RELIABILITY ANALYSIS FOR SENSOR NETWORKS AND THEIR DATA ACQUISITION: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

The use of sensor networks (SNs) on the surface or the inside of large-scale components allows the continuous acquisition of data on the applied loads and their structural integrity. A lot of publications on SN's system reliability deal with this topic from a hardware- or a data- and energy-oriented viewpoint. To give an overview on the state of the art in the field of reliability-oriented concept-optimization of SNs, a Systematic Literature Review is conducted. The found literature is used to investigate how different models combine the different viewpoints to analyse the system reliability. By analysing the results regarding the used reliability indicators and methods to assess the system reliability from the different viewpoints, it can be observed that most publications deal with the accuracy, loss and delay of data as well as the energy consumption in SNs. Few publications use common modelling methods like reliability block diagrams or Markov chains with a focus on the hardware reliability. Furthermore, none of the found publications combines the data, hardware and energy perspective and uses them to optimize a SN regarding its reliability from all three viewpoints.

Keywords: Product modelling / models, Optimisation, Design methods, Reliability, Sensor Networks

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1 INTRODUCTION

The continuous development in the field of sensor networks (SNs) has led to an increasing use of such systems in the field of mechanical engineering and aerospace technology for monitoring structural components. Such SNs on the surface of or integrated inside a component are used, for example as Structural Health Monitoring (SHM) systems, to detect and characterise structural defects and damages (Beard *et al.*, 2007). Using such monitoring systems allows to overcome the conflict of saving weight of components for better performance and gaining weight to ensure their safety by a continuous inspection of the structures condition (Sause and Jasiūnienė, 2021; Dong and Kim, 2018). Furthermore, it allows to gain data for the development of new product generations (Lachmayer *et al.*, 2014). However, the data acquisition of monitoring systems has to be reliable to acquire trustworthy data for the product development, to avoid false alarms or, even more important, to ensure the detection of critical damages and defects. This leads to challenges in engineering design, since the reliability of a SN has to be taken into account regarding the hardware (sensors, etc.), data (accuracy, etc.) and energy (battery lifetime, etc.). Especially before applying SNs on the surface of or even integrating them inside of a component, the reliability assessment is important because the modification of the network configuration would lead to further costs or might even not be possible (Dobmann *et al.*).
In the last decades, a lot of work has been done on the topic of SN reliability regardless the application in engineering design or other fields (e.g. reviewed in (Xing, 2020) and (Xing, 2021)). Commonly, the SN's system reliability and availability are analysed with methods like the reliability block diagram, fault tree analysis, Markov Chains, or Petri Nets (following referred to as commonly used methods). Previous works present different strategies on how to analyse or maximise the reliability of a SN with these methods from different points of view, like e.g. (Gurupriya and Sumathi, 2022) from a battery-lifetime and (Mallorquí *et al.*, 2021) from a data accuracy perspective. However, the use of these methods with a view on the lifetime and the data accuracy for optimal sensor placement (OSP) still represents a gap in research. To help fill this gap, this paper aims to give an overview on the reliability indicators and methods used to analyse the system reliability of SNs and to point out research gaps for using them for the OSP problem as a result of a Systematic Literature Review (SLR) (Denyer and Tranfield, 2010). For this purpose, the paper is organized as follows. Section 2 describes the chosen SLR-methodology, which steps to use and how these steps are performed for the aim of this paper. In Section 3, the results of the SLR are described and analysed. Section 4 concludes this paper with a summary of the results as well as the identified research gap and gives an outlook for future work.

2 METHODOLOGY

For the purpose of reviewing the state of the art in the topic of reliable data acquisition with SNs, the SLR-methodology (see Figure 1 for the procedure) was used. The use of it was motivated by the statement of (Snyder, 2019) that traditional reviews are conducted ad hoc instead of following a specific methodology, which leads to questions about the quality and trustworthiness of a review. Furthermore, a research gap is only valid, when boundaries of already available knowledge are clearly and consistently delimited, so the SLR aids in identifying and justifying research questions for future research in a specific area (Xiao and Watson, 2019; Torres-Carrion *et al.*, 2018).

