third complex summarizes the current status in the food industry, where, in contrast to electrical and thermal energy technology, there are still no uniform parameters.

In Section 4, based on resilience characteristics of earthquake research, quality curves are defined that take on the character of an objective function. Different approaches in the characterization of the curves result in different variants for system design. One example is a discretization of the curve under the specification of transition rates. States can be defined from the discretization and a state graph can be derived which can be used to design a resilient system.

2. Background theory and state of the art

The term resilience does not refer to a physical quantity, but describes a progress of designing systems in a way to enable as flexible reactions as possible to disturbances. The primary objective of resilience is to keep a system in functional state and to guarantee the fulfilment of its supply task. In general, resilience of a socio-technical systems assume a) resistance, b) adaptability and learning ability, as well as c) regeneration capacity, cf. [7–11].

Furthermore, one can differentiate between Engineering Resilience (Efficiency of Function) and Ecosystem Resilience (Existence of Function) [12]. Engineering Resilience means stability in the sense of efficiency, constancy, and predictability. Regarding technical design, resilience requires to remain nearby an equilibrium state for which a measurement value has to be defined. Ecosystem Resilience comprises dynamic properties, which help a system to adapt flexibly to new conditions. In this context, the extent of disturbances to be absorbed without changing the system are a resilience measure.

Some simulation-based approaches for analyzing resilience during catastrophes have already been published. Specific behaviors and recovery durations of communities after natural disasters were studied in [13]. Using event-discrete simulation approaches, researchers analyzed, how emergency departments react to rapidly increasing emergency cases [14]. In contrast, an agent-based comparison was applied for an airport terminal case [15]. Furthermore, an evaluation method exists for the resilience of production systems used in discrete parts manufacturing, which considered the relation of external disturbances, internal spatial and temporal adaptions, and resilience [16, 17]. These factors are part of a decision support method, which include simulation-based evaluation of configuration alternatives. Finally, [18] combines different perspectives on resilience by relating resilience of productions systems to robustness of systems in general. This enables to describe resilience by methods of system theory according to which resilience is the capability of a system to hold the target value of a key figure within certain boundaries while exposed to changing conditions. It does not matter whether this target is fulfilled by adjustment of system structure (adaptability) or system tolerance towards disturbances (resistance). A comparison of completely different systems is possible within this framework. To do so, key figures must be defined. Table 1 lists relevant ones for electrical, thermal and production systems.

Within this framework, on the one hand, *process variables* represent physical key figures, which only appear with changes of system state describing the change process. Process variables are dependent on the path of a system change. On the other hand, *state variables* are measureable key figures, which describe the state of a system at a certain point in time. In case of an open system, state variable are those variables, which describe input and output flows [19, 20].

2.1. Key figures of energy systems

Regarding energy systems, supply security and reliability are close related to the term resilience. Physical quantities describe the processes of conversion, storage and transport, which constitute the energy system. Security of supply requires that energy demand and provision are always in balance. While calculating energy balances, thermodynamics differentiates between closed, impermeable systems and open, permeable systems using direct mass transfer as the distinctive feature, cf. Fig. 1. According to this classification, electrical and thermal energy

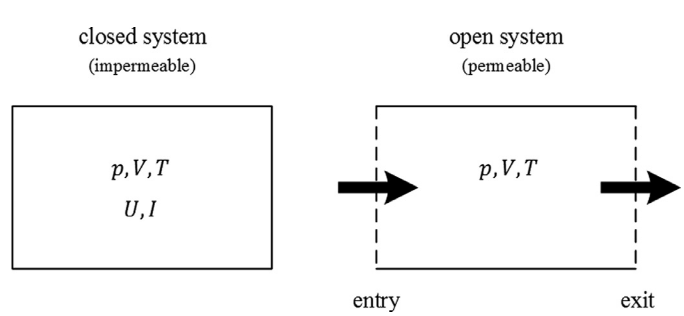

Fig. 1. Schematic representation of the state variables for the energy balance (symbols cf. Table 1), divided into a closed and open system.

[1] A process of responding to challenges and changes by adapting the system behaviour is characterized by resilience. This process includes factors of influence that require resilience, factors that encourage resilience, and consequences.

Table 1
Comparison of state and process variables for electrical, thermal and production systems.

	Key figure of electrical energy supply systems	Key figure of thermal energy supply systems	Key figure of food supply systems
State variable	Voltage U	Pressure p	Quality criterion Δq_{max},
	Current I	Volume V	Quality grade Q
		Temperature T	Availability A
		Calorific value (H_i / H_s)	Current output p_M
Process variable	Work W	Heat Q	Quality output p_Q
	Power P	Heat flow $\dot{Q}$	
		Mass flow $\dot{m}$	

systems are closed systems[2] transmitting energy, and chemical energy systems are open systems only transferring gas. Energy balances can therefore represent both types of systems and disturbances then appear as interruptions of the energy flow, which disrupt the necessary equilibrium. Buffer capacities significantly determine resilience of a system towards disturbances of the energy balance and must be taken into account while evaluating resilience of an energy system.

