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Reliability Model of an Automatically Switching Radon Exposimeter for System Design Evaluation

Thomas Gwosch, Julian Peters

IPEK - Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Germany.
E-mail: Thomas.Gwosch@kit.edu, Julian.Peters@kit.edu

Johanna Pehlivan, Christian Naber

Safety and Environment, Karlsruhe Institute of Technology (KIT), Germany.
E-mail: Johanna.Pehlivan@kit.edu, Christian.Naber@kit.edu

Reliability of technical systems that measure safety or legally relevant values is of great importance. Such a device is an automatically switching radon exposimeter, which is focused on in this contribution for reliability assessment. In certain areas it is legally required to measure the radon dose on persons, which can lead to health risks like lung cancer. An early evaluation of reliability helps to prevent costly iterations in production phase. The problem is, that reliability data is hard to get in early stages of development, when most of the components are not even fixed yet. Therefore, in this contribution the reliability is assessed by using available generic failure rates data for device classes similar to the ones used in the radon exposimeter. Together with methods like reliability-block-diagrams (RBD) and failure-mode-and-effects-analysis (FMEA) the failure rates and mean-time-to-failures (MTTF) are calculated. Critical components are identified and improvements like redundancy are introduced to improve the MTTFs. This helps product developers to avoid flaws and reduce risk of loss of function at an early stage, avoiding structural changes later in the process.

Keywords: system reliability, reliability model, product development, design structure evaluation, radon, dosimeter.

1. Introduction

Reliability is an important requirement of technical systems and has already to be considered in the design phase of the product (O'Connor and Kleyner 2012). It is not only expected that a technical system is without failures at the start of operation, but also for a specified time interval (Birolini 2017).

In addition, complexity increases as well with the ongoing integration of engineering disciplines for e.g. mechatronic systems, making it even more challenging to achieve high reliabilities (Bernd Bertsche et al. 2009).

Especially for safety-relevant devices or for devices that measure legally relevant values, reliability is a key concern, making it necessary to improve reliability by e.g. fail-safe operations (Birolini 2017).

One such device is in focus in this contribution: an automatically switching radon exposimeter (au-raex). This device has the function to measure legally relevant doses of radon-222, a naturally occurring radioactive noble gas, on persons.

Depending on various factors and characteristics such as for instance geological factors, permeability, hydrogeological factors, anthropogenic factors or weather conditions, different concentrations of radon-222 can emit from the soil.

Outdoors, radon-222 mixes with the ambient air and usually occurs in low concentrations (in Germany 9 Bq/m³ average at the ground level atmosphere) (Bundesamt für Strahlenschutz 2021). If radon-222 enters buildings via convection and diffusion processes, it can accumulate there and depending on the building characteristics, it can reach concentrations of several 1000 Bq/m³ (European Commission. Joint Research Centre. 2020) (Figure 1).

When radon-222 is inhaled, it can cause damage to the DNA of the cells of the respiratory tract. Due to defective repair mechanisms, the cells can mutate and lung cancer can occur.

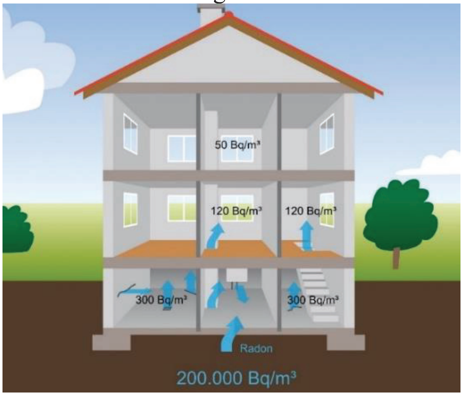


Figure 1: Ingress of radon-containing soil air through leakage points and diffusion of radon through building components (SUM KIT)

Therefore, radon-222 and its decay products are the second largest risk factor for lung cancer after smoking (9% of lung cancer deaths, 2% of cancer deaths in Europe) (Darby et al. 2005).