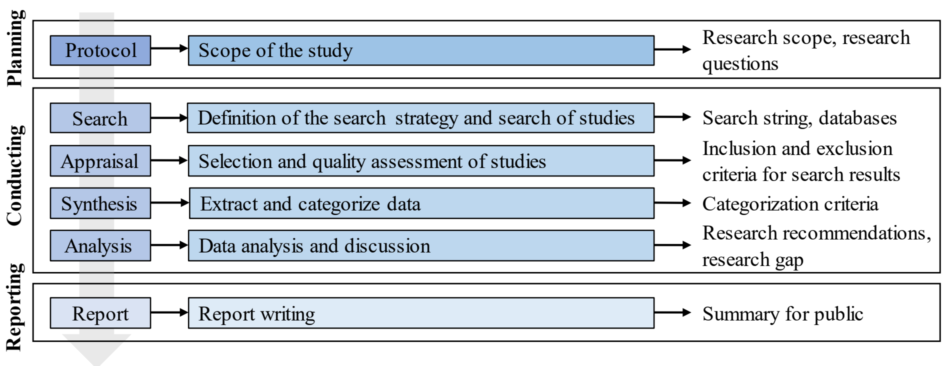

Figure 1. Process defined in the SLR-methodology with three phases and six steps according to (Xiao and Watson, 2019; Torres-Carrion et al., 2018)

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The process defined in the SLR-methodology differs from the traditional narrative review, since it is replicable, scientific and transparent. To achieve this distinction, the user of the SLR must work through three main phases: Planning, conducting and reporting the review (Xiao and Watson, 2019). These phases can be split into six steps, as listed in Figure 1 (Mengist *et al.*, 2020).
In the following, the phases and steps are described generally and how they are applied for the scope of this paper. Since the paper itself is the report at the end of the SLR with a conclusion, an identified research gap and recommendations, this phase is not described in more detail.

2.1 Planning

In the planning phase, the review's protocol is established and elaborated to determine the research scope. This helps to formulate the research questions and the research boundaries (Mengist *et al.*, 2020). Regarding the aim of this paper being to provide an overview of reliable data acquisition with SNs, there are three research questions (RQs) to be answered. These RQs were identified using the context-interventions-mechanisms-outcomes (CIMO) framework of (Denyer and Tranfield, 2010). This framework was exemplarily used by (Wurst *et al.*, 2022) and helps to make the review questions more specified and focused with the following four aspects. The context (C) is referring to the systems under consideration and their interrelationships, while the interventions (I) focus on the effects or actions investigated. With the mechanisms (M), an explanation is given on how the intervention may affect outcomes (O) (Wurst *et al.*, 2022). For this paper, it results in the following RQs:

1. Which indicators can be used to measure the reliability of the data acquisition process in SNs? (RQ 1)
2. How do models of the system reliability of SNs include the reliability of the acquired data? (RQ 2)
3. In which way do the authors of found publications use the models of the system reliability for the problem of optimal sensor placement? (RQ 3)

2.2 Conducting

At the beginning of the second phase, the so called “conducting”, the research strategy must be formulated. In this step, the keywords and their combination as a search string as well as the review's title are defined (Mengist *et al.*, 2020). Since we already defined the review's title, the search string is defined in the following. Initially, the keywords for the search must be chosen and combined correctly to form the search string. With the focus of this publication being on the system reliability in SNs, the terms "sensor network" and "sensing network" are applied, combined by an OR operation. This allows to find publications with a different syntax of the search term. Furthermore, the terms "system reliability" and "reliability of the system" are used to find publications with either the first or the second formulation. Since the paper's scope is to analyse how the common methods to model the system reliability take the reliability of the whole data acquisition process into account, the term "model" is used as well. Also, this is why the term “data acquisition” is linked to different synonyms by an OR operation. By covering these different formulations of the search terms, we are able to compile an as complete collection of available literature as possible. This leads to the following search string:

(“sensor network” OR “sensing network”) AND (“system reliability” OR “reliability of the system”) AND “model” AND (“data acquisition” OR “data collection” OR “acquisition of data” OR “collection of data”).

