Development of a Smart Maintenance System for UV Lamps

by
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Declaration

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Abstract

The supply of customer-specific products is leading to the increasing technical complexity of machines and plants in the manufacturing process. In order to ensure the availability of the machines and plants, maintenance is considered as an essential key. The application of cyber-physical systems enables the complexity to be mastered by improving the availability of information, predictive maintenance strategies and the provision of information.

The present research project deals with the development of a cost-effective and retrofittable smart maintenance system for the application of ultraviolet lamps. UV lamps are used in a variety of applications such as curing of materials and water disinfection, where UV lamps are still used instead of UV LED due to their higher effectiveness. The smart maintenance system enables continuous condition monitoring of the UV lamp through the integration of sensors. The data obtained are compared with data from existing lifetime models of UV lamps to provide information about the remaining useful lifetime of the UV lamp. This ensures needs-based maintenance measures and more efficient use of UV lamps. Furthermore, it is important to have accurate information on the remaining useful lifetime of a UV lamp, as the unplanned breakdown of a UV lamp can have far-reaching consequences.

The requirements for the smart maintenance system are determined from a comprehensive literature review about smart maintenance, cyber-physical systems and UV applications. Derived from the literature review, a functional model is defined. The model describes the functional dependencies between the sensors and actuator, the condition monitoring system as well as the IoT platform. Based on the requirements and the functional model, the hardware and software are selected. Finally, the system is developed and retrofitted to a simulated curing process of a 3D printer to validate its functional capability.

The developed smart maintenance system leads to improved information availability of the condition of UV lamps, predictive maintenance measures and context-related provision of information.

Keywords: smart maintenance, cyber-physical system, UV lamps

Opsomming

Die verskaffing van klant spesifieke produkte lei tot die toenemende tegniese kompleksiteit van masjiene en aanlegte in die vervaardigingsproses. Om die beskikbaarheid van masjiene en aanlegte te verseker, word onderhoud as 'n noodsaaklike sleutel beskou. Deur die toepassing van kuber-fisiese stelsels word die kompleksiteit bemeester deur die beskikbaarheid van inligting, voorspellende instandhouding strategieë en die verskaffing van inligting verbeter.

Die huidige navorsingsprojek handel oor die ontwikkeling van 'n koste-effektiewe en aanpasbare slim instandhouding stelsel vir die toepassing van ultravioletlampe (UV). UV-lampe word in verskillende toepassings gebruik, soos om materiale te verhard en die ontsmetting van water, waar UV-lampe steeds gebruik word in plaas van UV-LED vanweë hul hoër effektiwiteit. Die slim instandhouding stelsel maak dit moontlik om die UV-lamp deur die integrasie van sensors deurlopend te monitor. Die data wat verkry is, word vergelyk met die data van die bestaande lewenslange modelle van UV-lampe om inligting te verskaf oor die oorblywende nuttige leeftyd van die UV-lamp. Dit verseker behoefte-gebaseerde onderhoud maatreëls en meer doeltreffende gebruik van UV-lampe. Verder is dit belangrik om akkurate inligting te hê oor die oorblywende bruikbare leeftyd van 'n UV-lamp, aangesien die onbeplande ineenstorting van 'n UV-lamp verreikende gevolge kan hê.

Die vereistes vir die slim instandhouding stelsel word bepaal uit 'n uitgebreide literatuuroorsig oor slim instandhouding, kuber-fisiese stelsels en UV-toepassings. 'N Funksionele model is afgelei van die literatuurstudie. Die model beskryf die funksionele afhanklik hede tussen die sensors en die motors, die toestand moniteringstelsel sowel as die IoT-platform. Op grond van die vereistes en die funksionele model word die hardeware en sagteware gekies. Laastens word die stelsel ontwikkel en toegerus op 'n gesimuleerde verhardings proses van 'n “3D-printer” om die funksionele vermoë daarvan te bevestig.

Die ontwikkelde slim instandhouding stelsel lei tot verbeterde beskikbaarheid van inligting oor die toestand van UV-lampe, voorspellende instandhoudings maatreëls en konteks verwante verskaffing van inligting.

Sleutelwoorde: smart maintenance, cyber-physical system, UV lampe

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List of Acronyms

CAD	Computer-Aided Design
CMS	Condition Monitoring System
CPS	Cyber-physical System
GPIO	General Purpose Input Output
GUI	Graphical User Interface
HSSE	Health, Safety, Security and Environment
HTTP	Hypertext Transfer Protocol
I2C	Inter-Integrated Circuit
IoT	Internet of Things
IT	Information Technology
JSON	JavaScript Object Notation
LED	Light-Emitting Diodes
MES	Manufacturing Execution System
MQTT	Message Queuing Telemetry Transport
SLC	Stereo-Lithography Contour
SME	Small and Mid-sized Enterprise
SMS	Short Message Service
STL	Surface Tessellation Language
USB	Universal Serial Bus
UV	Ultraviolet
VRML	Virtual Reality Modelling Language
XML	Extensible Markup Language

Chapter 1
Introduction

"Industry 4.0 marks the beginning of a new industrial era worldwide."

Henke, Heller, and Stich (2019, p. 6) use this motto to underline that the vision of industry 4.0 is transforming an entire industry. In order to be globally competitive, they are of the opinion that the industry must rely on strong networking of machines and plants as well as on the application of state-of-the-art automation, information and communication technology. This enables real-time, high-volume and multimodal communication as well as networking between cyber-physical systems and people. The availability of data and information enables understanding of correlations and provides the basis for fast decision-making processes. If the organisational prerequisites are also fulfilled, companies can adapt their processes and react more rapidly to increasing market dynamics. This results in the central capability of companies in industry 4.0 – agility (Schuh, Anderl, Gausemeier, ten Hompel, & Wahlster, 2017, p. 10).

Here, innovative and sustainable maintenance in the sense of smart maintenance acts as an enabler in order to ensure the functionality of all entities that ultimately represent the vision of an industry 4.0 (Henke et al., 2019, p. 6).

Up to now, maintenance is perceived in companies as a cost driver and not as a potential value-adder. However, maintenance measures restore and preserve the functionality of machines and plants and lead to value preservation or even value enhancement, and preventive maintenance measures avoids unplanned breakdowns. The value-adding potential of maintenance, therefore, results from the three to five times higher follow-up costs avoided as a result of inadequate or neglected maintenance (acatech, 2015, p. 14).

1.1 Background and rationale of the research

So far, there are only a limited number of established methods to monitor the condition of critical components in machines and plants. Vibration analysis is the most commonly used method for condition monitoring as it uses accelerometers which are relatively inexpensive sensors. Another method is the ultrasonic analysis which is used, for example for rotating machines and is an extension to the standard acoustic analysis. Physical phenomena which generate short impacts and propagate into the air or in the metal are detected.

Furthermore, oil analysis is used as a method to determine the friction in a machine as it leads to wear. For this purpose, a sensor measures the parameters of the lubricant, which are indicators of component wear. Another method used is electrical parameter analysis, which among other things, measures high-frequency acquisition of voltage and current signals. This allows the detection of faults in components of electrical machines (Barszcz, 2019, pp. 27–30). However, for a large number of critical components, there is still no established method for condition monitoring which is the foundation of predictive maintenance strategies. In particular, there is no method described in the literature for the condition monitoring of UV lamps, although UV lamps are used in a wide range of industrial applications and have a leading role in the respective processes, which is outlined in present research work.

The fact that a UV lamp is a critical component is shown in the Logistics Learning Factory of the ESB Business School, an exemplary manufacturing company with its entire industrial supply chain is depicted. Processes in the area of product and work system engineering, incoming goods, storage, commissioning, production, assembly, and additive manufacturing as well as distribution are simulated with a practical orientation and are holistically considered (Hummel, 2014). Within the additive manufacturing process, the 3D printer Object500 Connex3 from Stratasys is used to cure the printing material with UV lamps. Thereby the incident occurred that the UV lamps failed without warning, and the printing process could not be continued. The 3D printer does not have a system that provides current condition data of the UV lamps during the printing process and therefore has no data basis for predictive maintenance strategies that indicate the remaining useful lifetime of the UV lamps.

1.2 Research problem statement and questions

This initial situation that there is so far no system which improves the availability of condition data of UV lamps, enables predicting maintenance strategies and provides information in order to restore and preserve the operating conditions, leads to the following primary research question.

Table 1-1: Primary research question of the thesis

PRQ	Can a smart maintenance system be developed for the use case of UV lamps?	Chapter 5 and 6

The following secondary research questions must be considered in order to answer the primary research question:

Table 1-2: Secondary research questions of the thesis

SRQ 1	What are the characteristics and requirements of a smart maintenance system?	Chapter 2 & Chapter 4
SRQ 2	How can cyber-physical systems improve maintenance?	Chapter 2
SRQ 3	What factors are described in the literature that influences the lifetime of UV lamps?	Chapter 2
SRQ 4	How can lifetime models be developed for components and systems?	Chapter 2
SRQ 5	Can the developed smart maintenance system also be applied in the context of other UV lamps?	Chapter 7

From an economic point of view, the implementation of a smart maintenance system only makes sense if it generates added value. This can be reflected in different ways, such as increased availability, reliability, and safety of the machine as well as improved product quality through better provision of information. The challenge that there is no flow of information about the condition and remaining lifetime of UV lamps can be addressed. Moreover, there is a huge potential to enhance the maintenance of UV lamps.

1.3 Research objectives and contribution

The principal objective of the research thesis is the development of a smart maintenance system for UV lamps. In order to achieve the objective, the nine following objectives were defined:

i. Analyse the structure of smart maintenance systems.
ii. Investigate the influencing factors for the lifetime of UV lamps.
iii. Examine the structures and literature of cyber-physical systems.
iv. Examine research projects and realised concepts of smart maintenance systems.
v. Determine the requirements for a smart maintenance system for UV lamps.
vi. Develop and validate a demonstrator of the smart maintenance system.
vii. Analyse if existing lifetime models of similar UV lamps can be used to predict the remaining useful lifetime of the UV lamps.
viii. Examine whether the smart maintenance system can be used for other UV lamp applications.

The principal aim must be fulfilled under the following framework conditions:

i. The safety of the smart maintenance system must be given at all times.
ii. The system must be retrofittable for UV lamp applications
iii. The financial means to develop the smart maintenance system should be as minimal as possible to enable, among other things, the deployment in African countries.

1.4 Research methodology and design overview

The research study examines the development of a smart maintenance system for UV lamps. In the study, only the UV lamps of the Stratasys Object500 Connex 3D printer will be considered before a review for further UV lamp applications is made. The study is carried out as qualitative research, which is divided into two phases. In contrast to quantitative research, qualitative research is based on non-numerical data and data collection as well as evaluation is non-standardised (Saunders, Lewis, & Thornhill, 2015, p. 165).

Figure 1-1 illustrates a detailed overview of the research methodology. The foundation for the first qualitative phase of this research is secondary data. These include a variety of sources such as books, journals, publications, articles and websites. The second qualitative phase consists of the validation and verification of the results. The smart maintenance system is developed in the form of a demonstrator and is integrated into the context of a printing process simulation. In this way, the functions are demonstrated. Furthermore, it will be examined whether the developed smart maintenance system is also valid for other applications with UV lamps.

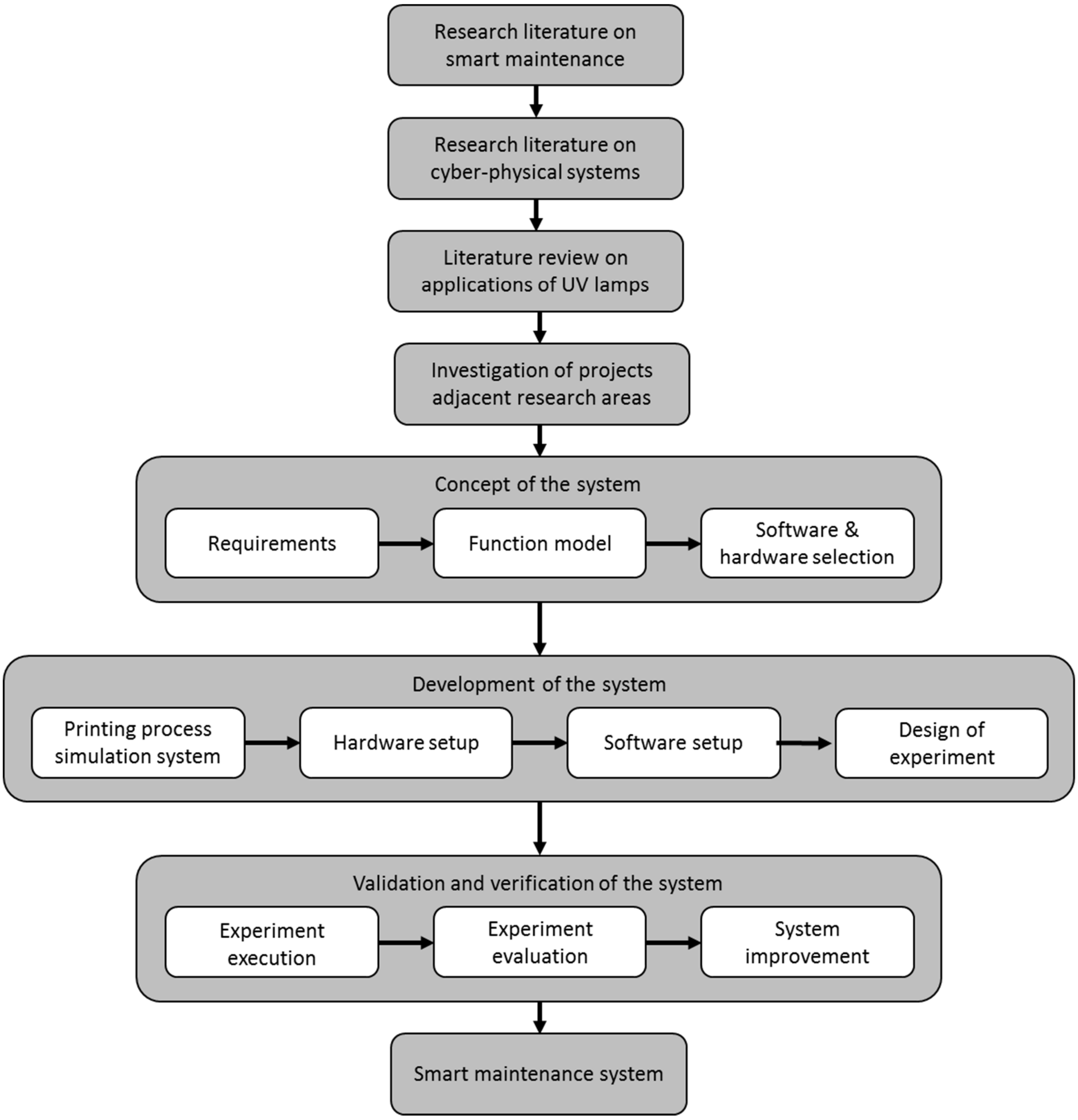


Figure 1-1: Research methodology

1.5 Ethical considerations

According to the Faculty Ethics Screening Committee of Stellenbosch University, no ethical clearance is required for the procedure of the present research project. This is based on the fact that no data are collected through interviews or surveys, for example. Furthermore, no confidential data or information from organisations, institutions or companies will be used, nor will any cooperation take place. Besides, no person-related information from databases is used and no data from public domains will be collected for this study.