European Directive 2013/59/Euratom (Council of the European Union 2013) prescribes national reference levels for indoor radon-222 concentrations in workplaces which the member states must implement in their national legislation.

In Germany, employers must therefore measure the radon-222 concentration at workplaces in designated areas and at workplaces where increased radon-222 exposure can be expected due to their nature, such as workplaces in underground mines, shafts and caves, including visitor mines, workplaces in radon spas and workplaces in water extraction, processing and distribution plants. When the reference value of 300 Bq/m³ is exceeded, the dose to employees must be determined (“StrlSchG” 2017).

There are already portable passive dosimeters for measurements on persons which, however, measure continuously throughout an entire day Figure 2 (Kernforschungszentrum Karlsruhe GmbH 1985; Feige, Friedrich-Kees, and Oeh 2020). Therefore, complex reference measurements and calculations are required to determine the dose during actual working hours.

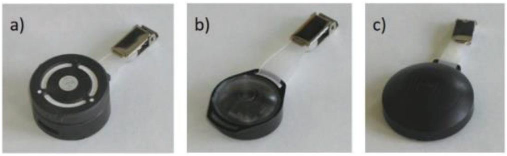


Figure 2: Passive Radon Dosimeters (Feige, Friedrich-Kees, and Oeh 2020)

To simplify personal dosimetry, a portable passive radon dosimeter shall be further developed in such a way that it can automatically interrupt the measurement outside working hours using different modes (further called au-raex). The modes include a manual button-controlled mode, a time-controlled mode and a movement-controlled mode. The detector used is a solid-state nuclear track detector made of macrofol.

Reliability of the au-raex must be high, as it is a safety-relevant device for measuring legally relevant values. For maximizing the reliability, it is necessary to evaluate the system reliability already in early development phases by using appropriate methods and models. However, this task is challenging especially for new systems because of missing or uncertain system design and knowledge which is needed for using reliability methods (Bernd Bertsche et al. 2009). Moreover, even if predictions can be made they often have low accuracy because of uncertainties in the data and models (Birolini 2017).

Moreover, it is essential to shift verified design decisions in earlier development stages, thus estimating reliability to be able to make improvements already in design phase in order to avoid costly structural changes (Engel 2013; Thomke and Fujimoto 2000).

In practice, however, there is a lack of models that support the prediction of reliability performance during system design in early development phases. In particular, the evaluation of design alternatives of critical components in terms of system reliability is challenging because existing models require a lot of reliability data of the final design that is not yet available in early development phases.

In order to solve this problem, this paper presents a reliability model to evaluate the system reliability of different design structures of the au-raex during development and identify critical components in the process.

In the following chapter, first we give a short overview of the system and the most important reliability requirements, then we present the procedure for the development of the reliability model.

2. Materials and Methods

2.1. Function and Requirements for the Automatically Switching Radon Exposimeter (au-raex)

The main function of the au-raex is to house the solid-state nuclear track detector and be wearable by persons (users), see system overview in Figure 3. The detector needs to be in a measuring chamber with a defined volume of air, that can be opened and closed gas-tight to the environment in 3 modes, which are pre-set before handing out to the users. The modes are:

- Movement control (by accelerometer)
- Time control (by real-time-clock, RTC)
- Manual control (by button)

The users are not able to change the pre-set mode to avoid frauds and wrong measuring.

The evaluation of the radon doses the au-raex (resp. the user) experienced is done by analyzing the detector with a microscope and calculating the dose by formulas using the exposition time, which are the times the measuring chamber is open to the environment. These times are written on a flash memory inside the au-raex.