The quantitative evaluation of power transmission and energy balance do not suffice for evaluating supply system resilience. Qualitative aspects of power and energy are necessarily to be considered. The specific quality aspects are current and voltage for electrical energy systems, certain temperature levels for thermal energy systems and gas composition for chemical energy systems. In addition, thermal and gas systems show larger inertial effects, which are sometimes called energy robustness [21].

2.2. Key figures of food supply systems

Regarding food supply systems, security of supply means providing the required amount of safe food stuff for the population. This excludes considerations of consumer preferences or competition between individual food producers, because the reliable supply of the population with essential nutrients (protein, fat, carbohydrates, vitamins, minerals, trace elements) in critical situations is the overriding objective. Therefore, the following considerations refer only to measureable production quantities and quality criteria. An explicit description of the underlying production and distribution processes based on physical balance equations is not possible due to the multitude of different physical, chemical and biological processes involved. For example, the production of cheese, starting e.g. with the homogenization of milk and ending with the packaging of the final product. This includes biological syntheses, biochemical ripening processes, thermal heating processes and slicing processes. Therefore, the balancing of product quantities is an alternative, which lead to a mass flow balance, if the mass of the individual products is known. Commonly used in production management and reliability analysis [22–24], statistical analysis methods provide key figures, which can be used to derive state and process variables:

Product quality Δq is the basis of statistical production analysis describing the deviation of the current value of a quality key figure q_{actual} from the required target value q_{target} by [22]

$$\Delta q = q_{\mathrm{target}} - q_{\mathrm{actual}},\ \mathrm{vgl.}\ . \tag{1}$$

Quality thereby refers to the single product and quality key figures are e.g. food safety, mass or color of food stuff as well as packaging tightness. The key figures quality grade Q and current output p_M derive directly from product quality, by dividing food products into reject products ($\Delta q > \Delta q_{\max}$) and quality products ($\Delta q \le \Delta q_{\max}$) according to the quality criterion $\Delta q_{\max}$. The current output p_M corresponds to the sum of produced amount of reject products n_R and quality products n_Q per time interval t_{interval} by

$$p_M = \frac{n_R + n_Q}{t_{\mathrm{interval}}}\ . \tag{2}$$

[2] Referring to thermal systems: Impermeable system.

The quality grade Q describes the ratio between the produced products during the considered time interval, cf. [24], by

$$Q = \frac{n_Q}{n_R + n_Q}\ . \tag{3}$$

Depending on the reference quantity and context, other similar ratios are also recorded, of which availability A is the most common, cf. [23, 24]. If the quality criterion $\Delta q_{\max}$ is known, the state of a food production system is determined by the state variables instantaneous output and quality grade. The relationship between the state variables is shown in Fig. 2. However, the number of quality products produced per time interval is of primary interest for supply reliability, which is given by the quality output p_Q to

$$p_Q = Q \cdot p_M = \frac{n_Q}{t_{\mathrm{interval}}} \tag{4}$$

and which represents the relevant process variable of the system.

This consideration refers only to the operational environment of food production. However, the supply performance concerning individual nutrients, which are relevant for the nutrition of the population, remains unaddressed. The quality criteria of production management and production quantities based on amounts of individual food products do not appear to be useful, since they do not provide any information about the available quantity of nutrients. However, if quantitative variables of the health impact can be defined as quality key figures q including criteria for their safety to consumer $\Delta q_{\max}$ and nutrients amounts as quantity key figures p_M, a quantitative recording of the supply situation and a resilience consideration of the food supply system seems to be possible.

3. Resilience in power supply systems and food supply systems

In order to quantify the quality and reliability of a system, and with regard to securing the supply, companies in Germany can use the information and technical guidelines of the electrical and thermal power engineering industry associations for effective crisis and risk management, e.g. [4, 25–28]. In relation to the respective system, various threat constellations are created and risk factors are estimated, which are used for the weighting and requirements for the operational safety of various components. For example, the failure of physical assets or communication structures due to natural disasters or sabotage/cyberterrorism should be covered by an accountable design or predefined emergency procedures.