1.6 Delimitations and limitations

Smart maintenance can be categorised into the following subject areas (Henke et al., 2019, p. 14):

i. Maintenance strategies
ii. Spare parts management
iii. Knowledge management
iv. Assistance systems
v. Competence development
vi. Economic view

This research study will only focus on the maintenance strategy for UV lamps and has intersections with the spare parts management. UV lamps are used in a wide variety of industrial applications and are a decisive component in the processes.

The smart maintenance system for UV lamps developed in this research study illustrates the functionalities. The system is fully validated and can be improved by further tests in its predictive accuracy of the remaining useful lifetime of UV lamps.

1.7 Thesis outline

The section summarises the content and structures the thesis in four parts. Figure 1-2 shows the structure of part 1 and 2. The thesis begins with the central section, continuous with the comprehensive literature review and refers to existing approaches in adjacent research areas. Part 2 contains the concept of the smart maintenance system. The basis of the requirements and the function model are the findings of the literature review and the projects in adjacent research areas.

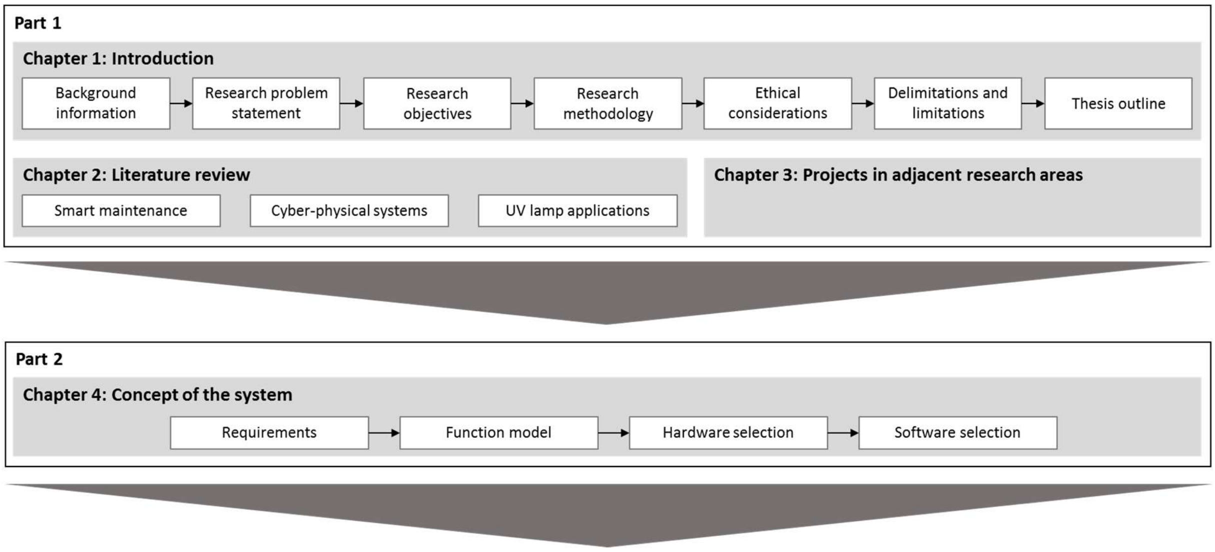


Figure 1-2: Structure of the thesis part 1and 2

Figure 1-3 depicts the structure of part 3 and 4 of the thesis. Part 3 consists of the development of the smart maintenance system and the printing process simulation system as well as the determination of the design of the experiment, followed by the validation of the system. Part 4 covers the summary, conclusions and recommendations of the thesis.

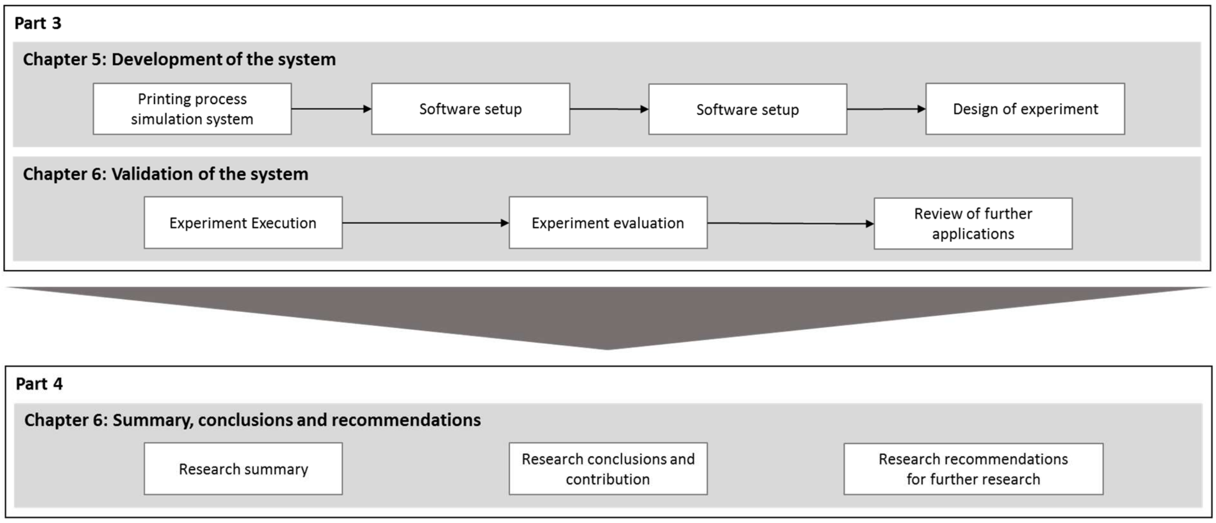


Figure 1-3: Structure of the thesis part 3 and 4

By the outlined layout, the next chapter presents a comprehensive overview of the literature on smart maintenance, cyber-physical systems and UV lamp applications.

Chapter 2
Literature review

The following chapter shows which literature is used as a basis and explains the terminology. The following sections examine the function of smart maintenance, the structure of cyber-physical systems and the different industrial applications of UV lamps as well as the UV lamp and printing process of the Stratasys Objet500 Connex3.

2.1 Function of smart maintenance

The section explains the function of smart maintenance. First of all, an overview of the objectives of maintenance is given. In addition, the definition of maintenance is presented, as well as the task areas of maintenance are stated. The next step is to review the development of maintenance towards smart maintenance. This is followed by the definition and structure of smart maintenance.

All the maintenance measures are intended to achieve the following objectives, according to Leidinger (2017, p. 15). The objectives are either equivalent to each other or are to be achieved according to specific prioritisation:

- Safety
- Availability
- Reliability
- Value preservation

The first objective determines that there is no danger from the machine or plant. The implementation takes place by applying the topics health, safety, security and environment, which are abbreviated as HSSE. Their application is primarily determined by legal regulations in which the form, scope, and frequency of recurring inspections of the condition and/or safety facilities are specified. Since the legislator cannot predict all potential hazards that may occur, it is the responsibility of the operator to ensure that the machine or plant does not cause any hazards. In the case of a safety-relevant incident, the operator must prove that he did not act negligently, but that his maintenance program takes into consideration the state of the art as well as the legal requirements. The state of the art is defined, for example, by literature, conference publications, recommendations of associations and recommendations of insurers.

In contrast, the objectives of availability, reliability, and preservation of value are seen as the internal objectives of the operator. Availability means that the plant or machine can be brought into operation. Reliability describes that the machine or plant can be operated without interruptions. The last goal describes that the value of the plant is to be preserved by maintenance measures, which means that long remaining service life is to be achieved. The operator can decide to meet these three objectives on the basis of the criteria of overall cost-effectiveness (Leidinger, 2017, pp. 15–16).

The German Institute for Standardisation defines maintenance in DIN 31051 as the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function [.]" (DIN Deutsches Institut für Normung e. V., 2018, p. 8) Maintenance can be divided into the following basic measures, see Figure 2-1.

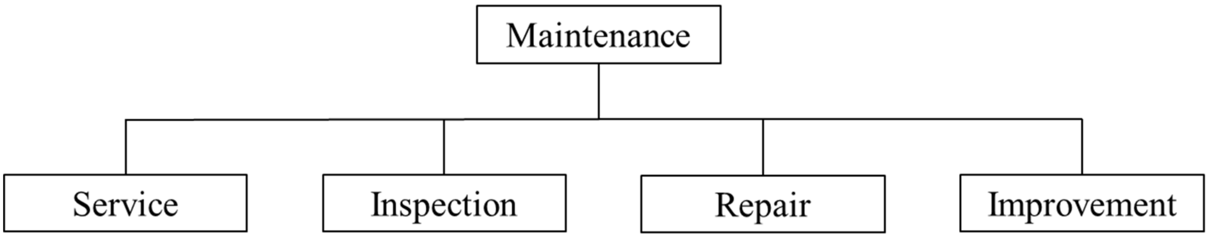


Figure 2-1: Subdivision of maintenance (DIN Deutsches Institut für Normung e. V., 2019)

In the following section, the four different measures that are carried out during maintenance are introduced according to DIN 31051.

1. Service means all "measures taken to delay the depletion of the existing wear margin [.]" (DIN Deutsches Institut für Normung e. V., 2019, p. 5) The target state is, therefore, to be restored. Figure 2-2 shows the depletion of the wear margin over a certain period of time. The largest margin of wear exists immediately after manufacture and decreases over time until the wear limit is reached. As long as the wear margin is above the wear limit, reliable operation is ensured. If the wear margin falls below the limit, a failure-free operation is no longer guaranteed. The intention of maintenance is to extend the period between the initial condition after manufacture and the wear limit.

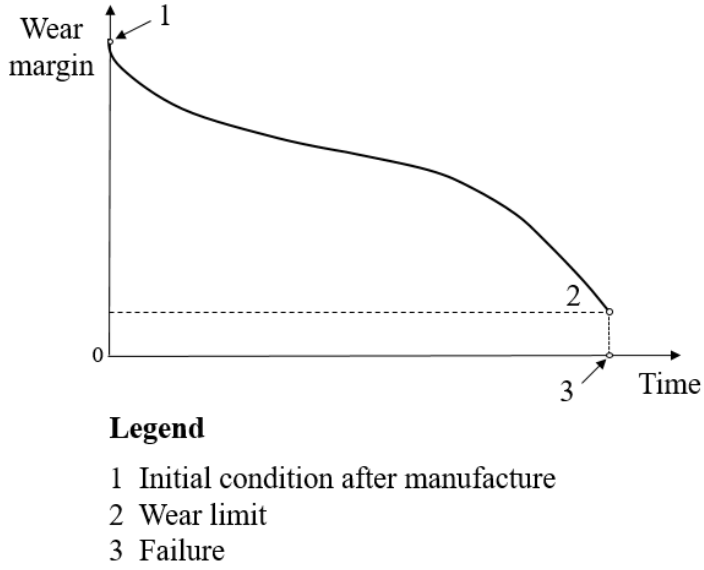


Figure 2-2: Depletion of the wear margin, own representation based on DIN Deutsches Institut für Normung e. V. (2019)

2. Inspection is the "examination for conformity by measuring, observing, or testing the relevant characteristics of an item [.]" (DIN Deutsches Institut für Normung e. V., 2018, p. 41) A comparison of the initial and actual conditions is determined, which should take place under constant operating and environmental circumstances. The prerequisite is that the scales and tolerances are given in the same dimensions as the initial state to be able to make a valid comparison (Matyas, 2013, p. 28).
3. Repair is the "physical action taken to restore the required function of a faulty item [.]" (DIN Deutsches Institut für Normung e. V., 2018, p. 44) The faulty part is either repaired by processing it or replaced to restore it to the original condition (Matyas, 2013, p. 32).
4. Improvement is the "combination of all technical, administrative and managerial actions, intended to ameliorate the intrinsic reliability and/or maintainability and/or safety of an item, without changing the original function [.]" (DIN Deutsches Institut für Normung e. V., 2018, p. 36) Reliability can be increased, for example, by eliminating weaknesses where failure occurs more frequently than required availability and where improvement is possible and economically justifiable (Matyas, 2013, pp. 33–34).

The following section explains the development of maintenance on the basis of a maturity model, see Figure 2-3. No machine or production data are gathered during the first development stage of maintenance. This is followed by the development stages of monitoring, diagnosis and prognosis and self-preservation. Monitoring and diagnosis can be classified in the category "transparency". In the following, the maintenance stages mentioned are discussed, their respective innovations explained and distinguished from each other. In the following, the maintenance stages mentioned are described, their respective innovations explained and distinguished from each other. In the initial form of maintenance, no machine or production data are collected. At this stage, the failure-dependent (reactive) and time-dependent (preventive) maintenance strategy is applied. The reactive maintenance is only executed as soon as a failure or downtime occurs at the machine or plant. The maintenance measures are not planned in advance but are performed quickly and spontaneously (Mühlnickel, Kurz, Jussen, & Emonts-Holley, 2018, p. 352). The failure-dependent maintenance strategy can be applied where machines and plants are underutilized, where production interruptions do not lead to delivery problems, where redundant systems and a high spare parts inventory are available, or where safety regulations are not affected (Verein Deutscher Ingenieure e. V., 2012, pp. 25–26). In preventive maintenance, regular maintenance and inspections are carried out on the machine and plant in order to reduce the probability of failures or downtimes (Mühlnickel et al., 2018, p. 354). This strategy is used when considerable production downtimes are to be expected, when legal regulations require an inspection or when machines and plant failures cause a hazard to personnel or facilities (Verein Deutscher Ingenieure e. V., 2012, p. 26).

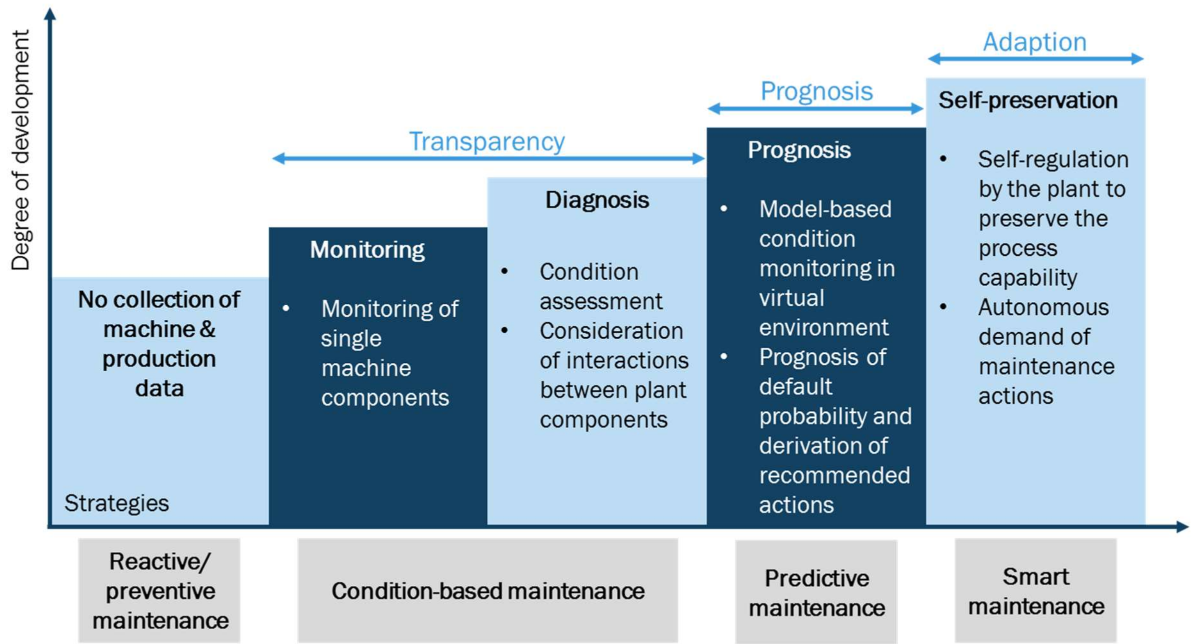


Figure 2-3: Reference model, own representation based on Emonts-Holley (2016)

The next degree of development in maintenance is condition-based monitoring. The goal of this strategy is to minimize unplanned machine downtimes by monitoring the machine. For this purpose, a condition monitoring system (CMS) is used, see Figure 2-4. Sensors are mounted on machine components or tools in order to record critical data, such as acceleration, force or temperature, for wear and tear. The data measurement is either realised continuous or event-driven. The CMS processes the raw data by reducing the data and forming characteristic values of each machine component. The processing of different data volumes takes place in a timely manner. The data are filtered and, among other things, maxima and average values are created. In addition, characteristic values are linked to each other. The next step is to store the measurement data in a database structure. The trends of the characteristic values are displayed e. g. in a dashboard. Damage cases that occur are documented immediately and are included in the machine history. The causes of failure are also illustrated. On the basis of changes in the characteristic values, possible damages to the components can be determined and an alarm is triggered if a damaging event is imminent. In addition, CSM recommends the appropriate maintenance measures that must be executed to fix the imminent damage. This strategy enables proactive and optimal scheduling of maintenance, as the condition of the machine is known at any time (Mühlnickel et al., 2018, p. 354).