The reliability target for the whole system is defined to be 1 year minimum without maintenance. The top-malfunctions are:

- Detector closure unit does not open or close
- Logtimes not saved or saved incorrectly

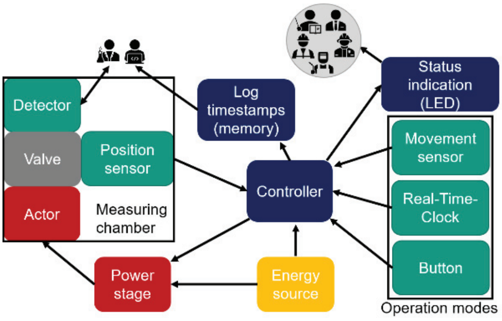


Figure 3: System overview of au-raex

2.2. Reliability Assessment for the Automatically Switching Radon Exposimeter (au-raex)

Based on the methodology for reliability assessment in early development phases by Bertsche (Bernd Bertsche et al. 2009; Gäng et al. 2007), the system reliability of the au-raex is assessed. The methods and models are selected in such a way that they are applicable with the limited knowledge in the early development phase. The procedure is as follows:

(i) Reliability target & top functions/malfunctions (section 2.1)
(ii) System representation
    a. System diagram with flows of material, energy and information
(iii) Reliability block diagrams
    a. Failure rates based on handbooks (MIL, NPRD)
    b. Calculations of mean-time-to-failures (MTTF) using formulas from DIN EN 61078 and Birolini (2017)
(iv) FMEA – identify critical components
(v) Iteration: reduce risk

First, the reliability target for the whole system is defined. Furthermore, the top functions/top malfunctions are identified (see section 2.1). Against these values (operating time) the results from the analysis is checked.

Second, a system representation is created which is oriented to input/output structure using material, energy and information. This serves as a basis for the reliability block diagrams, which is described in the following.

Third, the structure of the system representation from the previous step is merged into a reliability block diagram (RBD) (DIN EN 61078 2018).

The system reliability is evaluated with a focus on the critical components. The criticality evaluation is based on a systematic FMEA and expert assessment. Quantification with available generic reliability data at component level is used to decide between competing design alternatives.

Therefore, generic failure rates for the components are researched in literature and catalogues like MIL-HDBK-217F (US Department of Defense 1991), NPRD-91 (Denson et al. 1991). Based on this, a guess for the mean-time-to-failure (MTTF) is made and checked with the requirements from step 1.

Fourth, the identification of critical components of the au-raex through a failure modes effect analysis (FMEA) (*DIN EN 60812:2015-08* 2015) is performed.

Fifth, the risk is reduced by improving severity, probability or detection through reliability-increasing measures, such as redundancy or emergency modes. The components to improve are based on the FMEA evaluation. The decision of the different types of redundancy is expert based with a strong consideration of the existing sensors and logic parts under the condition of low costs for additional hardware. These improvements are reconsidered in the RBD.

3. Results

The result is a model that describes the system reliability of an automatically switching radon exposimeter (au-raex) in the focus of the critical components and allows an evaluation of the system reliability of different variants of these critical components. In the process, it is identified by which components the reliability is strongly influenced. To begin with, the system representation is shown which is the basis for the reliability models.

3.1. System representation

Derived from the functional description and requirements from section 2.1 the system representation was created using functional block diagrams with material, energy and information flows, see Figure 4.

The center of the au-raex is the measuring chamber, holding the detector. A piston-like mechanism, called valve, opens and closes the measuring chamber to the environment, allowing air exchange.

The valve is actuated by a stepper motor via 2 transmissions (gearsets). Transmission 1 is a worm gear and transmission 2 is a specifically designed rotating frame with grooves (further called frame) that moves the valve in the linear direction needed to close or open the air inlet. The stepper motor is connected to a microcontroller via a power stage, the motor drive control.

The end positions of the transmission are detected by measuring the current peak of the motor when it hits the hard end stops.

Furthermore, the position of the transmission 2 can be seen in the housing, like a toilet door lock, allowing the user to detect failures in the open or close movement directly without further sensors.