Next, the databases for the search are selected and the search is performed. So, the formulated string is applied to Google Scholar and Scopus because these databases represent the most of available publications. Due to that, the current state of the art can be reflected the most complete. Scopus is an international database consisting of peer-reviewed publications, maintained by the scientific publishing company Elsevier. Google Scholar refers to other databases and thereby presents additional results (Mengist *et al.*, 2020). As a result of the first search, 1,020 publications were found. on Google Scholar and 232 on Scopus.
After performing the search, the found literature has to be selected by defining criteria for inclusion and exclusion as well as quality criteria in the "appraisal" step. To find which publications to include or exclude, the following criteria are applied to the found results: (1) Time of publication, (2) screening by title and abstract and (3) only peer-reviewed publications.

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The time of publication is used as criterion because of the fast development of microelectronic systems and sensing technology. So, the results should cover the recent state of the art. To do so, the finding of publications is limited by the time of publication to the last five years. This limitation reduces the results to 578 publications. Figure 2 depicts the quantity of publications found for the defined search string.

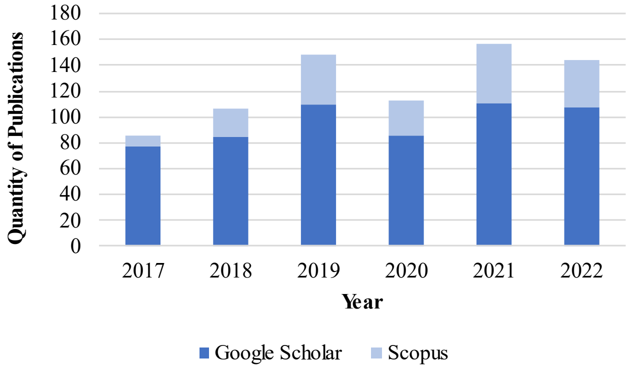

Figure 2. Quantity of publications over the last five years for the search string

In Figure 2 an increasing trend of publications per year over the last five years is clearly visible. For example, the quantity of publications increased by a factor of 1.83 from 2017 to 2021. In 2020 and 2022, there were less publications found for the applied search string than in 2019 and 2021. One reason for this lower number of publications in 2020 might be the beginning of the Covid-19 pandemic. Due to that, many conferences were cancelled and less papers were published. The lower quantity in 2022 could stem from the reason that the search has been carried out in the month of September and further publications might follow in the remaining months of the year.

After the search results are limited by their year of publication, the found publications are screened by their title first. By doing so, publications that might fit the search string but address a different topic can be filtered out. For example, a publication which addresses a topic in the field of medicine, where data is acquired by a sensor and a specific concentration is measured as the reliability indicator of the analysis, these results don't fit the scope of this review and is filtered out. After limiting the findings through this method, the remaining publications are screened by their abstracts. Furthermore, publications with a focus on IT-security are sorted out. Attacks in SNs might lead to faulty data, but the integration of security mechanisms isn't part of the paper's scope. This allows to reduce the number of findings to 85 publications.

To ensure the scientific correctness and quality of the remaining publications, publications that are not peer reviewed are excluded. Following this exclusion criterion, found results like PhD-these or not peer-reviewed papers are filtered out. This leaves to a total of 88 publications that will be included for the further analysis in this review.

From the included literature that fits the quality criteria, the relevant data is extracted and categorized in the "synthesis" step. This organized data is used in the analysis to build up quantitative categories, descriptions and to analyse it narratively (Mengist *et al.*, 2020).

3 RESULTS

After filtering and limiting the found publications, the remaining ones are utilised for answering the research questions (RQ). To do so, the publications are categorized first in the "synthesis" step of the SLR and analysed afterwards ("analysis" step). This is presented in the following sections.