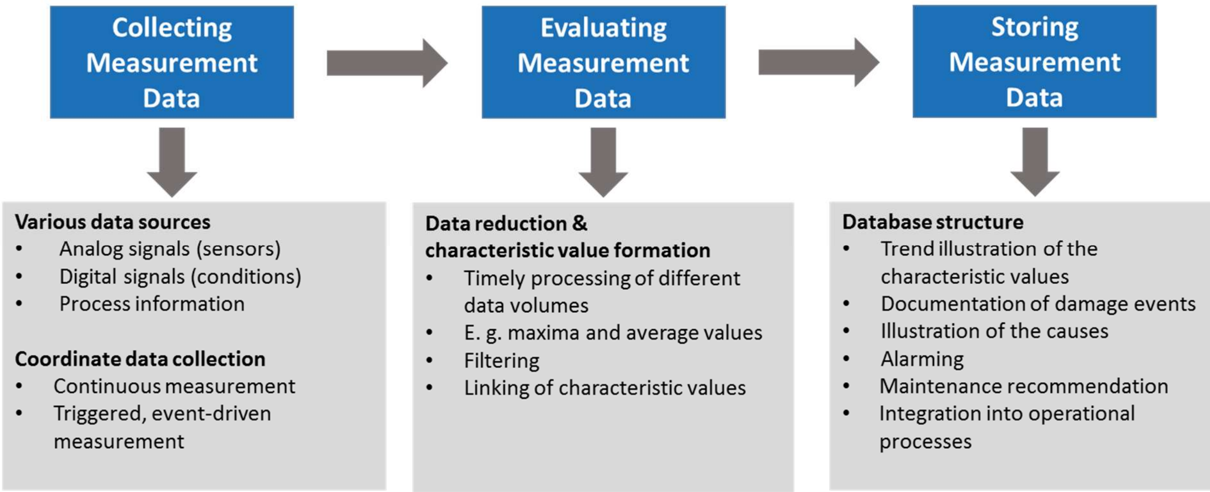


Figure 2-4: Structure of a condition monitoring system (Fischer & Langer, 2017, p. 17)

The previous maintenance strategies only focused on the condition monitoring and evaluation of individual machine or plant components. The next step in development is the diagnosis, where the plant or machine is considered as a whole by integrating all the components of a machine or plant. As the complexity of plants and machines increases, condition monitoring becomes more difficult because interactions between plant and machine components must also be taken into account. The objective of this strategy is to determine and evaluate the condition of the machine or plant as a whole. As with the previous strategy, critical machine data are summarised and analysed. The evaluation of the machine and plant condition is carried out by defined limit values (Mühlnickel et al., 2018, pp. 354–355).

The further development of condition-based maintenance is predictive maintenance, which belongs to the level of the prognosis (Mühlnickel et al., 2018, p. 355). Predictive maintenance is a "condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the wear of the item [.]" (DIN Deutsches Institut für Normung e. V., 2018, p. 35) The sensor data obtained are evaluated and interpreted using analysis or simulation methods in order to identify fault patterns and predict failures (Mühlnickel et al., 2018, p. 355). The prognosis is based on wear models and the determination of the remaining lifetime of tools and components. The objective of the strategy is to use the machine or plant component until the end of their life and only then replace them. In contrast to the conventional condition-based maintenance strategy, this strategy allows planning with greater foresight (Lucke, Defranceski, & Adolf, 2017, pp. 76–77).

The condition or remaining useful lifetime of components will be determined by experience-based methods such as component failure history assessment, evolutionary or trending methods such as comparison of measured values of condition describing features with already known reference values, neural networks, Hidden Markov models, or modelling of physical correlations.

The following figure illustrates the different prognostic approaches in relation to their applicability as well as cost and accuracy. The accuracy, but also the costs for the development of the models increases with the use of experience-based approaches, from the evolutionary or trending models to the physical models. An experience-based model requires few sensors, is designed for a wide range of applications and is the least complex. In contrast, the physical model is the one in which the use case and the condition for predicting the remaining useful component life should be specified as precisely as possible (Byington, Roemer, & Galie, 2002, pp. 2815–2824).

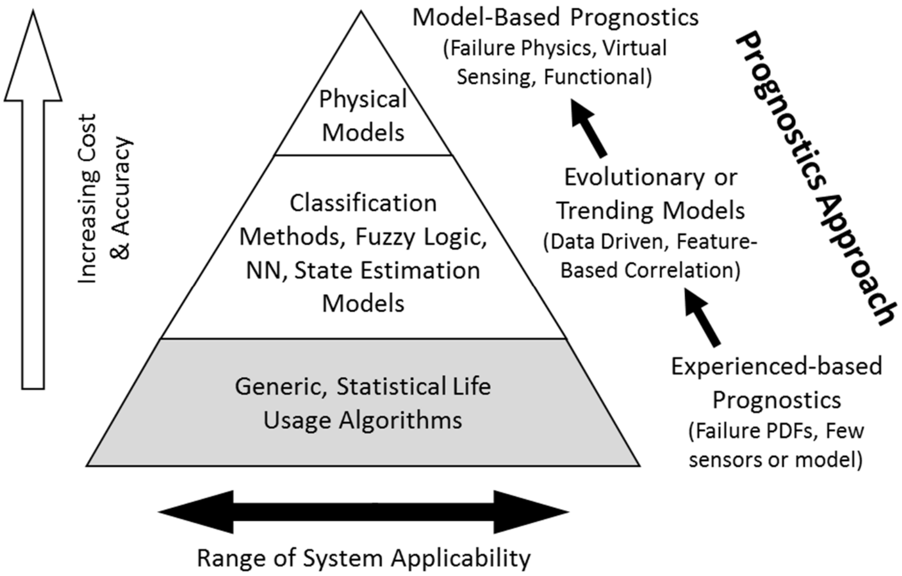


Figure 2-5: Hierarchy of prognostic approaches (Byington et al., 2002, p. 2815)

The next step in the development of maintenance is the self-preservation of machines and plants, which ensure their process capability through self-regulation. The maintenance strategy is adapted continuously based on the current and expected load. In the event of an imminent failure, the machines and plants automatically request the appropriate maintenance measures and thereby ensure their process capability. This stage of development is called smart maintenance and is described in the following two sections (Mühlnickel et al., 2018, p. 355).

2.1.1 Definition of smart maintenance

There is no clear scientific definition of smart maintenance in the available literature. However, in order to ensure a uniform terminology, the following definition of Henke et al. (2019, p. 11) is applied:

"Smart Maintenance refers to a learning-oriented, self-regulated, intelligent maintenance with the objective of maximising the technical and economic effectiveness of maintenance measures through the use of digital applications, taking into consideration the respective existing production system".

2.1.2 Structure of smart maintenance

This subsection explains the structure of a smart maintenance system. The basis of a smart maintenance system is a planning system that manages maintenance objects, schedules, and controls maintenance tasks. In addition, other functions can also be integrated with the planning system, such as spare parts and ordering, maintenance controlling or maintenance personnel management. The IT system thus supports the maintenance staff in the planning and execution of maintenance activities (Lucke et al., 2017, p. 81).

According to Lucke et al. (2017, pp. 81–82), however, there are still a number of deficits in the currently implemented maintenance planning systems, which are listed below:

- The integration of additional functions often still takes place in separate IT systems and there are often only application-specific insular solutions. This means that the interfaces have to be connected with enormous expenditures.
- A function that supports maintenance staff in the selection and decision of an appropriate maintenance strategy is insufficiently available in previous maintenance planning systems.
- Condition and remaining lifetime information of components are mostly considered manually.
- Maintenance activities that are performed or planned are not simultaneously coordinated with production planning.

The reason for the deficits is that if an unplanned machine and plant downtimes occur, the existing plan is deviated from and replanned reactively. Also, only a limited number of time slots are available for maintenance in production so that the resulting maintenance activities must be constantly re-prioritized.

Due to the existing deficits, Lucke et al. (2017, p. 82) have made the following requirements on future maintenance planning systems:

- Support in the selection of the maintenance strategy decision for machines and plants: The decision-making process should take into account object-related information on maintenance as well as its consequences in the value creation network.
- Improvement of the utilization of machine assemblies and components: By using wear models and load-dependent remaining lifetime provisions, these can be fully used and replaced in time.
- Acceleration of maintenance planning:
    - Through continuous networking of cyber-physical machines with maintenance planning modules,
    - Reduction of search times for required information through improved user guidance and

  - Application of planning assistants, which propose a multicriteria optimized maintenance plan.
- Increase in planning quality: Use of valid and situation-related information, which is valid and reliable.
- Improvement of usability: Simplify planning with context-related information for the maintenance staff.
- The flexibility of IT systems: Reduction of the effort required for networking: IT systems for maintenance should be able to be adapted quickly and easily to new situations, even by less qualified personnel.
- Modular structure of functions, which enables fast adaptability to application-specific cases.

This results in the underlying architecture of a future maintenance planning system, which is shown in Figure 2-6. Additional modules extended a current maintenance planning system to meet not only the basic requirements but also the requirements of future maintenance planning systems. The focus is on a dynamic maintenance planning assistant who supports the maintenance staff in adapting the maintenance strategy and planning. This assistant considers the remaining lifetimes of the monitored components. The calculation can be performed, for example, directly from the smart components or from a subsequent calculation service when using a condition monitoring system. As a result, the maintenance staff receives a recommendation for an optimized maintenance plan (Lucke et al., 2017, pp. 82–83).

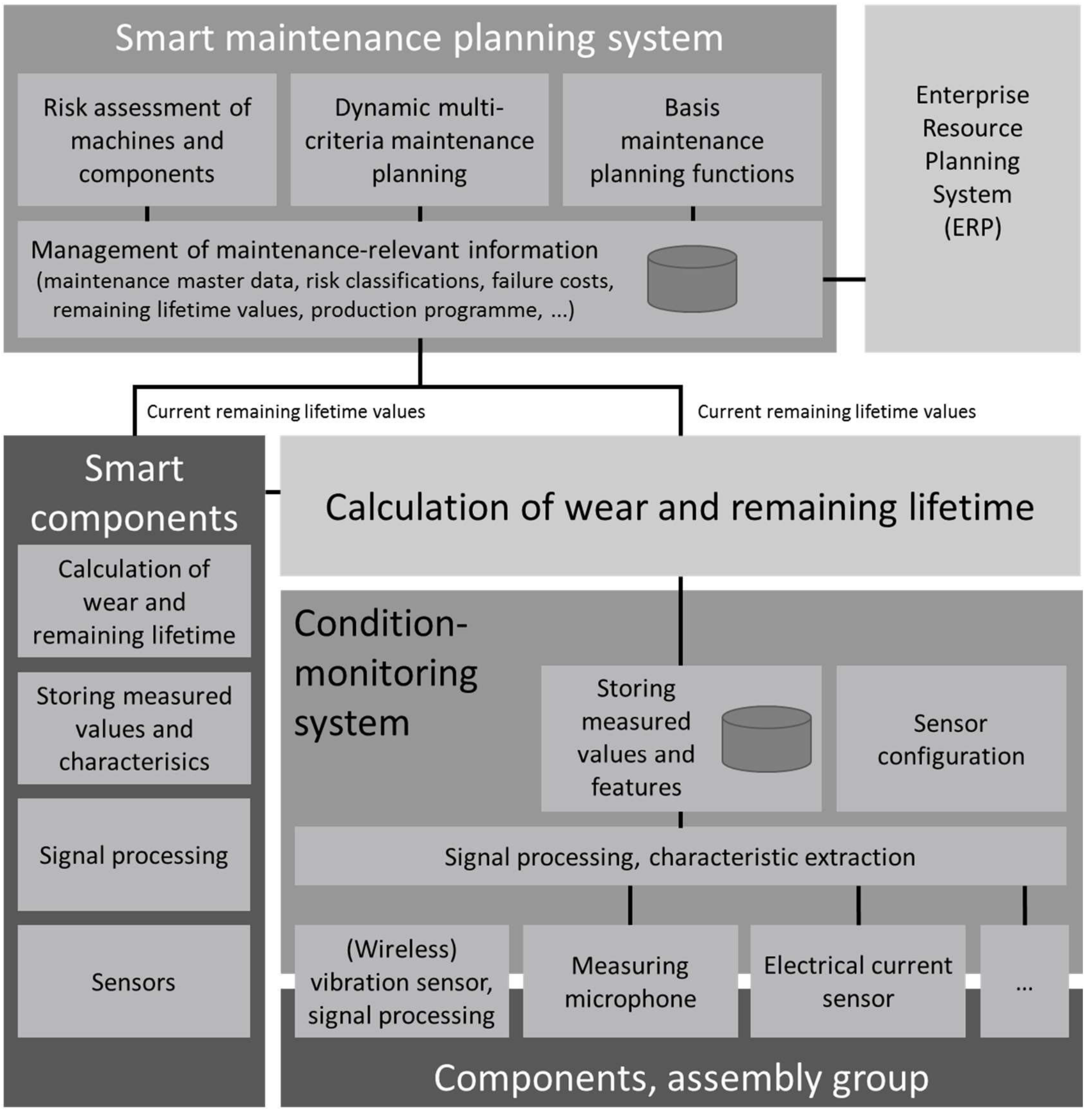


Figure 2-6:Architecture of a future maintenance planning system (Lucke et al., 2017, p. 83)

Another approach to a smart maintenance planning system is described below. The software solution offers predictive maintenance management that takes into account the current machine condition and the expected machine load from production planning. The software enables the holistic determination of the best possible maintenance plan for a maximized availability of the production system. The software consists of modular software tools that can solve multi-criteria, multi-layer decision problems. The objective is a need-synchronous, safe, and flexible optimization of maintenance and production by providing multidimensional optimized recommendations for maintenance measures (FIR e. V., 2015, p. 33).

The focus is on the smart objects libraries, which consist of several smart objects. These are so-called cyber-physical systems, which are explained in more detail in Section 2.2. The smart objects collect sensor data from machines and are responsible for a continuous exchange of information between the single software modules. These have a variety of functions such as identification, communication, and sensor technology. Furthermore, they are responsible for the software representation. The smart objects library has an interface to the advanced planning and scheduling system so that the smart objects can request maintenance measures independently. The maintenance priorities are assigned automatically and need- and production-optimised maintenance management is performed. The smart objects are responsible for the self-preservation of the production plant by interpreting and comparing their data with the plant data stored in the smart objects library (Mühlnickel et al., 2018, p. 356). According to the previous research of FIR e. V. (2015, p. 34), the following data sets for the smart objects library were identified as required:

- The slope of the wear curve for the component to be monitored.
- Influencing factors on the slope of the wear curve.
- Age and degree of wear of the monitored component.
- Limit values from which maintenance tasks are performed that are displayed, for example, with a traffic light function.