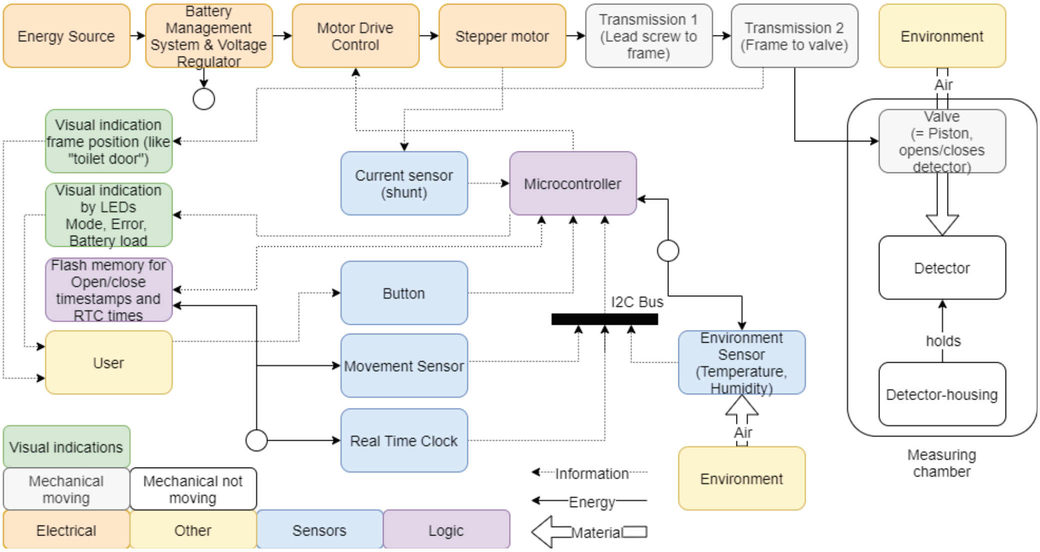


Figure 4: System representation of the Automatically Switching Radon Exposimeter

The energy source is a rechargeable lithium-polymer battery. It provides energy to parts of the system via a battery management system (BMS) and a voltage regulator.

The user carries the whole system on the body and is only supposed to read the visual indications of the LEDs and the frame position. In manual mode (see section 2.1) the user also operates the button (regarded as sensor) to open or close the valve.

3.2. Reliability Block Diagram (RBD)

In the following, the RBDs for the 3 operation modes are presented. In every box, generic failure rates (λ, failures per million hours) for the parts retrieved out of MIL-HDBK-217-F and NRPD-91 are included (always for the application field ground mobile). The RBD for the button-controlled mode has a serial structure (Figure 5).

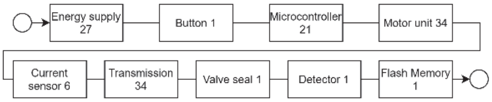


Figure 5: RBD button mode

The RBDs for the time- and movement-controlled mode have a similar structure, only the button is replaced by a real-time-clock (RTC) or a movement sensor, see Figure 6 and Figure 7.

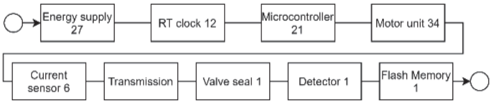


Figure 6: RBD time mode

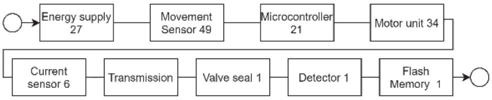


Figure 7: RBD movement mode

Several components of serial structure have been merged into subsystems, shown in the following Figure 8, the block failure rates have been summed up.