3.1. Electrical energy supply systems

In electrical power engineering, the state variables voltage and current are primarily used to record the quality criteria, which can be converted into the process variables. In this respect, the European standard EN 50160 [2] describes and defines the characteristics of the supply voltage with regard to curve shape, level, symmetry and frequency ($f_{\mathrm{target}} = 50\,\mathrm{Hz}$), among other things. In addition to the European standard, the technical guidelines of the grid operators should be mentioned, which define similar criteria for grid operation, [29, 5]. Deviations from the setpoints in defined tolerance bands and with certain frequency are

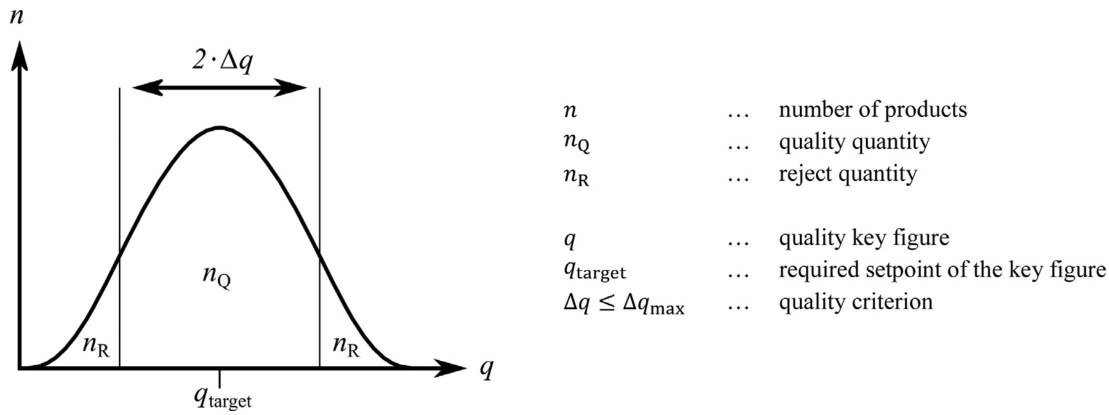

Fig. 2. Relationship between the state variables of production systems. Quantities are defined within a given time interval.

Table 2
Assessment parameters for supply interruption [3].

Index	Description	Calculation	Unit
SAIFI	System Average Interuption Frequency Index	$\frac{\sum(\text{Interrupted customers per case})}{\text{Total number of customers served}}$	$\frac{1}{a}$
SAIDI	System Average Interruption Duration Index	$\frac{\sum((\text{Interrupted customers per case})\cdot(\text{Duration per case})}{\text{Total number of customers served}}$	$\frac{min}{a}$
CAIDI	Customer Average Interruption Duration Index	$\frac{\sum((\text{Interrupted customers per case})\cdot(\text{Duration per case})}{\sum(\text{Interrupted customers per case})}$	min

quite acceptable here, since the system as a whole has a stochastic character. Compliance is important in that the connected consumer and generation systems are generally only rated for a certain characteristic of the supply voltage and can disconnect from the grid outside this range for reasons of self-protection or no longer function as intended. In order to maintain the tolerance bands, the grid operators carry out operational adjustments and, if necessary, technical safety interventions. It should be noted that, in principle, frequency has an interregional spread, voltage level a regional spread and waveform a local spread. Accordingly, responsibilities and coordination strategies are distributed (inter)nationally and regionally.

Subsequently, measures of supply interruptions according to IEEE Std 1366-2021 [3] can be derived, which are listed in excerpts in the scope used today in Table 2. These can be created starting with the smallest unit of a supply area and accumulated up to the total system.

The causes of a supply interruption can be either a physical defect in a piece of equipment or a sufficiently long violation of the tolerance ranges of the quality parameters of the voltage, cf. [2]. The presented indices result from a multidimensional quality vector and can be interpreted as *a* resilience measure.

Consequently, it is worth detecting whether existing industry-specific evaluation variables can be further developed in order to obtain a higher resilience-specific significance. As an example, the adaptation of the interruption index SAIDI[3] of the electrical grid is suggested. Instead of equal weighting of interruptions, those up to half an hour are generally not critical and should be weighted lower.

3.2. Thermal/Chemical energy supply systems

In thermal power engineering, the measurable state variables that describe the quality of the supply are primarily the temperature and the volume flow and pressure. Here, the temperature level has the greatest influence on the quality, since heat must always be transferred in relation to a system-dependent temperature level. The temperature tolerances are highly dependent on the application. If we consider, e. g., the supply condition of domestic hot water preparation, temperature conditions of $\vartheta \geq 65°C$ are mandatory here due to the risk of legionella. In the case of heat-only supply, the temperature levels are set depending on the heat conversion equipment. In terms of compliance, a temperature range of $\vartheta \approx \pm 3\,K$ can be assumed safe here. In addition to the temperature, the mass flow, or in the case of room air and gas systems, the volume flow plays a significant role. For these, too, quality criteria exist in practice in the sense of fluctuation ranges, which are strongly dependent on the respective use case and cannot be stated in general terms. However, the volume flow to ensure a minimum power to be transmitted can be assumed in a range of $\pm 2\,\%$.