The smart objects not only communicate with each other but also interact with their environment, such as the maintenance staff. In the event of a predicted failure, the appropriate maintenance measures are displayed on a dashboard (Mühlnickel et al., 2018, p. 356).

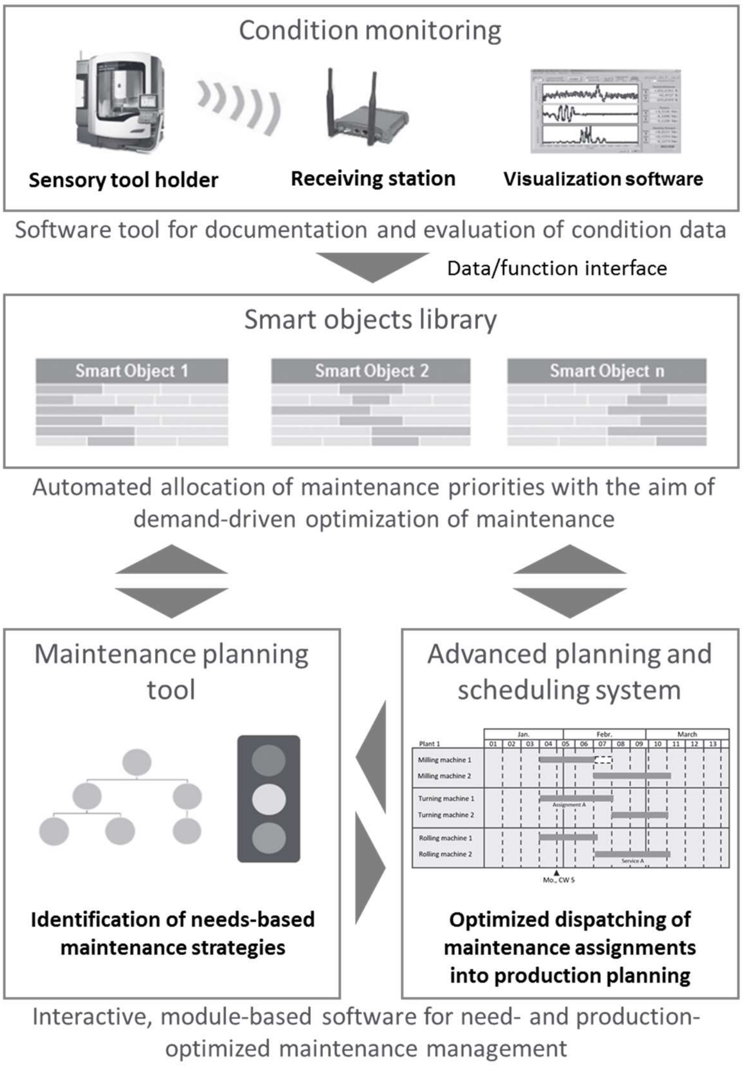


Figure 2-7: Scheme of the desired overall solution and the individual modules (FIR e. V., 2015, p. 33)

In the following, the general procedure for the implementation of a smart maintenance system is mentioned. The procedure concept of smart maintenance consists of a total of six steps (Kinz & Biedermann, 2016, p. 31):

1. Identification of critical parts in machinery and plants
2. Validation of condition monitoring technologies
3. Data analysis (machine data, production process data and product quality data)
4. Recognizing and evaluation of cause-effect relations
5. Methods of failure prognostics
6. An improved maintenance strategy mix

2.2 Structure of cyber-physical systems

The following section considers cyber-physical systems. First, cyber-physical systems are defined, followed by a classification of smart objects.

2.2.1 Definition of cyber-physical systems

Cyber-physical systems are the basis of the smart factory, which is the centre of Industry 4.0 (Bauernhansl, Hompel, & Vogel-Heuser, 2014, p. 15). Industry 4.0 means "[…] the intelligent networking of machines and processes in the industry with the help of information and communication technology."(Plattform Industrie 4.0/BMWi, 2019) According to a survey conducted in 2018, the strategic relevance of Industry 4.0 for 80 % of manufacturing companies in Germany is very important or rather important, see Figure 2-8.

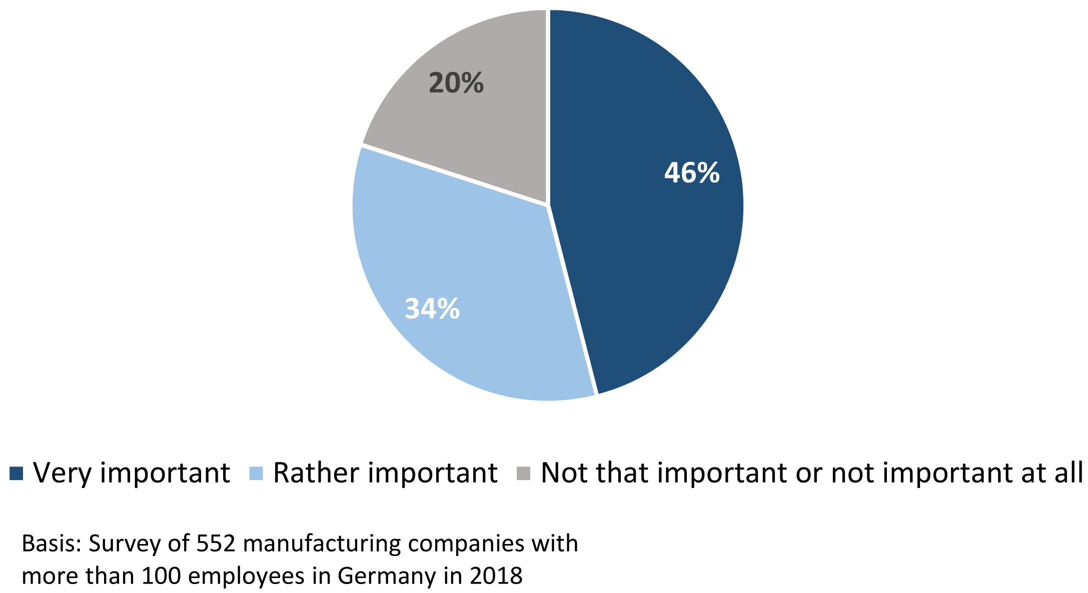


Figure 2-8: Strategic relevance of Industry 4.0 for manufacturing companies in Germany in 2018, based on Bitkom Research, Ernst & Young (2019, p. 8)

In the present literature, there are many different definitions of cyber-physical systems, but so far, there is no generally accepted definition. However, a definition is given below to ensure consistent use of technical terms and expressions. The definition is provided by the German Academy of Science and Engineering and states as follows:

"Cyber-physical systems are systems with embedded software […], which:

- *directly record physical data using sensors and affect physical processes using actuators;*

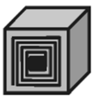
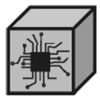
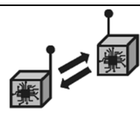
- *evaluate and save recorded data, and actively or re-actively interact both with the physical and digital world;*
- *are connected with one another and in global networks via digital communication facilities (wireless and/or wired, local and/or global);*
- *use globally available data and services;*
- *have a series of dedicated, multimodal human-machine interfaces."* (acatech, 2011, p. 13)

In the context of a smart factory, cyber-physical systems can be devices, objects, production plants, logistics components, etc., for example.

2.2.2 Classification of smart objects

Smart objects have a key function in smart maintenance systems due to their abilities. These can be evaluated and classified according to their degree of intelligence using the model developed by Reinhart et al., see Table 2-1. Intelligent objects can be divided into four categories, and each wins an ability with ascending class. Thus a cyber-physical system belongs to category 4 because of its abilities of identification, data storage, and data processing, as well as the possibility of interaction and communication.

Table 2-1: Levels of intelligent objects (Reinhart et al., 2013, p. 85)

	Intelligent Objects			
	Category 1	Category 2	Category 3	Category 4
				
Abilities	Identification	Identification	Identification	Identification
	-	Memory	Memory	Memory
	-	-	Intelligent data processing	Intelligent data processing
	-	-	-	Interaction/ Communication

2.3 Applications of UV lamps

The following section deals with various industrial applications of UV lamps, the UV lamp used in the 3D printer, and a detailed description of the printing process.

The UV radiation is short-wave radiation in the range of 100 nm - 380 nm. The radiation is divided into the following four ranges (DIN Deutsches Institut für Normung e. V.):

- VUV: 100 nm - 200 nm
- UVC: 200 nm - 280 nm
- UVB: 280 nm - 315 nm
- UVA: 315 nm - 380 nm

The VUV radiation is the vacuum-ultraviolet radiation that cannot spread in the air because it is absorbed by oxygen. The UVA radiation follows directly on the visible light. The energy content of electromagnetic waves is dependent on the wavelength. The shorter the wavelength, the higher is the energy level of the radiation.

The UV radiation is used with the help of UV lamps in various industrial applications. These can be divided into the following areas:

- Curing applications
- Disinfection applications
- Material testing

In the following, some applications from the individual areas are introduced. UV lamps are used in surface engineering for the curing of paints, varnishes and adhesives. The materials have been specially developed for curing. The UV radiation cures the UV paints, varnishes and adhesives in a few seconds. The UV curing process is a polymerization process in which photoinitiators are activated by intense UV light. Chemical compounds are first broken down and then crosslinked again to form new compounds. The crosslinked system is dry and abrasion-resistant in a fraction of a second. This has the advantage that it can be processed immediately. UV lamps doped with gallium or mercury are used as light sources. The emitted wavelength determines the place of hardening. While UVA radiation cures coatings on the surface, UVC radiation cures at depth. The following factors influence the curing process:

- Emission spectrum and intensity of the UV light source
- Characteristics and thickness of the material to be cured
- Process velocity
- Working distance between material and UV light source
- Carrier material and ambient temperature

UV light sources precisely matched to the process increase both reliability and throughput speed, reduce the load on the material, save costs and especially energy (Bopp & Henze, 2017, p. 58).

For instance, UV curing is used in the automotive industry to provide parts of a car with a protective coating or finishing. This makes the surface of varnishes particularly scratch-resistant (Bopp & Henze, 2017, p. 56).

Another area of application of UV lamps is in disinfection processes. This area can be divided into water, air and surface treatment. Industrial applications in the three areas are described below.

In water treatment, the UV radiation disinfects contaminated water used during an industrial process. A wavelength of 240 nm to 290 nm damages the genetic material of DNA and RNA of microorganisms such as bacteria, viruses, parasites or fungi. As a result, the cells can no longer multiply. To ensure safe disinfection, irradiation of at least 400 J/m^2 is necessary. A UV disinfection device is used, which consists of an irradiation chamber through which the water to be disinfected flows. In the irradiation chamber, several quartz tubes are used, which are equipped with UV lamps. UV irradiation of water does not produce any disinfection by-products. No chemicals such as chlorine dioxide or ozone are required to treat the water. This means, among other things, that there is no unpleasant smell or taste (Baur et al., 2019, p. 358). For instance, the UV disinfection device is used for process water of the aquacultures, agricultures, chemical and pharmaceutical industries but also for ballast water of the shipping industry. In this case, an international convention stipulates that released ballast water must be disinfected in order not to endanger the ecological balance through inverse species (International Maritime Organization, 2019, p. 1).

In the air treatment, UV lamps are used for the disinfection of air. In addition to cleaning the air, the odour of the exhaust air is also eliminated. Low pressure and medium pressure mercury vapour lamps are mainly used for this application. The disinfection is performed with UVC radiation. In a reaction chamber, there are the UV lamps where the exhaust air is led through. The UV radiation leads to the total or partial degradation of organic compounds. (DIN Deutsches Institut für Normung e. V., 2016, 8-10).

The last application of UV lamps in disinfection is surface treatment. For instance, the surfaces of food packaging are disinfected. The intense UV light destroys food spoilage germs on the packaging. Uv lamps are also used in the packaging of pharmaceuticals and medical devices. UVC radiation is also used for this disinfection process.

UV lamps are also used in material tests of e.g. of coatings and plastics. Instead of testing the coatings and plastics in long-term outdoor weathering tests, devices were developed in which test influences have a homogeneous and consistent effect on the samples. In these short weatherings, the effects of light and water are optimized in such a way that the chemical degradation reactions occur more rapidly. The ageing behaviour is shown by the change of the coating properties. In addition to rain and dew, the influences of sunlight are simulated by means of UV lamps. The UV lamps produce visible, infrared and primarily ultraviolet light in the UVA and UVB spectrum (Pietschmann, 2019, pp. 353–354).

2.3.1 UV lamp

In the following section, the characteristics of the UV lamp are mentioned, which is used in the Stratasys Objet500 Connex3. The influencing factors for the wear of the lifetime of UV lamps are presented. In addition, an already existing lifetime model of UV lamps is shown. Finally, a comparison is made between the properties of UV lamps and UV LEDs.Figure 2-9 shows the UV lamp used in the 3D printer. It is a gas discharge lamp based on an electrical discharge in gas and vapour. The discharge is achieved by ionising mercury vapour and the noble gas krypton (Jüstel & Schwung, 2019, p. 73). Ignition takes place through the two tungsten electrodes, which serve as cathode and anode. The discharge vessel of the lamp is made of quartz glass, which is permeable to UV light. The lamp has a length of 65 mm and a diameter of 15 mm. The arc length is 24 mm. The two bases of the UV lamp are mounted in an Rx7S socket.

Figure 2-9: UV lamp used in the Stratasys Objet500 Connex3

The nominal voltage is 125 V, and the nominal power amounts 250 W. The spectral range of the lamp is between 300 nm and 450 nm and therefore lies in the UVA as well as in the UVB spectrum, see Figure 2-10. The power density of the generated radiation is 104 W/cm^2. In comparison, the average annual irradiance on the earth's surface is 1,413 W/m^2 – 1,321 W/m^2 (Jüstel & Schwung, 2019, p. 166). The manufacturer specifies the lifetime as 600 hours at which the lamp has its functionality (Lamp Express, 2019). Figure 2-10 shows the spectral power distribution of the UV lamp used in the Stratasys 3D printer. The present UV lamp is doped with iron to adjust the spectral power distribution to the application (Jüstel & Schwung, 2019, p. 43).