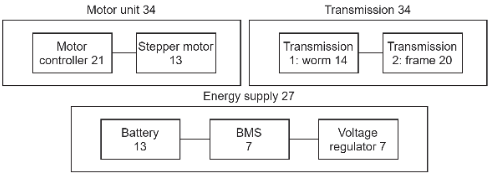


Figure 8: RBD subsystems

The failure rates (λ) and the mean-time-to-failure (MTTF) calculate as follows, using values from the previously shown RBDs, assuming constant λ (DIN EN 61078 2018 (Birolini 2017):

$$\lambda_{button} = \sum_{i=1}^{n} \lambda_{button,i} = 126 \tag{1}$$

$$\mathrm{MTTF}_{button} = \frac{1}{\lambda_{button}} = 7936\ h = 0.9\ y \tag{2}$$

$$\lambda_{time} = \sum_{i=1}^{n} \lambda_{time,i} = 137 \tag{3}$$

$$\mathrm{MTTF}_{time} = \frac{1}{\lambda_{time}} = 7299\ h = 0.83\ y \tag{4}$$

$$\lambda_{move} = \sum_{i=1}^{n} \lambda_{move,i} = 185 \tag{5}$$

$$\mathrm{MTTF}_{move} = \frac{1}{\lambda_{move}} = 5405\ h = 0.62\ y \tag{6}$$

These values are generic and most likely not realistic in an absolute manner, but serve as a first indication if the reliability target can be reached with the current system and to rate the probability of failure causes in the FMEA (next section).

As the values show, the reliability target of 1 year cannot be reached with the current system, improvements need to be made.

3.3. Failure Modes Effect Analysis (FMEA)

Extracts from the FMEA are shown in Figure 9. The top-malfunctions from section 2.1 are used as failure description. Possible causes for these failures are derived, including the mechanical transmission, motor controller, microcontroller, battery management system, memory and the sensors for the operating modes.

The failure rates from the RBDs serve as an assessment for the failure occurrence (O). The severity (S) for failure 1 *measurement not analyzable* is rated as highest throughout (S = 10). Using the risk priority number (RPN = S * O * D) the most critical causes for failures are identified (marked dark red in the FMEA, Figure 9). These are:

(i) Movement sensor failure
(ii) Microcontroller failure
(iii) Real-time-clock (RTC) failure
(iv) Transmission failure
(v) Battery management (BMS) and voltage regulator failure

Movement sensor failure is critical, because the microcontroller hardly has a chance to detect if the sensor is at failure or simply does not sense a movement. There are status registers in the sensor that can be polled, but they do not show every possible failure. Also, generic movement sensor failure rates from the cited literature are high.

Microcontroller failure is critical because it is the heart of control for the system. Some failures cannot be shown by LEDs or only by a lack of flashing LEDs and have to be detected by the mechanical visual indication (principle of a toilet door) of the transmission 2. RTC failures are similar to movement sensor.

Transmission failure is critical because both probability and detection is at a medium level.

Battery management and voltage regulator failure is critical because the detection is hard, similar to the microcontroller failures. Without energy, the microcontroller cannot work.

3.4. Improvements

For the **movement sensor** an emergency mode is implemented to reduce the severity (value S). The system falls back to the time-controlled mode in case of a movement sensor failure. This is convenient in terms of cost reduction because the RTC is included anyway. The detection of the movement sensor failure can be achieved by implementing a maximum time of no motion, knowing the daily routines of the user. The change in the respective RBD is shown in Figure 10 as cold redundancy. In the FMEA, the severity is halved.

Microcontroller failure detection is improved by ensuring good visibility of the LEDs and implementing a buzzer for acoustic warning.

RTC failure detection is improved by showing the failures on the LEDs and instructing the user how to identify them.

Transmission failure detection was improved by adding detector switches that serve as end stops as hot redundancy to the current sensing, indicating the totally open and closed positions which are critical to the overall functionality. These are closer to the overall function (open/close the measuring chamber) and introduce a parallel structure in the RBDs, see Figure 10.

BMS and voltage regulator failures are improved by hot redundancy. A second set of battery, BMS and regulator are implemented.