With regard to chemical energy technology, the quality (composition) of a gas is also decisive. This state variable is described by the calorific value of a gas. Since natural gas as a natural product is subject to natural fluctuations, it is necessary to define a permissible fluctuation range within the individual gas families for the security of supply and the correct operation of a plant, e.g. the calorific value for natural gas H in the standard state is in the range of $H_s = 10,1 \dots 13,1\,kWh/m^3$ [30, 31]. With regard to the resilience evaluation, the criteria of Table 2 can also be applied in thermal and chemical energy technology.

3.3. Food supply systems

The authors are not aware of any assessment criteria that represent the resilience of the food supply in Germany. Similarly, no sources of statistics on the security or quality of food supply in Germany could be identified. What is known are regulations on food safety, which serve to protect consumers, and rationing quantities, which were applied in historical crises. This provides the first approaches for the quality and quantity criterion of resilience.

Behind the regulations on food safety is the requirement that food must not pose a risk if it is prepared and eaten in the manner intended [32, 33]. In agricultural production, there are specifications on pesticides or medication of animals. In the area of processing, specifications apply to the physical, chemical and biological contamination of food. Preventive measures include e. g. hygiene, cleaning, quality control and tracking & tracing [34, 35]. The trade and sale of food is affected by regulations on minimum shelf life or documentation and information requirements [36–38]. These regulations define the quality standard in quantifiable quantities, e. g. in the form of limit values for microbial contamination, deviations in the contents and contaminants or minimum guaranteed shelf life. The European Rapid Alert System Food and

[3] As a reminder, this represents the reciprocal of availability.

Feed (RASFF) collects, evaluates and disseminates information on food- and feed-related hazards for the consumers [39, 40]. On this basis, quality criteria of a resilience assessment could be formed. A key element in deriving these criteria is a process abstraction in form of a model. This can be a state model, a graph or a dynamic system. Defining limit values for state variables makes it possible to tune the model further in regard of resilience.

The last time there were quantitative standards for the supply of food in Germany was during the Second World War and in the years thereafter. The decisive factor was the energy requirement of a person, which was set at between 1,550 kcal and 2,500 kcal depending on age, the work performed and the supply situation. The rations were allocated with the help of ration cards, on which the energy quantities were converted into volume or weight quantities of certain products such as flour, butter, bread or meat. As soon as the available quantity of food had increased again and the supply was thus secured, such rationing measures were abolished [41, 42]. Today, the nutrient requirements of a person can be broken down in more detail, and thus it is possible to determine the required supply quantity based on the population figures according to the different nutrients. It could form the quantity criterion of a resilience assessment.

A first comprehensive approach to assessing food supply resilience has been proposed in the UK [43]. A map of indicators is proposed comprising i) domestic, ii) intra-sectoral, and iii) inter-sectoral factors that influence food supply security. In addition, the dependence of the domestic supply situation on foreign developments is mapped. The indicators represent a kind of early warning system including following features:

a) Availability of sufficient quantities of food (origin and variety of supplies)
b) Access to food (meeting demand)
c) Affordability of food also for low-income groups
d) Diet and quality
e) Food safety
f) Resilience of the food supply system under difficult conditions and in the event of a crisis
g) Confidence in the food supply.

The influencing variables and threats recorded in the model can in principle be transferred to Germany and other countries, but they do not represent quantitative parameters for the critical supply case considered here. As an evaluation parameter for the resilience of the food supply, parameters are required that are based on quality and quantity criteria, analogously to the parameters of electrical energy technology. Finally, it does not always seem possible to draw a clear distinction between the indicators; e. g., the failure of a large-scale production facility would have an impact on indicators a), c) as well as f).

4. Resilience assessment

4.1. Evaluation metrics

Despite differences in the structure and distribution mechanisms of the supply systems, similar measures and evaluation approaches are possible both in the subsectors of food industry and in the subsectors of energy supply. There is always an evaluation key figure, which refers to a quality criterion (state variable) and a quantity criterion (process variable), cf. Table 3. The quality criterion represents the target value of a quality key figure, which is characteristic for the supply good. The quantity criterion is the target value of the supply quantity that should be available.