3.1 Categorization of the results

An initial screening of the found results shows that there are different points of view on the topic of reliability in SNs. The distinction we can obtain is into a hardware-focused and a data-oriented viewpoint of the publications and is shown in Figure 4. On the one hand, publications with a focus on the hardware in a SN's system reliability mostly address spontaneous failure and failures due to the degradation of the components. Another hardware-focused failure is the end of the battery lifetime because of the energy consumption in a sensor network. On the other hand, publications that are data-oriented mostly address the topics of faulty data, data jam or data delay respectively as well the

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problem of data loss. Furthermore, topics like the network coverage or connectivity as well as the signal quality loss are of great importance in the publications with this point of view because these can often affect the data quality and lead to faulty, delayed or lost data.
Especially interesting from the data point of view and used protocols, existing reviews can be found like (Kafi *et al.*, 2018), who reviewed the challenges regarding the security in power Internet of Things (IoT) applications and (Kumar *et al.*, 2017), who focussed on the energy efficiency in IoT, wherein Wireless Sensor Networks (WSNs) are an integral part of. Furthermore, reviews can be found that deal with the different approaches to model the reliability of networks, but don't show explicit reliability indicators (Ahmad *et al.*, 2017).

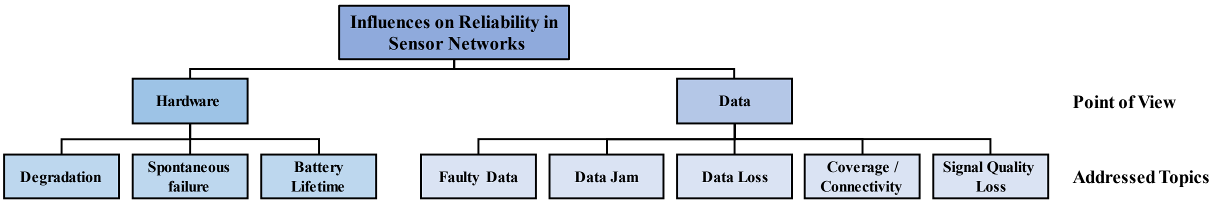

Figure 4. Classification of the publications by their point of view on the topic of reliability in sensor networks

To answer the formulated RQs, each publication is read and the used reliability indicators and system models are recorded. Regarding the analysis of used reliability indicators for the data acquisition process (see RQ 1), the classification from Figure 4 can be used for a first categorisation of the used reliability indicators in the publications. The results are shown in Figure 5, where the reliability indicators are categorised in hardware, data and energy focuses as well as their combinations, should a publication address more than one of these categories.

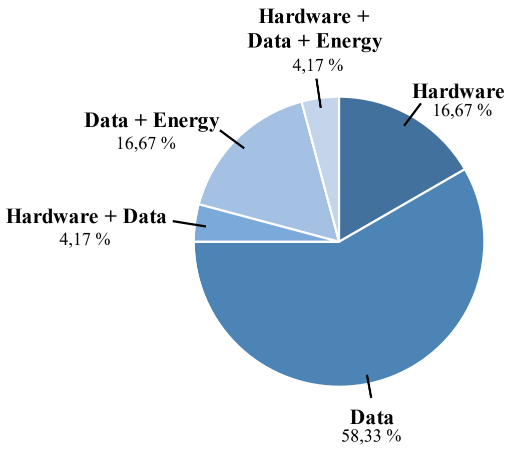

Figure 5. Categories for reliability indicators and percentage of the 88 publications assigned to them

As one can see, the category "energy" is added in contrast to Figure 4. This is due to the fact, that publications with a focus on hardware often address the topic of battery lifetime by modelling it with the use of an exponential distribution. In contrast, publications that focus on the reliability from a data perspective can instead use the energy consumption for data transmission as a reliability criterion/indicator. Since the energy consumption per transmission of a single senor node in a network differs as an indicator from a lifetime distribution, this category is distinguished from the hardware perspective. Furthermore, one can easily observe that the majority of publications are using data-oriented reliability indicators only or in combination with energy- and/or hardware-oriented reliability indicators. The used criteria and methods to estimate their value are discussed in the following sections.

3.2 Reliability indicators without a specific reliability model

Most of the publications on the topic of reliability in data acquisition with SNs are based on a reliability estimation with a system model. However, some publications were found that didn't use a system model but used SNs for data acquisition while taking a more probabilistic view on the acquisition process itself.