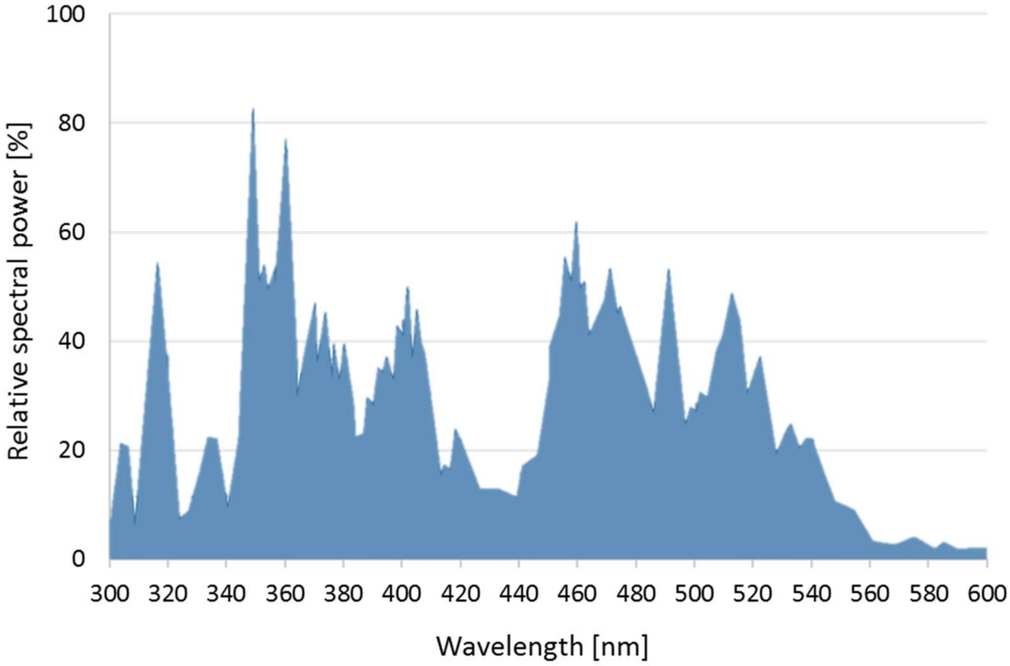


Figure 2-10: Spectral power distribution of the UV lamp (Lamp Express, 2019)

The product data sheet of the manufacturer does not provide a lifetime model of the UV lamp, which is required in particular for the development of a smart maintenance system. Also, intensive research and an inquiry addressed to the manufacturer remained without result. The literature review of lifetime models for other UV lamps also proved to be difficult. Only the lifetime model of uv-technik meyer GmbH has proven to be suitable, see Figure 2-11. The lifetime model shows a UV lamp with mercury spectrum, which has a life time of 1500 hours as specified by the manufacturer.

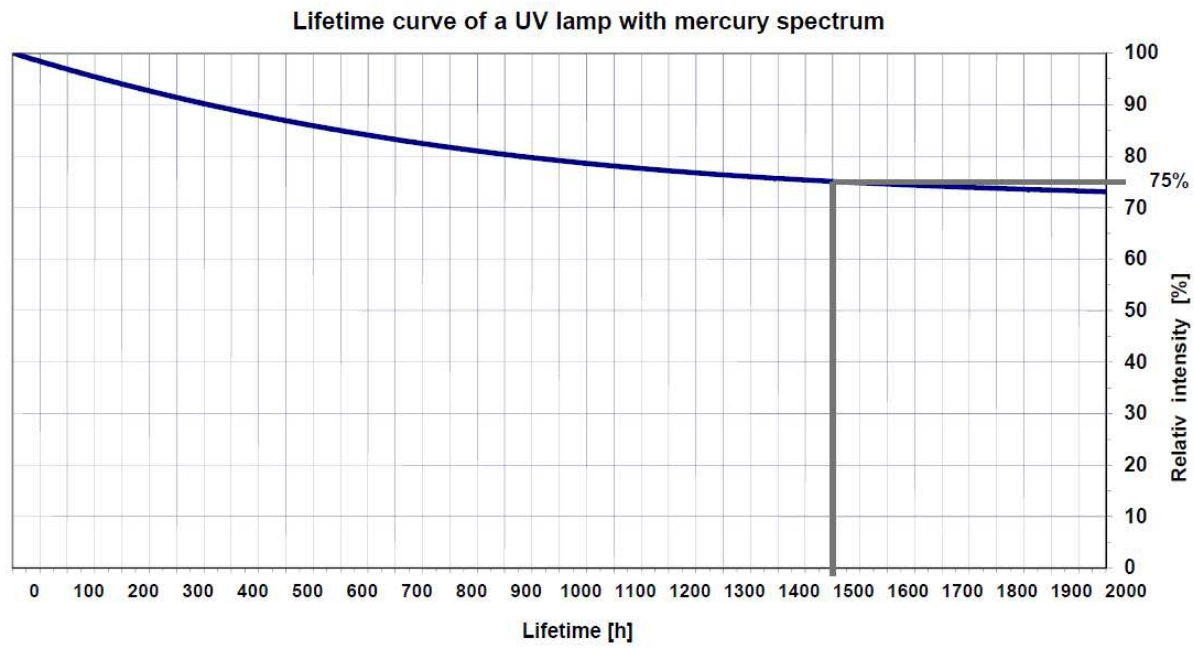


Figure 2-11: Lifetime diagram of a UV lamp with mercury spectrum (uv-technik meyer GmbH, 2019b, p. 8)

The emitted UV radiation of a UV lamp decreases with increasing operating time due to physical effects. As soon as 75 % of the initial UV intensity is measured, the useful lifetime is exhausted. The lamp can still be operated, but it can no longer be used for curing. The lifetime of the UV lamp is stated under the premise that a maximum of three starts per day are permitted. Each additional switching on and off of the UV lamp leads to a reduction of the lifetime by 0.5 hours (uv-technik meyer GmbH, 2019b, p. 8). Furthermore, UV lamps have to be cooled, because the glass temperature is about 600 °C – 900 °C and from temperatures above 1000 °C the quartz softens and the UV lamp inflates or bends. For optimum cooling, an air volume of 100 m^3/h applies per kW UV lamp output. In addition, the resulting hot air cushions are aspirated above the UV lamp (uv-technik meyer GmbH, 2019a, p. 15). In highly accelerating lifetime tests with discharge lamps, the vibration experienced by the lamp is considered as vibration has an influence on the liftime (Illuminating Engineering Society of North America, 2000, p. 70).

In the following the factors are summarised, which lead to the wear of UV lamps:

- Burning time
- Switching on and off
- Increased temperature
- Vibrations during operation

The literature research revealed that UV light can also be produced with other light sources. Table 2-2 shows the differences between the properties of UV lamps and UV LEDs.

Table 2-2: Comparison of the properties of UV lamps and UV LEDs, own representation based on Burger (2011, p. 40)

Property	UV lamp	UV LED
Technique	Gas discharge	Electro luminescence
Wavelength [nm]	Spectral range between 200 - 500	Spectral range between 365 - 405
Spectral distribution	Wide	Small
Thermal radiation	Yes	No
Efficiency	Up to 40 %	Up to 50 %
Energy consumption	High	Low
Operation	Warm-up phase necessary Standby mode (15-40%) Reflector required	No warm-up phase Immediate switching on and off No reflector required
Cooling	Air or water	Water (rarely air)
Lifetime	Up to 12,000 h	Up to 50,000 h
Investment costs	Low	High

In summary, it can be said that the UV lamps cover a broad emission spectrum, whereas the UV LEDs only cover individual wavelengths. So far, there are only a few materials that can be used for UV LEDs, as they first have to be optimized for the new light source and adapted to the LED emission spectrum. In contrast, there are a large number of materials that can be used for UV lamps (Starzmann, 2016, pp. 29–30).

2.3.2 Printing process

The component that is the subject of this study is a UV lamp, which is used in the printing process of the 3D printer Stratasys Objet500 Connex3, see Figure 2-12. This process is explained in more detail in this section. First, additive manufacturing is introduced in general. Afterwards, the complete additive manufacturing process of a component using the Stratasys Objet500 Connex3 is explained.

Figure 2-12: Stratasys Objet500 Connex3 (Stratasys, 2018a, p. 1)

In additive manufacturing, different technologies are used to produce objects using sequential layering. It is a layer-based automated manufacturing process for the creation of scaled three-dimensional physical objects. The objects are created directly from CAD data without the need for part-dependent tools (ASTM International, 2015, pp. 1–3). In addition to the subtractive manufacturing process, such as milling or turning, and the formative manufacturing process, such as casting or forging, the additive manufacturing process is the third process in manufacturing technology (Burns, 1993).

In contrast to the other two types of manufacturing, the material properties of an additive component are only partly determined by the raw material. A part receives its features in the course of the manufacturing process, which consists of the material, the construction process, and the design. The primary raw materials are plastics, metals, resins, sandstones, ceramics, or waxes, which are processed as filament, powder, liquid, or foil (Gebhardt, Kessler, & Thurn, 2016, p. 172).

The additive manufactured objects are used over the entire product life cycle. In pre-production, additive manufacturing can be applied for the production of samples and prototypes. This is called rapid prototyping because the development from the product idea to the product is shortened. In comparison to the traditional process, no tools need to be engineered and manufactured, or attention has to be paid to batch sizes of individualised products. The produced prototype enables an evaluation of the product properties (Gebhardt, 2016). Furthermore, tools and tool inserts for the production of components can be developed with additive manufacturing. Rapid tooling enables fast production of tools that can be highly complex, such as internal cavities for contour-adapted cooling (Gebhardt, 2016, pp. 411–415). In small series and serial production, additive manufacturing is used for the direct production of (end) products and tools suitable for series production. This process is called rapid manufacturing, and the products manufactured have all the characteristics of marketable products. In the later part of the product life cycle, additive manufacturing can be applied for the repair or maintenance of worn-out components. This process, in which spare parts are loaded from databases and manufactured on demand, is called rapid repair (Gebhardt, 2016, p. 473).

The following explains the process chain of the manufacturing process of a component with the Stratasys Objet500 Connex3:

1. CAD data generation: The basis for the production of a physical component are computer data, which describes the 3D volume entirely and error-free. As a rule, the data comes from 3D CAD designs, which are created with CAD tools but can also come from a coordinate-measuring machine, for example (Gebhardt, 2016, p. 24). The Objet 500, among others, supports the file formats STL, SCL, and VRML (Stratasys, 2018b, p. 22).
2. Data processing: As a first step, the 3D dataset is fragmented into slices or layers using a computer and specialized software (Gebhardt et al., 2016, p. 9). This procedure is described in more detail using the STL file format. This format represents the model surfaces by triangle facets, whereby triangles approximate curved geometries such as radii of spheres (Kumke, 2018, p. 10). With the Objet500, it is possible to choose a component resolution of 30 or 15-micron layers (Stratasys, 2018b, pp. 88–89). In the STL file format, this is reflected in the size of the triangles. The next step is to determine the position and orientation of the component in the 3D printer. Besides, the software calculates the required support structure, which connects the component to the building platform, stabilizes it during the building process and additionally conducts heat. Finally, the component is cut into layers during so-called slicing and information is defined for each layer for its creation (Kumke, 2018, pp. 10–11). This information

consists, for example, of the contour data, the layer thickness, and the layer number (Gebhardt et al., 2016, p. 9).

3. Construction process: The additive manufacturing process of the Objet 500 is named polymer printing or poly-jet modelling. The design of the printing unit is shown in Figure 2-13 below. The patented process can be considered as a 3D printing process, but it is a polymerization or stereolithography process due to the production of components by UV curing of the printing material, which consists of liquid monomers (Gebhardt et al., 2016, pp. 45–46). The photosensitive printing material is a resin that is applied to the building platform via four nozzles piezoelectric print head. The printing material is cured by two high-performance UV lamps which move synchronously with the print head and are continuously switched on (Gebhardt et al., 2016, p. 45). As a result, the liquid monomers combine to form long molecule chains through the action of UV light. The resulting polymers form a stable network and are firmly bonded together. As soon as a layer is cured, the building platform lowers in the z-axis and a new layer is applied (Fastermann, 2016, p. 18). In addition to the printing material, the support material is also applied to each layer, which is automatically generated and simultaneously applied from a second nozzle set (Gebhardt et al., 2016, p. 45). The optimum processing temperature of the resin is approximately 25 to 30 °C, as the material has a favourable flow behaviour in this range (Gebhardt, 2016, p. 51). The quality of the printed object, the speed of the printing process as well as the print material or materials are determined in advance. The first step is to select the printing material or materials that have various properties such as shore hardnesses or different colours. In the next step, the print mode can be chosen from the following three modes:

    - High-quality mode
    - High-speed mode
    - Digital material mode

   In the high-quality mode, the component is manufactured in 16-micrometre layers. This print mode is suitable for the production of detailed and delicate parts with a smooth surface. With this setting, the material is output from the four print heads. On the one hand, the same material can be provided from all four print heads, on the other hand, two different materials can be supplied from two print heads each, which results in an arbitrary mixture. These two processes are termed single material printing. The printing time required for most components in this print mode is twice as long as in high-speed mode. In high-speed mode, the objects are produced in 30-micrometre layers. It is suitable for making larger objects because it takes less time than the previous mode. The third mode is the digital material mode and is used when objects are created from two or more materials such as a wheel consisting of a hard plastic rim and an elastic tyre. This mode is also used when one or more objects are printed simultaneously with different materials. The individual layer thickness is 30 micrometre, but the print quality is nearly the same as high quality (Stratasys, 2018b, pp. 88–89).

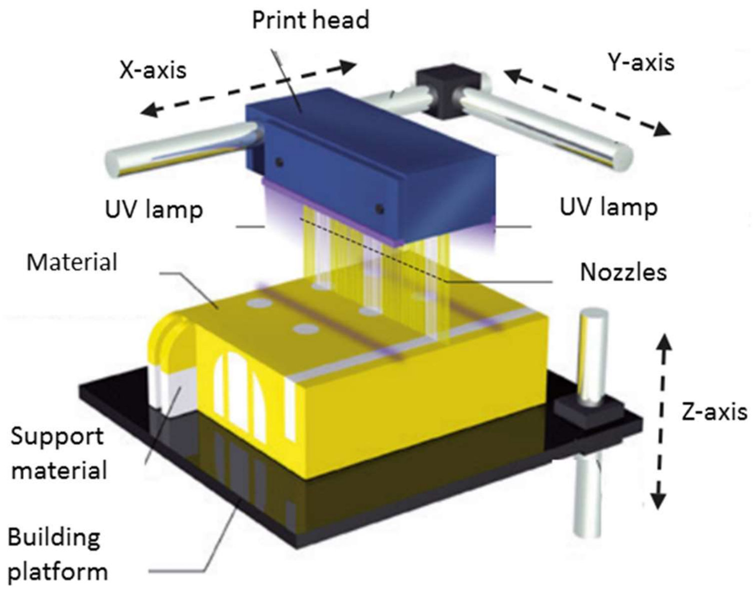


Figure 2-13: Design of the printing unit (Stratasys, 2018a)

4. Post-processing and finishing: In this step, the objects produced are processed to improve the physical properties such as surface quality and haptic (Verein Deutscher Ingenieure e. V., 2014, p. 22). The first step is to remove the support material after the printed objects have cooled down. Different methods can be used, depending on the support material, the size of the object, how delicate it is as well as the amount and location of the support material. The Objet500 uses two different support materials. Depending on the support material, it can be removed with water and a caustic soda solution or with water and a mixture of caustic soda solution and a sodium metasilicate solution. Depending on the nature of the object, for example, a brush or high-pressure water jet can be used (Stratasys, 2018b, pp. 205–206). Additionally, the printed objects can be coated, for example with a varnish or galvanization (Verein Deutscher Ingenieure e. V., 2014, p. 10).

2.4 Literature summary

The purpose of the literature review is to serve an overview of the definition and structure of smart maintenance to provide a scientific basis for the development of a smart maintenance system for UV lamps. Next follows the definition and classification of cyber-physical systems, which are a key role in the implementation of smart maintenance systems. UV lamps are used in many different industrial applications and are the core elements of the respective processes. The lamps installed in the 3D printer also play a decisive role in the present additive manufacturing process of objects. However, despite the importance of UV lamps in industrial processes, there is still no established system that monitors and predicts the condition of UV lamps. The starting point for the development of the smart maintenance system is the factors influencing the lifetime of the UV lamp as well as the factors of the UV lamp that are responsible for the result of the curing process.

Chapter 3
Projects in adjacent research areas

The chapter gives an overview of research approaches and established applications that belong to the adjacent research area of smart maintenance.