At this point, the authors want to give a rough picture of actors and interactions assuming a system distortion such as a physical defect of equipment within the electrical energy supply sector. A defect of a line or busbar leads to a new system state, i.e. that the current flow is adapted to the new grid topology and in consequence nodal voltages also change. As still in normal operation mode, the voltage has to be within boundaries and voltage control must be performed, which in turn is reflected also in a reactive current adjustment. At the end, the new current distribution has to be checked against the current load capacity of each equipment. Possible overloads must be preevaluted using n-1 contingency analysis and countered by precautionary power adjustment, cf. annual energy cutted off. Additionally, the actual power balance of the grid might still be affected, e.g. because of power generation or load was disconnected from the grid through the equipment defect. This triggers mechanisms of power balancing, which are carried out by different types of energy resources and can have short- and long-term character. In this roughly depicted scenario, each step, e.g. the provisioning of evasion paths or balancing energy, can be represented by an activation function, which in reality is subject to a certain probability of failure. The result is, for example, the SAIDI. These considerations can in general be transferred to a quality measure of system, as formally described in Section 4.2. Subsequently, each step in this exemplarily described chain of actions can consequently be seen as a state change with associated probability and enables an approximation of the system behavior from a resilience perspective. Present evaluation key figures, cf. Table 3, can support a related system assessment.

Due to the focus on food industry, the sector is divided in food production and food supply. The comparison in Table 3 shows that there is no known evaluation parameter for resilience in food supply. However, the existing statistical key figures of the operational analysis in food production can serve as a starting point for such resilience evaluation if food safety standards are used as quality criterion and energy similar food rations as quantity criterion.

Influences of disturbance variables and their effect on the availability of a system are difficult to describe in a formalised way. Therefore, in classical risk assessment the probability of occurrence of an event is often combined with the extent of damage and classified into risk categories. An example of characterizing the resilience of a complex system against earthquakes is presented in [45] and [46]. The criteria defined there are:

- Failure probabilities of the components,
- mitigation of post-failure consequences, particularly with regard to the number of fatalities, damage incurred, and economic and societal impacts, and
- short recovery times.

Quantitative measures referring to probabilities and time intervals are then derived from the demands made. Fig. 3 shows a visualization of the relationship.

4.2. Resilience measure

Furthermore, the assessment of a system in terms of metrics and resilience measures must be undertaken in a multi-dimensional approach. A normalized measure for the quality[4] of a system is denoted by $Q(t) \in [0, 1]$, this measure is time-varying and remains in ideal state if a system has an infinite robustness with respect to this quality measure. The introduced quality measure refers to parameters according to Table 3 and the measures of product quality presented in the previous chapter.

The initial state of a quality measure is normal, which is expressed by the quality level 1. At a time t_0, a disruptive event acts, that means, the quality has been abruptly reduced. This can be e. g. i) a sudden failure of an energy system suppling a food factory, ii) sudden supply chain interruption due to border rejection of raw material or iii) sudden failure of a drinking water supply, which can have similar disruptive dimensions as the earthquake event presented in [46]. There may also be

[4] From this point, *quality* is used to describe the overall goodness of a system incorporating quality and quantity criteria.

Table 3
Comparison of the evaluation parameters, divided into quality and quantity criteria for electrical and thermal energy supply systems and food supply systems.

Sector	Quality criterion	Quantity criterion	Evaluation key figure
Electrical energy supply	Frequency and amplitude of the grid voltage	Power flow / energy	Via duration of uninterrupted supply (cf. Table 2: SAIFI, SAIDI, CAIDI)
	Superposition of harmonic current and voltage components		Flicker value P_{st}, P_{lt} Harmonic current level
	Balancing power	Energy	Annual energy cutted off Used balancing power
Thermal energy supply	Chemical gas composition (Minimum) pressure Temperature / heat level Calorific value Min/max power	Volume flow /mass flow Energy / heat Minimum gas storage levels (20 % limit for shutdown of non-critical consumers)	Minimum pressures required for pressure ranges: Low/Medium/High pressure
Food supply	Food safety (e. g. limits of physical, chemical and biological contamination)	Food per capita; Required food according to the nutritional needs of the population, derived from the daily requirements of a person, (e. g., amount of energy ~2,000 kCal/d [44], amount of drinking water, or other nutrients)	Unknown
Food production	Specific quality criterion Δq_{max}	Required quality output $p_{Q,\ target}$	Quality grade Q Availability A

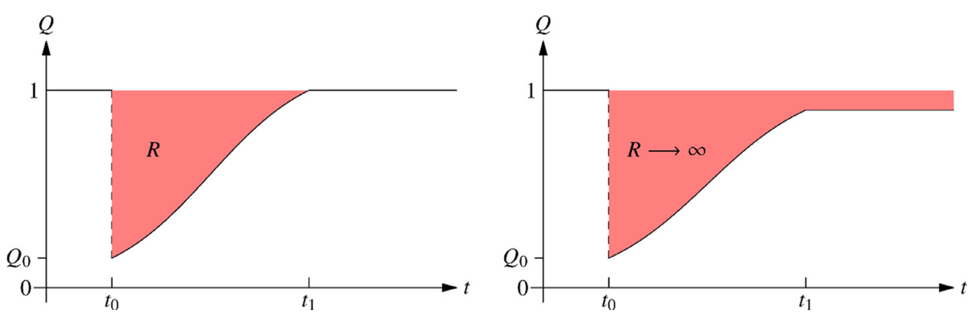

Fig. 3. Conceptual representation of a resilience measure.