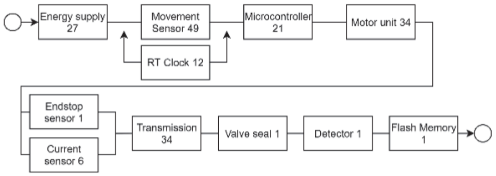
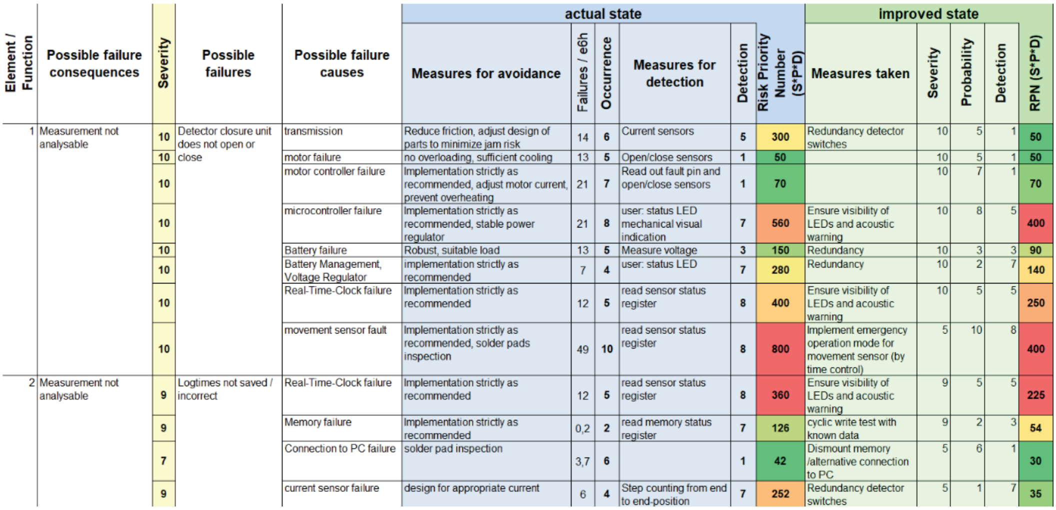


Figure 10: RBD movement mode with improvement



Element / Function	Possible failure consequences	Severity	Possible failures	Possible failure causes	actual state						improved state				
					Measures for avoidance	Failures / e6h	Occurrence	Measures for detection	Detection	Risk Priority Number (S*P*D)	Measures taken	Severity	Probability	Detection	RPN (S*P*D)
1	Measurement not analysable	10	Detector closure unit does not open or close	transmission	Reduce friction, adjust design of parts to minimize jam risk	14	6	Current sensors	5	300	Redundancy detector switches	10	5	1	50
		10		motor failure	no overloading, sufficient cooling	13	5	Open/close sensors	1	50		10	5	1	50
		10		motor controller failure	Implementation strictly as recommended, adjust motor current, prevent overheating	21	7	Read out fault pin and open/close sensors	1	70		10	7	1	70
		10		microcontroller failure	Implementation strictly as recommended, stable power regulator	21	8	user: status LED mechanical visual indication	7	560	Ensure visibility of LEDs and acoustic warning	10	8	5	400
		10		Battery failure	Robust, suitable load	13	5	Measure voltage	3	150	Redundancy	10	3	3	90
		10		Battery Management, Voltage Regulator	implementation strictly as recommended	7	4	user: status LED	7	280	Redundancy	10	2	7	140
		10		Real-Time-Clock failure	Implementation strictly as recommended	12	5	read sensor status register	8	400	Ensure visibility of LEDs and acoustic warning	10	5	5	250
		10		movement sensor fault	Implementation strictly as recommended, solder pads inspection	49	10	read sensor status register	8	800	Implement emergency operation mode for movement sensor (by time control)	5	10	8	400
2	Measurement not analysable	9	Logtimes not saved / incorrect	Real-Time-Clock failure	Implementation strictly as recommended	12	5	read sensor status register	8	360	Ensure visibility of LEDs and acoustic warning	9	5	5	225
		9		Memory failure	Implementation strictly as recommended	0,2	2	read memory status register	7	126	cyclic write test with known data	9	2	3	54
		7		Connection to PC failure	solder pad inspection	3,7	6		1	42	Dismount memory /alternative connection to PC	5	6	1	30
		9		current sensor failure	design for appropriate current	6	4	Step counting from end to end-position	7	252	Redundancy detector switches	5	1	7	35