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The reliability indicators used in these publications are purely data-oriented and are shown in Table 1. The used indicators are differentiated in the general data accuracy and the probability of detection (POD). The POD is a probabilistic approach to analyse the ability of a sensor or SN to detect defects (e.g. cracks in a structure) and is used by (Yadav *et al.*, 2021; Morse *et al.*, 2018; Ameyaw and Söffke, 2021; Sause and Jasiūnienė, 2021). On the other hand, the accuracy is the quotient of right detected/estimated data over the whole amount of data during a specified time and is a metric used by (MISHRA *et al.*, 2017; Saeed *et al.*, 2021; He *et al.*, 2018). Furthermore, the so called F1-score can be used as an accuracy metric. The authors (He *et al.*, 2018) used a belief-rule based approach to address the topic of data loss and data accuracy, but don't directly use a model for a SN, resulting in a generic approach. The topic of accuracy of the acquired data is also used as reliability indicator by (MISHRA *et al.*, 2017) and (Saeed *et al.*, 2021) in case studies of their SNs.

Table 1. Reliability indicators used in the publications to measure the system reliability

Used Indicator	**Publications**
Probability of Detection (POD)	(Morse *et al.*, 2018; Yadav *et al.*, 2021; Ameyaw and Söffke, 2021; Sause and Jasiūnienė, 2021)
Accuracy	(MISHRA *et al.*, 2017; Saeed *et al.*, 2021; He *et al.*, 2018)

3.3 Reliability indicators with specific models for their estimation

Since most publications using reliability indicators for the reliability of the data acquisition with SNs rely on a model of the network as a system, the methods for the used models and the reliability indicators can be combined. The resulting two-dimensional matrix is shown in Figure 6. One can clearly see that commonly used methods in the field of reliability engineering like Markov chains (MC), Fault Tree Analysis (FTA), Petri Nets (PNs) and Reliability Block Diagrams (RDB) are each used in only a few publications, whereas the modelling of the data paths with focus on the data point of view depicts the clear majority of the found publications.

Reliability Indicators

System Reliability Models	System Relia - bility / Availibility	Repair Time	Data Accuracy	Data Loss	Data Delay	Energy Consumption
MC	(Wang *et al.*, 2021; Ibrahim *et al.*, 2019; Nguyen and Ha, 2022)	(Ibrahim *et al.*, 2019)		(Ibrahim *et al.*, 2019; Flanigan and Lynch, 2022)	(Ibrahim *et al.*, 2019; Aalamifar and Lampe, 2018; Li *et al.*, 2022b)	(Li *et al.*, 2022b)
FTA	(Wang *et al.*, 2021)					
PN		(Li and Huang, 2017)				
RBD	(Tommaso *et al.*, 2020; Nuhu *et al.*, 2019; Sun *et al.*, 2022b)					
Data Paths	(Mallorquí *et al.*, 2021; Nuhu *et al.*, 2021; Nitesh *et al.*, 2018)	(Hu *et al.*, 2022)	(Mallorquí *et al.*, 2021; Farhat *et al.*, 2019; Ur Rahman *et al.*, 2021; Kartakis *et al.*, 2017; Sun *et al.*, 2022; Nuhu *et al.*, 2021)	(Gurupriya and Sumathi, 2022; Mallorquí *et al.*, 2021; Ahmed *et al.*, 2020; Abiodun *et al.*, 2017; Mohammadsalehi *et al.*, 2022; Shabanighazikelayeh and Koyuncu, 2022)	(Aalamifar and Lampe, 2018; Gurupriya and Sumathi, 2022; Šećerov *et al.*, 2021; Mallorquí *et al.*, 2021; Okafor and Longe, 2022; Li *et al.*, 2022b; Li *et al.*, 2022a; Nitesh *et al.*, 2018)	(Gurupriya and Sumathi, 2022; Ahmed *et al.*, 2020; Farhat *et al.*, 2019; Abiodun *et al.*, 2017; Kartakis *et al.*, 2017; Li *et al.*, 2022b; Li *et al.*, 2022a; Nuhu *et al.*, 2021)