other events, where the quality is degraded more slowly, e. g., declining raw material supplies. Another example is contamination with harmful microorganisms, which are gradually reducing the quantity of safe food products. The reduction of the quality has a negative impact on the subsequent processes, for example, this may lead to a failure of further products, which were based on the products of the previous production step. The restoration of the initial state may be reached after the time t_1. This relationship can be seen in the left half of Fig. 3. The reduction of Q represents a resilience measure. Mathematically, this is the area between the normal state and the time course of the quality growth until the final state is reached at time t_1

$$R = \int_{t_0}^{t_1} 1 - Q(t)\ \mathrm{d}t, \tag{5}$$

[45]. This measure can be interpreted as the probability of failure. In terms of an effective resilience strategy, this probability is minimized. Subsequently, a resilience measure $\tilde{R}$

$$\tilde{R} = \frac{1}{R} \tag{6}$$

returns an easy to interpret resilience value, which translates to high resilience for small R values and a small resilience for large values of R.

However, if the initial state can no longer be reached, then the integral does not exist either. Thus, there is no longer a valid resilience measure. Ideally, therefore, systems are hardened to the extent that the area R is finite and minimal. Analogous to the quality of a system, the resilience results from the interrelation of the individual resilience measures.

The quality of a system is described by a scalar quality function $Q(t)$. This function includes all parameters of the system and is, according to [46], proportional to the product of a loss and recovery function. The loss function evaluates the digression from optimal behavior whereas the recovery function describes the reestablishment of quality over time. The loss function in Fig. 3 is a step function, the recovery function is approximated with a logistic function

$$f(t) = \frac{g}{1 + \mathrm{e}^{-kgt}\left(\frac{k}{Q_0} - 1\right)}\ . \tag{7}$$

A downside of this approach is the lack of flexibility in the sense of influencing a *desired* resilience response from a system. When designing a resilient system a predefined recovery function might serve as a guideline in assessing the quality of the system response to a disruptive event. The following paragraphs summarize various methods of approximating a recovery curve.

4.2.1. Piecewise discretization

If the system response should include certain predefined states, then a piecewise uniform approach allows for a convenient simplification. The system remains in a certain state for a period of time $t_{i+1} - t_i = {\lambda_i}^{-1}$. At time t_i a jump to a new state level occurs, cf. Fig. 4. Introducing the increase between states as

$$\begin{aligned} \Delta_0 &= Q_0 \\ \Delta_i &= Q_i - Q_{i-1}, \end{aligned} \tag{7a}$$

the piecewise approximation between t_0 and t_{N-1} becomes

$$Q(t) = \sum_{i=0}^{N-1} \Delta_i h\left(t - t_i\right), \tag{8}$$

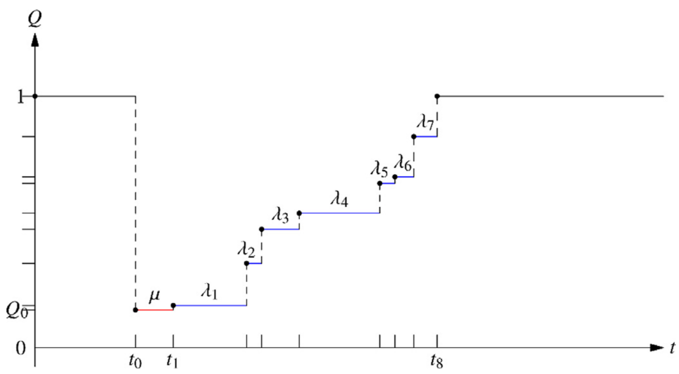

Fig. 4. Exemplary course of a quality measure with constant transition rates and intermediate states

where $h(t)$ is the unit step function. Using Eq. (5) to determine the resilience results in

$$R = \sum_{i=0}^{N-1} \left(t_{i+1} - t_i\right)\left(1 - \Delta_i\right) = \frac{1 - \Delta_0}{\mu} + \sum_{i=1}^{N-1} \frac{1 - \Delta_i}{\lambda_i} \,. \tag{9}$$

Evaluation metrics for the quality of processes are known from reliability theory. Since these processes are usually described by exponential distributions, the evaluation variables are constant rates. In particular, the Mean Time Between Failure (MTBF), the service life, or the quantities Mean Up Time (MUT) and Mean Down Time (MDT) should be mentioned here. The reciprocal of the constant service life is the failure rate μ. This can be used to describe the availability (11) and the reliability (12) of a system [47]:

$$MTBF = MUT + MDT \tag{10}$$

$$\text{Availability} = \frac{MUT}{MUT + MDT} \tag{11}$$

$$\text{Reliability}(\Delta t) = \exp\left(\frac{-\Delta t}{MTBF}\right) = \mathrm{e}^{-\Delta t \mu} \text{with}\ \mu = \frac{1}{\text{MTBF}} \tag{12}$$

In the previous explanations, a disruptive event has been considered and characterized by an abrupt change of the quality Q. If the transition from the initial state to the degraded state Q_0 is uniform, this transition can be approximated by a constant failure rate and thus resembles the reciprocal of the MTBF. Thus, parameters of reliability theory can be recognized in resilience considerations.