3.1 Reference architecture of IoT platforms

This chapter deals with the architecture of IoT platforms and provides a uniform abstract terminology. The research work serves as a basis for the implementation of the smart maintenance system.

Figure 3-1 illustrates the different components for an IoT application, but not all of them are necessary. For instance, an actuator is not required if the system only needs to measure the temperature. The sensor measures parameters such as temperature or acceleration and processes them into an electrical signal. Actuators are the counterpart of sensors and convert electrical signals in mechanical movement or physical quantities such as stepper motors.

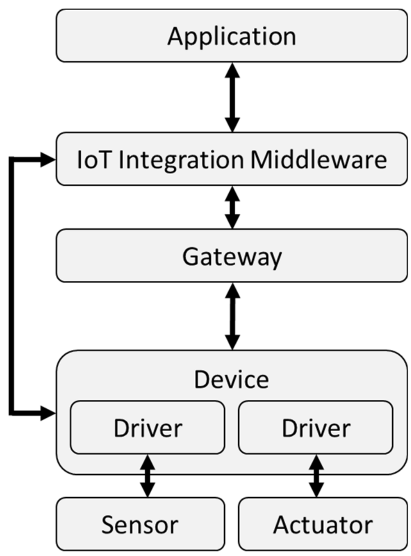


Figure 3-1: IoT reference architecture (Guth, Breitenbücher, Falkenthal, Leymann, & Reinfurt, 2016, p. 2)

The sensors and actuators are connected with a device by wire, wirelessly or are even integrated. For instance, Raspberry Pi's are used to which the gathered data of the sensor is sent or from which input data are sent to the actuator. On the one hand, drivers must be integrated on the device to access the sensors and actuators; on the other hand, further software is required to initialise, readout or send values. The device forms the interface between the physical and digital worlds.

The gateway enables communication between the device and further systems. It is required if the device cannot communicate via a particular protocol or is limited in technical features. The gateway can process the data through the use of technologies and functionalities to ensure compatibility (Guth et al., 2016, pp. 2–3).

The IoT integration middleware enables the receipt of data from the device, the processing and the provision of data to an application as well as the control of the device. A direct communication with a device and the IoT integration middleware is possible if the device meets the following requirements. The device supports communication technologies such as WiFi, a transport protocol such as MQTT or HTTP and a payload format, such as JSON or XML. If the requirements do not apply, the device must communicate with the IoT integration middleware via the gateway. The IoT integration middleware fulfils all functionalities required for the implementation of a cyber-physical system. The application is the software that uses the IoT integration middleware to query sensor data or control actuators (Guth et al., 2018, p. 85).

3.2 BCAP Bilfinger Connected Asset Performance

The Bilfinger Connected Asset Performance is a modular digitalisation solution for the process industry. The goal is to optimise and reduce the operating costs of process plants, especially for small and medium-sized enterprises.

Figure 3-2 shows the individual phases of the digitalisation procedure in the process industry (Bilfinger SE, 2019). The core of the solution is the IoT cloud, which provides data from engineering, operations, maintenance and external data. This includes data from sensors that continuously record the status of individual components. By processing and analysing the data, information can be obtained for the control and operation of the plant. The information is displayed context-based on a dashboard or in reports. Among other things, potential faults can be predicted and suitable maintenance measures can be initiated. As a result, unplanned maintenance can be reduced and the overall asset efficiency (Bilfinger Digital Next GmbH, 2019).

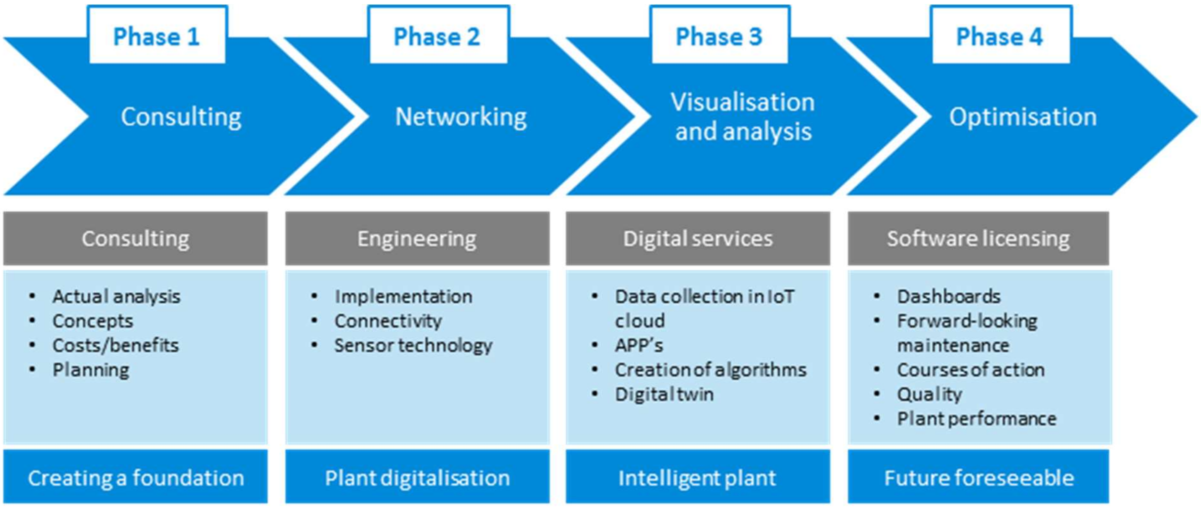


Figure 3-2: Procedure for the digitalisation of the process industry (Bilfinger SE, 2019)

3.3 ActiveCockpit of Bosch Rexroth AG

The ActiveCockpit is an interactive communication platform for the manufacturing industry. The objective is to quickly provide the user with complete information to enable optimal fault and deviation management. The ActiveCockpit continuously captures, processes and filters manufacturing data from existing system landscapes and other data sources. The information is displayed on interactive touch screens in the assembly line. All relevant quality and production key figures such as availability, production times and quantities are displayed in real-time. The system can be used interactively for decision-making processes by, e.g. upload, escalation and email functions (Bosch Rexroth AG, 2019).

Figure 3-3 shows the system architecture and functions of the ActiveCockpit. The software is installed on the customer's server without changing the existing IT infrastructure. The system can be used for several production lines and plants. Each dashboard can be configured individually. Different file formats can be displayed digitally via the desk link. The industry 4.0 interface provides a real-time connection to the ERP system, MES or other databases. In addition, self-developed applications can also be integrated. Data security is ensured by encryption of data as well as a role and authorisation principle.

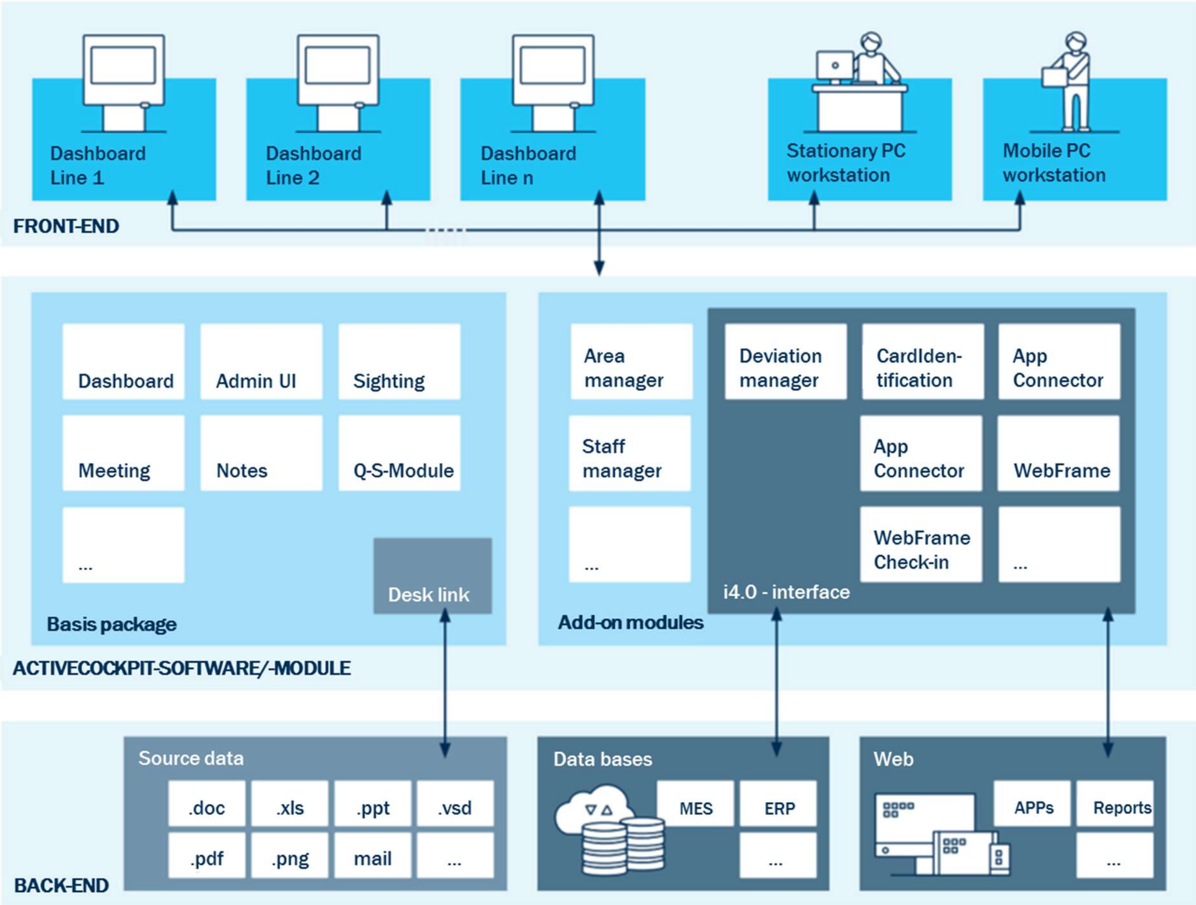


Figure 3-3: System architecture and functions of the ActiveCockpit (Bosch Rexroth AG, 2019)

3.4 Chapter summary

The chapter aims to provide insights into research approaches and established applications, which are in the area of smart maintenance. First, the scientific work for the reference architecture of IoT platforms is presented, which is used as a basis for architecture and the selection of components of the smart maintenance system. Applications already implemented in the area of smart maintenance are considered. The individual phases for the approach to digitalising industrial processes defined by Bilfinger can be used in part as a guideline for the development of the smart maintenance system. The ActiveCockpit of Bosch Rexroth AG displays information to enable fault and deviation management in the production process. Individual implementations can also be taken into account when providing information on the smart maintenance system for UV lamps.

Chapter 4
Concept of the system

The chapter introduces the concept of the smart maintenance system. First, the requirements of the system are defined and explained, which is followed by the functional model. Finally, the hardware and software are selected to develop the smart maintenance system as a demonstrator whose functionality can be validated.

4.1 Requirements

The requirements for the smart maintenance system are based on the findings of the literature review and the projects in adjacent research areas. All requirements are designed to ensure that the operating condition of the UV lamp is preserved using the smart maintenance system.
Table 4-1 defines the requirements of the smart maintenance system and prioritises them into 'must' and 'wish' targets. The 'must' targets are essential for successful implementation and without them, the implementation is considered failed. The 'wish' targets are regarded as desired targets and are not essential for the implementation success.

Table 4-1: Requirements for the smart maintenance system

Requirements			Target type	
			Must	Wish
1. Data collection	Relative UV intensity [%]	UV intensity of the UV lamp in UVA spectrum	X	
		UV intensity of the UV lamp in UVA spectrum	X	
	Temperature (0° C – 120 °C)	Temperature next to the UV lamp	X	
		External temperature	X	
		The temperature at the building platform		X
		An additional sensor in the printing chamber		X
	Accelerometer (-15 m/s^2 – +15 m/s^2)	Movement of the lamp in the x-axis	X	
		Movement of the lamp in the y-axis	X	

Requirements				Target type	
				Must	Wish
		Movement of the lamp in the z-axis		X	
	Power measurement	Voltage (0 V – 250 V)		X	
		Current (0 A – 10 A)		X	
		Frequency (49 Hz –51 Hz)		X	
		Effective power (0 W – 3000 W)			X
		Energy consumption (0 kWh – 3 kWh)			X
2. Data processing	Complete			X	
	Transfer interval [s]	Temperature values	2	X	
		Accelerometer values	2	X	
		UV intensity values	2	X	
		Power measurement values	2	X	
3. Data analysing and categorising	Temperature values			X	
	UV intensity values			X	
	Calculation of remaining useful lifetime of the UV lamp based on manufacturer specifications			X	
	Counting of the turn-on frequency of the UV lamp			X	
4. Data visualisation	Measured values			X	
	Analysed and categorised values			X	
	Context-related maintenance measures for categorised temperature values, UV intensity values and remaining lifetime			X	
	Notification function for categorised temperature values, UV intensity values and remaining lifetime by email or SMS			X	
	Availability of historical values			X	
5. Data access and security	Access by PC, smartphone and tablet			X	
	Location-independent			X	

Requirements		Target type	
		Must	Wish
	Authorised	X	
	Encrypted data transfer	X	
6. Modular expandability	Software: Integration of IT systems such as ERP-systems, production planning systems or advanced planning		X
	Hardware: Integration of additional sensors and actors		X
7. Setup of the final system	System retrofittability within one hour		X
8. Cost of the system	As cost-effective as possible: < 1000 Euro or 16,000 Rand		X
9. Safety of the system	No potential danger from the system for humans or the environment	X	

The first part of the defined requirements contains the data collection. The measurement of the UV intensity in the UVA and UVB spectrum is a ‘must’ target since a 75 percent UV intensity is decisive for curing of the printing material. The initial values of the UV intensity in the UVA and UVB spectrum are used as reference values. All subsequent measured values are set in relation to the initial values. The relative UV intensity is used since the measured UV intensity in the respective spectrum depends on the distance between the UV lamp and sensor. The closer the sensor is to the UV lamp, the greater the UV intensity measured.

The temperature sensors are mounted at different locations. The sensors used must have a measuring range of 0 °C to 120°C and an accuracy of 0.5 °C. A temperature sensor must be installed in the immediate vicinity of the UV lamp, as the ambient temperature of the lamp must not rise above 65 °C and overheating influences on the lifetime, as described in Section 2.3.1. A further sensor must measure the temperature outside the pressure chamber to obtain a reference value for the permitted operating temperature of the 3D printer. The temperature measurement at the hight of building platform would be desirable, as a given process temperature must prevail, as described in Section 2.3.2. However, the temperature at the printing platform does not influence on the lifetime of the UV lamp, so this sensor is prioritised as a ‘wish’ target. An additional temperature sensor placed in the upper part of the printing chamber serves as an additional reference value and is declared a ‘wish’ target. An acceleration sensor is required which records the acceleration in x-, y- and z-axis since the vibration influences on the lifetime of the UV lamp. Another requirement that must be met is the measurement of voltage and current, as it is checked whether conclusions can be drawn about the wear of the UV lamp. The implementation is defined as a 'must' target. A 'wish' target is the recording of effective power since this can also be calculated from the product of voltage and current. In addition, energy consumption is also defined as a 'can' target, since it does not influence the service life of the UV lamp. However, it can be advantageous to know the power consumption and therefore, the operating costs of the UV lamp. Another requirement that must be met is the measurement of voltage and current, as it is checked whether conclusions can be drawn about the wear of the UV lamp.