Figure 9: Excerpt of the Failure Modes and Effect Analysis (FMEA) for the radon exposimeter au-raex

To calculate the new failure rates and MTTF, the redundancy structure has to be considered. The RBD for the button-controlled mode can be reduced to this:

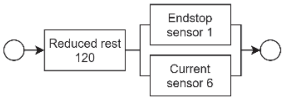


Figure 11: Reduced RBD for button mode

Assuming the system and parts are new at t = 0, using formulas from (DIN EN 61078 2018) (Birolini 2017), the new MTTF for button mode calculates to,:

$$MTTF_{S0,button} = \frac{1}{120+1} + \frac{1}{120+6} - \frac{1}{120+1+6} = 8327\,h = 1\,y \tag{7}$$

In a similar manner, the new MTTF for time mode calculates to:

$$MTTF_{S0,time} = \frac{1}{131+1} + \frac{1}{131+6} - \frac{1}{131+1+6} = 7629\,h = 0.87\,y \tag{8}$$

The RBD for movement-controlled mode can be reduced as follows:

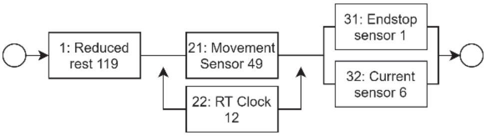


Figure 12: Reduced RBD for movement mode

Assuming ideal conditions for the cold redundant part (perfect switching, minimal stress for the dormant unit with λ = 0) the reliability functions are as follows:

$$\begin{gathered} R_{S0} = \prod_{i=1}^{3} R_i \\ = R_1 R_2 (R_{31} + R_{32} - R_{31} R_{32}) \\ = e^{-\lambda_1 t} \\ \left(e^{-\lambda_{21} t} + \frac{\lambda_{21}}{\lambda_{21} - \lambda_{22}} \left(e^{-\lambda_{22} t} - e^{-\lambda_{21} t} \right) \right) \\ \left(e^{-\lambda_{31} t} + e^{-\lambda_{32} t} - e^{-\lambda_{31} t} e^{-\lambda_{32} t} \right) \end{gathered} \tag{9}$$

$$\begin{gathered} MTTF_{S0,move} = \int_0^\infty R_{S0}(t)dt = 8173\,h \\ = 0.93\,y \end{gathered} \tag{10}$$

4. Discussion and Conclusion

The presented reliability model supports the product developer to evaluate an initial design and the system components at an early stage of product development when the design is still incomplete. The reliability model helps to identify critical components and flaws at an early stage, which can then be considered during development.

Furthermore, methodologies like reliability importance (Wang, Loman, and Vassitiou 2004) or a priori reliability allocation proposed in Saintis et al. (2019) can support the identification of the critical components. The proceeding helps a great deal to develop the au-raex, which plays a part of reducing the risk of harm to the health of people, thus contributing to a sustainable future.

This contribution shows how important it is to find a working concept early before going into production to avoid structural changes and costly iterations, which is also pointed out by Thomke and Fujimoto (2000). In this contribution, we could improve the design by adding redundant sensors and emergency modes for critical parts before define the final design. The target MTTF could not be reached fully, however the underlying data is generic, hence not be interpretable in an absolute manner from the beginning. This is a limitation of our work. We used generic failure rates for the components which are investigated under specific conditions. That may not exactly exist in the presented use case. Therefore, the absolute values of MTTF should be regarded with care. An issue remains with detecting a failure of the movement sensor for the implemented emergency mode. It depends on a fixed time receiving no signal from the sensor. However, in cases of vacation or illness of users this may lead to false failure detections.

In the reliability evaluation the user has to be considered as part of the system. In future human factors can be integrated in the reliability model. This allows further human influences to be considered.

Acknowledgement

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