Piecewise discretization might be useful when a specific system recovery is desired. In this case, the final model should reach certain states after a disruptive event. This might lead to increased redundancy and costs but provides the chance to build, within limits, a resilient system to specific events.

4.2.2. State graphs

In order to obtain a temporal development of the quality measure after the occurrence of the quality degradation, but it is not possible to predict exactly whether and when the states will actually be reached, the previously defined states Q_i are interpreted as probabilities of that state. All that is certainly known is that the new initial state Q_0 has actually occurred.

The occurrence probabilities of the desired states depend on external factors, which can be determined more and more precisely as the interrelationships are known more precisely. As mentioned above, auxiliary states give more control over the resilience behavior of the system. A versatile way to model the system in detail is the usage of state graphs, in which the nodes correspond to the states and the edges to the transition rates, [48]. The state graph has the advantage of scalability and can be created algorithmically in a computer program, which monitors the current state of the system and processes data from previous failures, errors and current data streams, thus employing machine-learning algorithms to construct the incidence matrix of the graph. This matrix contains the positions for the transition rates and represent the differential equation system. An example of a state graph and its transition rates λ_i is shown in Fig. 5.

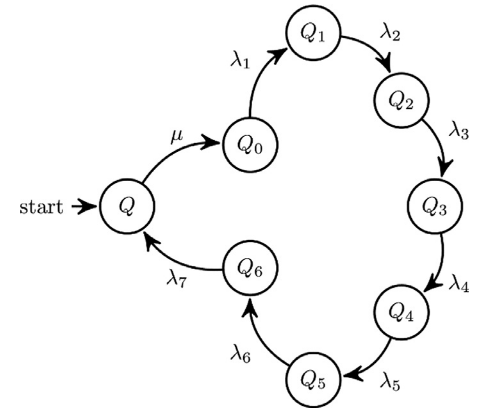

Fig. 5. State graph for an event at t_0 to regain the initial state Q.

A destructive event deteriorates the initial state Q at constant rate μ to the auxiliary state Q_0. The following intermediate states indicate constant system improvement. Each state has a certain transition rate λ_i. A direct interpretation is that it takes a certain amount of time for the system to advance to an improved state. In the diagram only outgoing arrows are included, this means that in order to reach the initial state, a fall back to previously reached states is not supposed to occur. The transition rates allow for an interpretation as expected occupation times that a certain state takes. This means, that the states are random exponentially distributed variables. Assigning a probability p_i to a state allows for the temporal development of these state probabilities in form of a differential equation system

$$\frac{\mathrm{d}p_i}{\mathrm{d}t} = \sum_{j=0}^{N-1} \lambda_{ij} p_j(t),\ i = 0, \dots, N-1. \tag{13}$$

For the case of the state diagram above, the differential equation system becomes

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} p_Q(t) \\ p_0(t) \\ p_1(t) \\ p_2(t) \\ p_3(t) \\ p_4(t) \\ p_5(t) \\ p_6(t) \end{pmatrix} = \begin{pmatrix} -\mu & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_7 \\ \mu & -\lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_1 & -\lambda_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_2 & -\lambda_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_3 & -\lambda_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_4 & -\lambda_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_5 & -\lambda_6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_6 & -\lambda_7 \end{pmatrix}\begin{pmatrix} p_Q(t) \\ p_0(t) \\ p_1(t) \\ p_2(t) \\ p_3(t) \\ p_4(t) \\ p_5(t) \\ p_6(t) \end{pmatrix} \text{with} \begin{pmatrix} p_Q(t_0) \\ p_0(t_0) \\ p_1(t_0) \\ p_2(t_0) \\ p_3(t_0) \\ p_4(t_0) \\ p_5(t_0) \\ p_6(t_0) \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{14}$$

It is certain that state Q is realised at time t_0. An additional constraint is, that the sum of all state probabilities equals one at all times

$$\sum_{i=0}^{N-1} p_i(t) = 1\ \forall t, \tag{15}$$

which means that at least one of the states is realized at time t.