After it has been clarified which measurements are to be collected, the requirements for data processing are described. The data processing of the measured values must be complete in order to have a reliable data basis. The length of the transfer interval of a sensor must be selected so that a meaningful statement can be made with changing input values. The temperature sensors must record new measured values every two seconds. The interval is considered suitable because temperature values do not rise or fall so quickly. The situation is different with the accelerometer, where a transfer interval of 0.1 s must be ensured since the acceleration values can change at shorter intervals. The UV intensity in the UVA and UVB spectrum must be detected every two seconds. The measurement interval is considered appropriate, as a sudden loss of UV intensity is not to be expected, as the manufacturer declares the lifetime of the lamp to be 600 hours and thus also a sufficient intensity for complete curing is associated.

The next step is to define the requirements for data analysis and categorisation. Measurands are analysed and categorised if measurement ranges are known that are considered critical or rejected by the printer manufacturer, lamp manufacturer or literature. In addition, the lifetime of components guaranteed by the manufacturer is used to calculate and categorise the remaining lifetime based on the lifetime already used. All measured values of the individual temperature sensors must be analysed and categorised into a range to be accepted, critical and rejected. The UV intensity values must also be analysed and categorised into the ranges mentioned. The remaining useful lifetime of the UV lamp is calculated by subtracting the used lifetime from the lifetime specified by the manufacturer. The resulting lifetime must then be categorised into an acceptable, critical and rejectable range. Besides, a function must be set up, which counts the turn-on frequency of the UV lamp as they influence the lifetime of the UV lamp.

The requirements for data visualisation described in the following are all classified as must ‘targets’. All currently measured values, as well as a meaningful amount of historical values, must be displayed in a dashboard according to measurands. The aim is to provide the maintenance staff with an overview of the current status of the UV lamp. The analysed and categorised values must also be presented in the dashboard. They must be displayed at an immediately recognisable position and must be highlighted in colour when critical or rejected ranges are reached. The maintenance staff is thus informed ahead of time that a measured variable is in the critical range so that measures can be taken to ensure that the range to be rejected is not reached. In addition to the information that a value is in the critical or rejected range, a context-based maintenance measure must be submitted to restore the operational condition. Improved user guidance reduces search times for the right information. Furthermore, a function must be set up that notifies the maintenance staff by email and SMS when a critical or rejected value is reached. For instance, the appropriate section of the user manual with the relevant maintenance measure can be attached to the email. All collected values of the measurands must be stored and always available in a database. The aim is to provide values over the entire lifetime of the UV lamp to conclude possible causes of failure.

Further requirements that must all be met refer to the area of data access and security. Access to the smart maintenance system must be possible via a PC or mobile devices such as smartphones or tablets. For instance, this allows the maintenance staff to access to the dashboard not only at fixed workspaces but also mobile at the machine on site. It must be possible to access the data from any location. This means that not only maintenance staff on-site can access the data, but also manufacturers or experts who can help with their specialist knowledge if problems arise. However, this implementation must ensure that only authorised persons can access the smart maintenance system. Data security must be guaranteed as well, by encrypting data transfer.

The ‘can’ target is defined as the expandability at the software level. It would be desirable if the smart maintenance system could be modularly expandable so that IT systems could be flexibly integrated and adapted to new applications. An example is an integration of an ERP system or a maintenance planning module. At the hardware level, it should be possible to integrate additional sensors and actuators. This requirement is a 'wish' target since all required sensors are already integrated.

The next requirement refers to the completed system. It is desirable if the system can be retrofitted within one hour. This means that the components used can be integrated into the 3D printer without changing the original function of the printer. Another requirement of the system is that it must be as cost-effective as possible. The 'wish' target is 1000 € and 1600 R, respectively. This should enable an economic integration of the system into the printing process.

The last requirement for the system is that there is no potential hazard to humans or the environment.

4.2 Functional model

The chapter defines the functions of the smart maintenance system and describes the functional dependencies between the subfunctions. The functional model is based on the system architecture of the smart maintenance systems described in subsection 2.1.2 and is aligned with the reference architecture of IoT platforms introduced in subsection 3.1. The functionalities of the model are geared to the previously defined requirements.

4.2.1 Sensors and actuator

The subsection describes the functionalities of the required sensors and actuator, see Figure 4-1. The temperature sensors, acceleration sensor, UV sensor and the electrical power measurement captures information about the current state of the UV lamp. The measurements are carried out automatically and at time intervals, which are defined in the requirements section. The actuator receives commands from the device, which are executed in physical action.

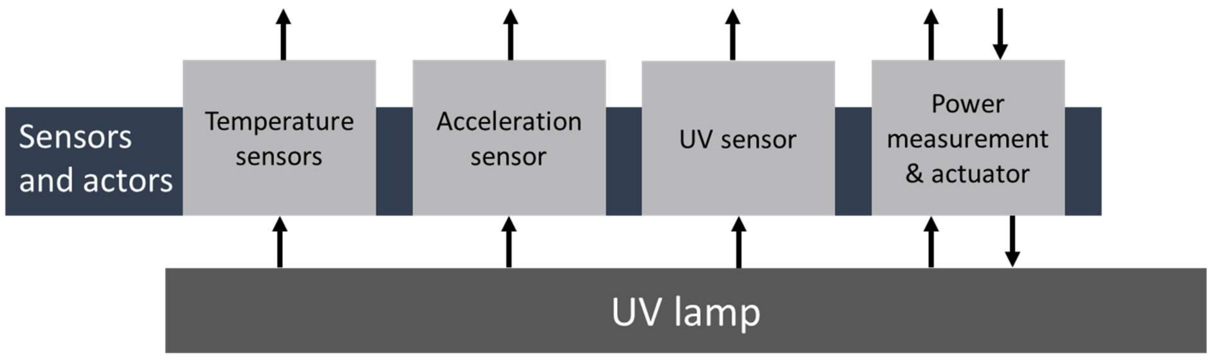


Figure 4-1: Functional model of the sensors and actuator

4.2.2 Condition monitoring system

The condition monitoring system is connected to the sensors and the actuator. In the present case, the device forms the condition monitoring system and aims to monitor the condition of the UV lamp and can intervene if required by the actuator, see Figure 4-2. Driver software integrated on the device allows uniform access to the different sensors. The source code also integrated on the device controls, initialises and measures the sensor values in prescribed time intervals. The data transfer between the device and the temperature, acceleration as well as the UV sensor takes place via a bus which is implemented with cables. Whereas the data transfer between the device and the power measurement as well as the actuator is carried out by radio. The device has communication technologies like IP over Ethernet or WiFi, a transport protocol like HTTP or MQTT and has a compatible payload format, which means that no gateway is needed for communication. The measured values are temporarily stored for a short time on the device and then sent to the IoT platform via a transport protocol.

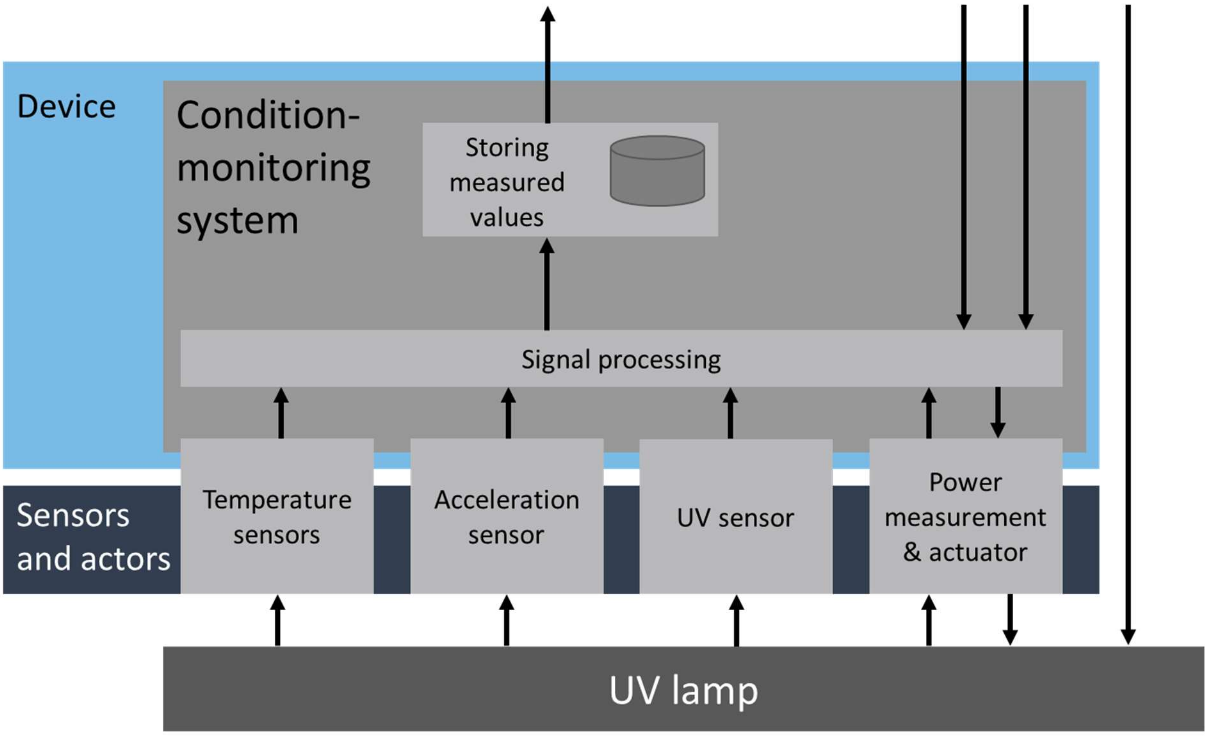


Figure 4-2: Functional model of the device

4.2.3 Smart maintenance planning

Smart maintenance planning is implemented on an IoT platform, see Figure 4-3. The IoT platform receives the protocol with all measured values sent by the device, adds a timestamp and stores it in a database. The individual measured values of the sensors are clearly displayed in diagrams in the dashboard of the IoT platform. The live values are presented here, but values from the past can also be viewed. Furthermore, the remaining useful lifetime of the UV lamp is stated as well as on and off switching operations. As a result, the maintenance staff can get an overview of the live status of the UV lamp and at the same time has information about the UV lamp during the currently running printing process as well as about past printing processes.

The following describes how the values of the measurands defined in the requirements are visualised in the dashboard. Also, the procedure of the values of the measurands to be analysed and categorised is explained.

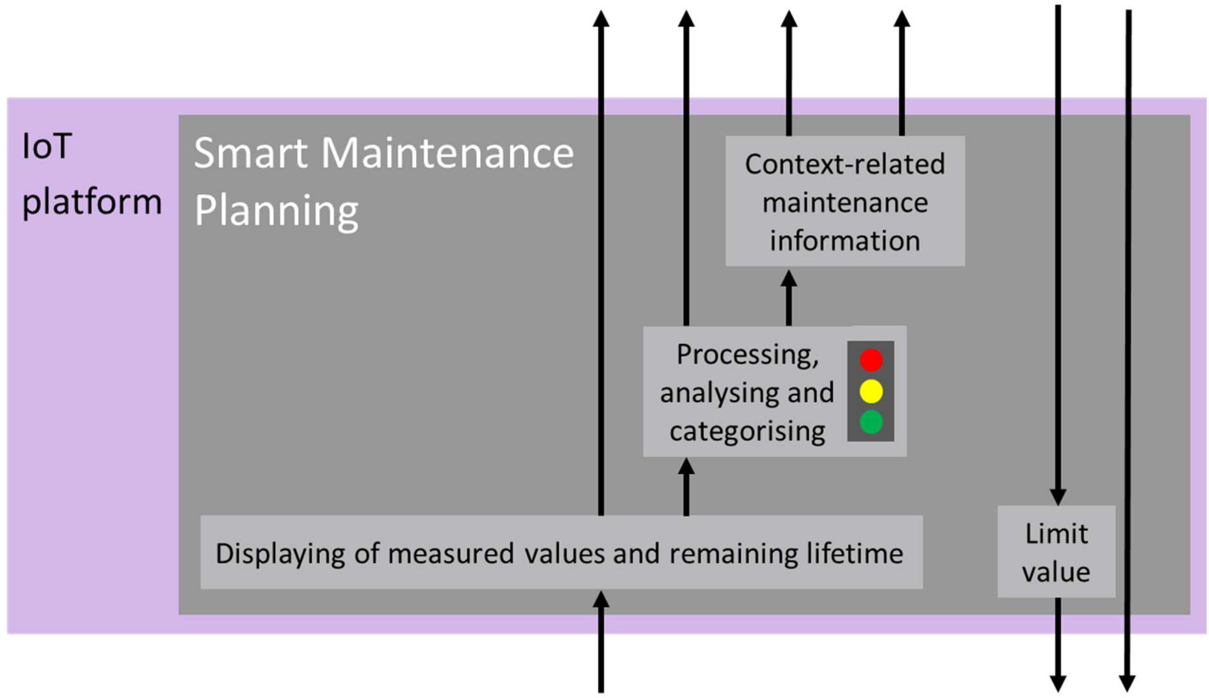


Figure 4-3: Functional model of the smart maintenance planning

The live and past values of the temperature sensors are plotted in a diagram to have a complete representation of the temperature curve over the entire printing process. An individual function for each temperature sensor categorises the values into an accepted, critical and rejected range. The temperature sensor in direct vicinity to the UV lamp has an acceptance range of up to 50 °C, a critical range of 50 °C to 65 °C and a rejection range of 65 °C and above. The sensor, which is mounted at the same distance as an object to be printed, has an acceptance range of 25 °C to 30 °C, as this is the optimum process temperature for curing. The critical range is determined from 22 °C to 25 °C and between 30 °C and 32 °C. All values below 22 °C and above 32 °C are in the rejected range. The sensor that measures the external temperature in the working environment has an acceptance range of 19 °C to 27 °C. The critical range is between 16 °C to 19 °C and between 27 °C to 30 °C and all values outside these two ranges are within the rejection ranges. For the temperature sensor in the upper area of the printing chamber, the same accepted, critical and rejected range is defined as for the sensor next to the UV lamp, since the sensor is mounted at the identical height and therefore must have a similar temperature range. In the dashboard, accepted values are highlighted in green background and no further information is required. Values in the critical range are highlighted in a yellow background, and a warning message appears. In addition, the information at which sensor location the exceeding occurred is displayed. In a second step, an email and SMS is sent to the maintenance staff informing them where the temperature has been exceeded. As soon as a value is measured in the critical range, the dashboard highlights in red and an alarm message pops up that the system must be switched off immediately. Besides, the relevant section in the user manual is named to provide the appropriate maintenance measure for the present case. At the same time, this message is also sent by SMS and email with the attachment of a PDF file containing the suitable maintenance measures. In this way, search times for required information are reduced through improved user guidance, as context-related maintenance measures are suggested to the maintenance staff.

The values of the acceleration sensor are given in a diagram in the dashboard. The acceleration is given in x-, y- and z-axes and is expressed in the unit m/s^2. There is no critical or rejection range, as the acceleration in the 3D printer as well as in this study is limited by the components specifications. The values are stored, and it is checked afterwards how significant the influence of vibration is on the lifetime of the UV lamp.