Figure 6. Classification of the found results regarding the used reliability indicator and methods to model the system reliability

From the commonly used methods, the Markov chains are used most frequently. This is due to the fact that this method allows the analysis of dynamic processes like repair, so the system reliability and availability of the SN can be obtained, like in (Ibrahim *et al.*, 2019; Wang *et al.*, 2021; Nguyen and Ha, 2022). Furthermore, issues like data loss or delay can be analysed by modelling the dynamic behaviour of sensor nodes (Aalamifar and Lampe, 2018; Ibrahim *et al.*, 2019; Li and Huang, 2017; Li *et al.*, 2022b). This point of view can also be used to model the energy consumption of these nodes, like in (Li *et al.*, 2022b). To model this behaviour is also the reason (Li and Huang, 2017) used PNs to analyse the availability of a SN with different failure and repair rates. Additionally, one can easily ascertain that the FTA and RBD are just used to analyse the system reliability and don't focus on the data point of view.

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The publications of (Xing, 2021) as well as (Nuhu *et al.*, 2019) and (Tommaso *et al.*, 2020) addressed the special challenges of the system reliability in SNs with the example of WSNs by focussing on the battery lifetime of sensor nodes as restrictive factor of their lifetime. The authors (Sun *et al.*, 2022b), utilised a RBD to consider the system reliability of the hardware for different technologies and operation modes. However, none of the publications includes the challenges of ensuring the accuracy of the acquired data besides hardware failures. This more hardware-oriented point of view on the system reliability can be found as part of the publication of (Zhang *et al.*, 2021), who used maintenance plans to estimate the systems reliability function for a monitoring system. Figure 6 also shows that most of the publications found use models of data paths or data transmission for reliability analysis. This is due to the fact, that SNs suffer from problems like data loss or delay, when the data transmission isn't reliable. For that reason, models of the data paths are used to estimate the reliability indicators. The topic of data accuracy is addressed by (Mallorquí *et al.*, 2021) through a ratio of faulty sensor data. Whereas publications from (Ur Rahman *et al.*, 2021; Farhat *et al.*, 2019; Kartakis *et al.*, 2017) measure the accuracy of the data with a sum square error approach, with respect to the measured and estimated data values. In contrast, (Sun *et al.*, 2022a) addressed the topic of data accuracy with a focus on the links between sensor nodes by using the signal-to-interference-plus-noise ratio as the system's state. Furthermore, Kalman filter as well as a linear quadratic regulator control are used to analyse the system's state.

Besides the data accuracy, the loss or delay of data are crucial factors for a SN's reliability. If the data can't be transmitted to the user, even the most accurate data is useless. The loss of data packets is measured by the authors of (Abiodun *et al.*, 2017; Ahmed *et al.*, 2020; Mallorquí *et al.*, 2021; Gurupriya and Sumathi, 2022; Mohammadsalehi *et al.*, 2022; Shabanighazikelayeh and Koyuncu, 2022) by the ratio of received data packets to the total number of send data packets in experimental and simulation studies. In the publications (Aalamifar and Lampe, 2018; Abiodun *et al.*, 2017; Gurupriya and Sumathi, 2022; Li *et al.*, 2022a; Li *et al.*, 2022b; Mallorquí *et al.*, 2021; Okafor and Longe, 2022; Šećerov *et al.*, 2021; Nitesh *et al.*, 2018), the topic of data delay is addressed. The authors of (Aalamifar and Lampe, 2018) defined a delay model for data paths, which are modelled with a Markov chain approach and calculated the probability of data traffic delay for each hop between sensor nodes. The Markov chain approach is also used in (Li *et al.*, 2022b), where the data delivery rate is used to calculate the packet delay in a simulation study. The authors (Flanigan and Lynch, 2022) also used a Markov chain to analyse the data transmission with a specified transmission rate. In (Gurupriya and Sumathi, 2022) the performance of a data transmitting algorithm is measured by the end-to-end delay for data packets in relation to the number of sensor nodes in the network. The authors (Li *et al.*, 2022a) proposed a wireless sensing system and used the delay of processing time for synchronising packets as reliability indicator.