Since constant transition rates are involved, the differential equation system is easily solvable; either with the help of a Laplace transformation or by employing the matrix exponential. From this, a continuous course of the state probabilities serves as input to supervising instances, which can be further algorithms or other kinds of control institutions. Fig. 4 shows how the state probabilities develop over time. Apparently, the initial state has a decreasing probability to remain in its state whereas the probability of state Q_0 increases. Those states that have a small occupation time have also a smaller chance of realization (Fig. 6).

In this way, much more complex systems are conceivable. The type of modelling presented allows different error cases to be modelled, resulting in instructions for action and, if necessary, optimization. Ideally,

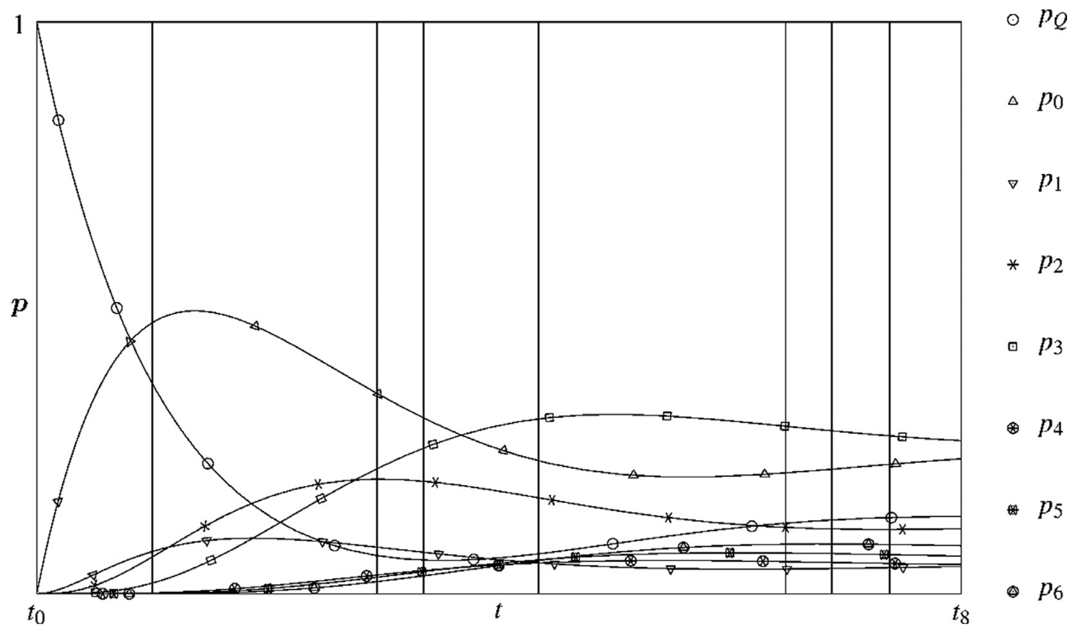

Fig. 6. Temporal development of state probabilities.

the initial state can be quickly restored by reducing the dwell times in the individual states, which corresponds to an optimization problem. Consequently, it would be possible to determine which dwell time has a significant influence on the behavior of the overall system and to derive technical recommendations for action based on this. Furthermore, with more advanced knowledge about the system and its behavior the transition rates itself can be functions of time distributed according to mixture distributions like Gaussian mixtures or mixed Erlang distributions, [48].

5. Conclusion

The explanations in this publication show that the concept of resilience can be transferred from energy systems to food production systems in a targeted manner. The evaluation must be carried out with state variables and process variables. In this context, state variables represent a description of quality, whereas process variables represent a quantitative characterization and thus a technical accounting variable. However, for energy processes as well as for food production processes, the degree to which resilience is achieved is a freely selectable variable. For energy technology, the transmission code in electrical energy technology and defined criteria for heating and calorific value in chemical energy technology provide initial quality criteria that are used in practice. However, it is often the case that specific additional criteria are defined for the respective technical application. Hence, the authors are of the opinion that attack vectors in the area of IT security in particular must be included in a resilience assessment in a highly prioritized manner.

For the food industry, the considerations of energy technology can be a template for resilience evaluation. In the authors' opinion, the introduction of state and process variables is appropriate for this field, since the primary objective in the food industry is also to meet the necessary calorific and food safety needs of humans. In addition, secondary conditions such as the coverage with vitamins and with minerals resulting from the biological functionalities must be fulfilled, as well as the assurance of the health safety of the foodstuffs.

In the future, the criterion of sustainability and environmental compatibility must be integrated into the resilience assessment for all subareas considered in this publication. For this purpose, new evaluation criteria must be defined.

Symbols

U Voltage V
I Current A
p Pressure Pa
V Volume m^3
T Temperature °C
H_i Lower calorific value $J/m^3{}_N$ [5]
H_s Gross calorific value $J/m^3{}_N$
W Work Wh
P Power W
$\dot{Q}$ Thermal power W
$\dot{m}$ Mass flow kg/s

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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