Most of the publications that deal with the data transmission regarding the problem of data loss or delay include the energy consumption for data transmission as well (Abiodun *et al.*, 2017; Ahmed *et al.*, 2020; Gurupriya and Sumathi, 2022; Li *et al.*, 2022a; Li *et al.*, 2022b). This combination of topics is suitable, since the development and performance evaluation of data transmission algorithms can easily regard the energy consumption per transmission as well, when testing how well the data transmission works from the data perspective. On the other hand, the publication of (Farhat *et al.*, 2019) evaluates the performance of different network topologies by analysing how accurate the measurements can be for specific area coverages and how these different topologies influence the energy consumption and battery lifetime. This combination of data accuracy and energy consumption as reliability criteria is used by (Kartakis *et al.*, 2017) as well, to analyse the systems energetic lifetime and the reliability of data estimates in the sensor network.

Interestingly, the publication of (Nuhu *et al.*, 2021) is the only study that addresses the system reliability with a lifetime distribution of the battery on the hardware side, the data accuracy as reliability criterion on the data side and the energy consumption of each node.

3.4 Usage of the system reliability models for optimal sensor placement

After analysing the used reliability models and indicators of the found publications, the answer of RQ 3 can be ascertained. Surprisingly, only two publications were found that use a reliability model of a SN for the issue of optimal sensor placement. Other publications mostly dealt with the optimization of the data transmission in an existing network. The authors (Aalamifar and Lampe, 2018) used an optimisation algorithm with the goal of maximising the reliability for packet transmission, based on a

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Markov chain model. For reaching this goal, the algorithm was used to optimize each sensor node's connectivity. The publication of (Shabanighazikelayeh and Koyuncu, 2022) used the particle swarm optimisation for optimising the data transmission reliability based on the probability of outage. However, these publications just address the data point of view on reliability of data acquisition with SNs.

4 CONCLUSION AND FUTURE WORK

Sensor networks can be used to monitor a products structural integrity and to collect data to support the development of new product generations. To allow this, the reliability of the data acquisition process is of great importance. So, in this paper the SLR-methodology was used to investigate the state of the art for reliability in data acquisition processes with sensor networks (SNs) with a focus on the used reliability indicators and integration of the data acquisitions process itself in the used reliability models.

The found publications were analysed and classified by their perspectives on the reliability in sensor networks. This classification showed that just a few publications use common methods to model the system reliability (Reliability Block Diagram (RBD), Fault Tree Analysis (FTA), Petri Nets and Markov chains). The publications using these methods are mostly focussed on the reliability of the hardware in SNs and assume other failures than the end of the battery lifetime as negligible. However, the majority of found publications use models of data paths and estimate the system reliability with a focus on data accuracy and packet delivery as well as energy consumption. Some publications address this topic by using Markov chains to model the data paths and transmission rates while others just simulate the data transmission without specifying a specific modelling method. However, there was no publication found that combines a commonly used model like a RBD and combined both, the hardware- and the data-oriented failure mechanisms in such a model. Furthermore, it was observed that the topic of optimal sensor placement (OSP) is included in just one publication, which didn't have a focus on the energetic and hardware perspective besides the data perspective and which wasn't based on a commonly used modelling method.

In future work, the combination of a hardware-, data- and energy-oriented viewpoint for a commonly used model might be a promising work, since no publications like that were found. Furthermore, the utilisation of such a model for the topic of OSP for SNs data acquisition can be addressed. For example, a RBD can be used to model the data paths in a SN while taking the signal degradation along this path into account. So, the MTTF and data accuracy can be used as indicators for the system reliability from a hardware and a data perspective. The POD and its degradation with increasing load cycles might also be an interesting indicator for the changing data accuracy, modelling a system failure when the it reaches a threshold for too little data accuracy. An optimisation based on this model can aid design engineers to design a SN with a maximisation of hardware, data and power reliability.

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