The values of the UV intensity in the UVA and UVB spectrum are also visualised in a diagram. The dashboard features live and past values. The initial values of the UV intensity in the UVA and UVB spectrum measured with the UV sensor is used as the reference values. All following measured values in the UVA and UVB spectrum are set in relation to the defined initial values. The acceptance range is defined as 80 % to 100 % of the initial UV intensity which corresponds to a remaining buffer of 20 % until insufficient UV intensity is achieved. The critical range is therefore from 75 % to 80 % of the initial UV intensity. The rejection range is from 75 % because the printing material is no longer sufficiently cured at this value and the requested quality of the objects can no longer be guaranteed. As with the temperature sensors, the acceptance range is highlighted green. The critical range is marked yellow in the dashboard, and a warning is displayed that the critical range has been reached. In addition, a message is sent by email and SMS to the maintenance staff. If the rejection area is reached, an alarm message is highlighted in red in the dashboard that the UV intensity is to low. A warning is given that the printed object should not be used as it may not meet the quality requirements. In addition, the relevant passage in the user manual is indicated where the appropriate maintenance measures are specified for the present case. This message is also sent by SMS and email with an attachment of the maintenance measures. In conclusion, the search times for relevant information are also shortened in this case, and the appropriate maintenance measures are suggested to the maintenance staff.

The power measurement captures the values such as voltage, current, effective power, frequency and energy consumption. The values are all displayed separately in a diagram. The measured values are evaluated afterwards to see if there were any abnormalities. For the measured values of the power measurement, limit values can be defined above, which the UV lamp is to be switched off with an actuator. The actuator offers the maintenance staff the possibility to switch the UV lamp on and off.

The remaining useful lifetime of the UV lamp is stated in the dashboard of the smart maintenance system. The starting point for the calculation of the lifetime is the useful lifetime of 600 hours specified by the manufacturer. In addition, the existing lifetime model is integrated into the calculation. The model describes additional wear of the UV lamp of half an hour per further start of the UV lamp, which is performed for the fourth time or higher within 24 hours. A function is generated to compute the remaining useful lifetime that uses the measured current and a timestamp to determine the burning time as well as the switch-on and switch-off operations within 24 hours. Subsequently, the remaining lifetime is analysed and categorised. The acceptance range is defined from 600 to 50 hours of remaining useful lifetime.

The critical range is stated between 50 and ten hours. The dashboard shows the message that the critical remaining lifetime has been reached. It also states that the stock of replacement lamps must be checked and ordered as required. This ensures that a replacement lamp is available when the remaining useful lifetime is over, and no unplanned machine downtime occurs. In addition, email and SMS will be sent to the maintenance staff with the above information. The email could also be sent directly to the spare parts supplier who provides a new UV lamp. The rejection range is accordingly from ten hours to the end of the useful lifetime. A red highlighted alarm message appears that the remaining useful life is reached. For finished printed objects, it must be examined whether the UV lamp has cured the printing material by the end of the printing process. For new print jobs, it must be ensured that the remaining lifetime of the UV lamp is sufficient for the printing time set by the 3D printer. In addition, the context-based maintenance measure is suggested. In this case, the place in the user manual where the UV lamp replacement is described is mentioned. The stated information is also sent by SMS and email with a PDF attachment to the maintenance staff. The maintenance staff can now access from a mobile device and perform the suggested maintenance measure with all relevant information.

4.2.4 Smart maintenance system

The complete functional model of the smart maintenance system is shown in Figure 4-4. The human being has a decisive role in the maintenance. The maintenance technician can use the dashboard to monitor and evaluate the current and past measured values of the individual sensors. Values are categorised and displayed to the maintenance staff in an understandable form. The maintenance staff is informed by their preferred output medium which maintenance measures he should carry out in order to preserve or restore the operating condition of the UV lamp. He can intervene on the UV lamp in different ways. For the actuator, power measurement values can be defined from which the UV lamp can be switched off. The UV lamp can also be switched off and on directly via the actuator.

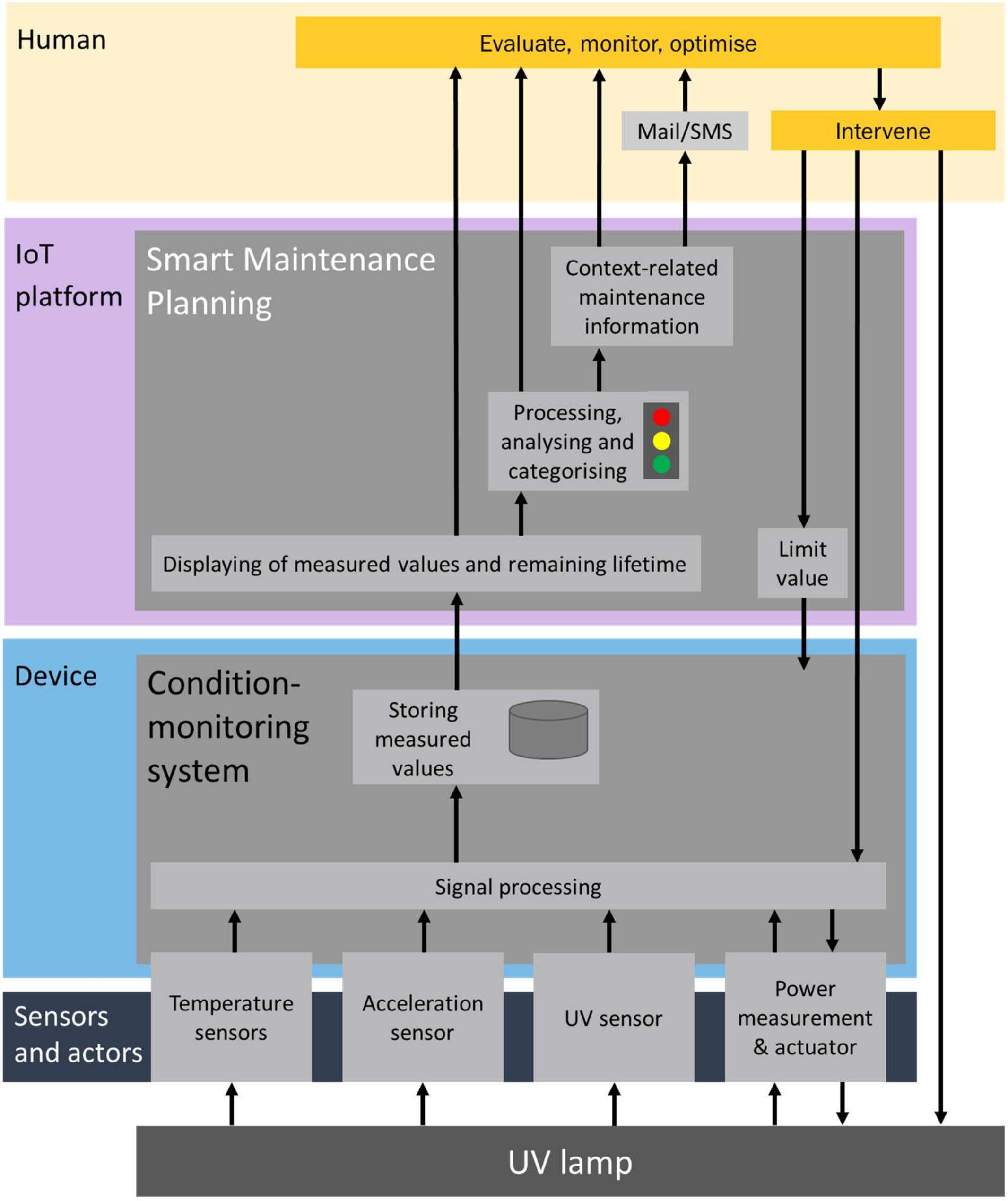


Figure 4-4: Functional model of the smart maintenance system for UV lamps, own representation based on Lucke et al. (2017, pp. 82–83) and FIR e. V. (2015, p. 33)

4.3 Demonstrator

This section describes the hardware and software selection for the demonstrator to cover the defined requirements and the created functional model. The demonstrator is used to validate the functionality of the smart maintenance system.

4.3.1 Hardware selection

The subsection specifies the individual hardware components to be selected for the implementation of the smart maintenance system. First, the selection of the appropriate device is explained, followed by the selection of the sensors and the actuator.

The choice for a device fell on the Raspberry Pi 3 Model B because it meets the required functionalities from the functional model in terms of communication technologies, transport protocol and payload format. The Raspberry Pi proved as the most suitable microcontroller due to the range of matching sensors, the option of a connection to an IoT platform and the open-source operating system Raspbian. In addition, the microcontroller enables modular expansion for further applications (Raspberry Pi Foundation, 2019a).

The sensors are chosen on the basis of the requirements specified for the smart maintenance system. In addition, the sensors must also be compatible with the Raspberry Pi 3. The following sensors are required:

- Temperature sensor
- Acceleration sensor
- UV sensor
- Power measurement

The properties of the individual sensors are explained below. The digital temperature sensor is from Adafruit Industries and has the model designation MCP9808. The measurable temperature range is between -40 °C and 125 °C, with a measuring accuracy of 0.25°C. The resolution of the sensor for measured values is 0.0625°C. The communication is carried out via the I2C bus. The power and logic voltage range are between 2.7 V and 5.5 V. In the smart maintenance system, the sensor measures the ambient temperature next to the UV lamp (Adafruit Industries, 2019c). The vibration is measured with the accelerometer Adafruit MMA845. The sensor detects motion, tilt and basic orientation with a digital accelerometer in three axes. The microcontroller communicates with the sensor via the I2C bus. The power and logic voltages are 3.3 V or 5 V.

In the smart maintenance system, the sensor measures the vibration the UV lamp is subjected to (Adafruit Industries, 2019a). The Adafruit VEML6075 measures the UV intensity. The integrated band light sensors also allow UVA and UVB radiation to be determined. The control also takes place via the I2C bus. The sensor operates with 3.3 V or 5 V power and logic (Adafruit Industries, 2019b). The last component is required for power measurement. The HomeMatic radio switching actuator with power measurement was selected for this purpose. On the one hand, it can switch connected loads via a channel, and on the other hand it can measure voltage, current, effective power, frequency and energy consumption. The measured values are recorded and stored cyclically. In addition, there is the function that consumers can be switched independently when a defined measured value is reached (eQ-3 AG, 2019). The values of the HomeMatic switching actuator radio socket are transmitted to another Raspberry Pi 3 with the help of a radio module board. The second Raspberry Pi is needed because the connections of the previous Raspberry Pi's are not sufficient.

4.3.2 Software selection

In this subsection, the software for the implementation of the smart maintenance system is selected. Since the selection has shown that the Raspberry Pi is used as the microcontroller, the manufacturer's own operating system Raspbian is used. The power measurement also uses the manufacturer's own software, which provides a graphical user interface.

The next step is to determine an appropriate IoT platform for the application. The requirements for the IoT platform result mainly from the requirements already established for the smart maintenance system and are listed in the following categories:

- Data collection and transfer
- Data processing, analysing and storing
- Data visualisation
- Data security and access
- Modular extension
- License fee

Table 4-2: Requirements for the IoT platform

Categories	Requirements
Data collection and transfer	• Feasible with the RaspberryPi • Complete and in real-time • Individual time intervals between two measurements
Data processing, analysing and storing	• Processing of a usual data volume in IoT applications with multiple sensors • Automated monitoring and reporting • Storage in a database
Data visualisation	• Display of key figures • High usability of the graphical user interface (GUI) • Display of context-based information • The function of an alarm message • Provision of information depending on users knowledge • Visualisation on PC, smartphone and tablet
Data security and access	• Secure data transmission • Authorisation concept
Modular extension	• Integration of IT systems such as ERP-systems, production planning systems or advanced planning and scheduling systems • Extension to further critical components
License fee	• Cost-effective as possible

According to Guth et al. (2018, p. 82) the range of IoT platforms has become very heterogeneous since due to a missing standardisation there are many different concepts and technologies as well as various terminologies on the market. However, they all have in common that they can be connected to different devices, are able to access and process their data, and are able to use the knowledge gained through this activity to realise automated control.

The range of IoT platforms was carefully examined, and an IoT platform was selected that met the specified requirements. The Losant IoT Platform was chosen for demonstration purposes and is introduced below. The analysis of the platform was carried out on the basis of the information available on the website.

The Losant IoT Platform enables data collection and transfer with the Raspberry Pi using the industry communication standards MQTT and REST. Connected devices can transfer data as often as needed. The data are processed and displayed in real-time. The platform can visualize complex aggregations across one or more devices. The platform stores all status information reported by the device.

The data are visualised in a dashboard, which can be individually adapted to the application by drag and drop. Important key figures can be displayed and averages can be calculated. In addition, alarm messages can be sent by email or SMS, for example, if a certain limit value is reached. The dashboard can be displayed on a PC, smartphone and tablet.

In order to ensure a high level of security, Losant uses industry-standard encryption methods. The data are fully encrypted during transfer and in sleep mode. Unauthorized access to the platform is prevented by using a 2-factor authentication scheme. It is also possible to create additional accounts that can connect to the platform.

The platform offers the opportunity to interact with third-party software such as ERP-systems or production planning systems. An extension with further devices is possible, but only the use of one device is free of charge (Losant, 2019).

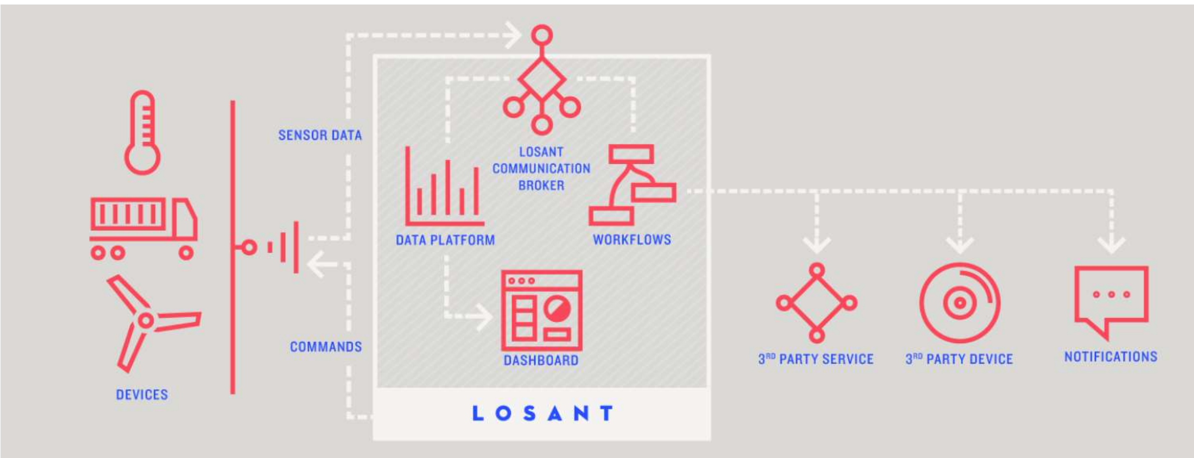


Figure 4-5: Architecture of Losant IoT Platform (Losant, 2019)

Chapter 5 Development of the system

The chapter introduces the printing process simulation system, on which the smart maintenance system is validated. The smart maintenance system is assembled with the selected hardware components and retrofitted to the printing process simulation system. Afterwards, the setup of the software is described. Finally, the design of the experiment is explained, according to which the validation is carried out.

5.1 Printing process simulation system

This section clarifies the requirements and setup of the printing process simulation system. The objective is to imitate the printing process realistically to validate the smart maintenance system.

5.1.1.1 Requirements

The first requirement is that the system must be completely safe to operate. A danger to people and the environment must be excluded from the outset. The following three steps are applied for the implementation, which is also used in the design of safety-oriented products (Neudörfer, 2016, p. 194):

1. Hazard potentials are excluded or reduced in the design so that no hazards can arise even with complete release.
2. Safety measures are integrated into the design to reduce the probability of the hazard occurring and to control the hazard potential.
3. Technical and organisational measures limit the effects of damage or accidents such as safety glasses or warning signs.

In particular, it must be ensured that there is no danger to people from an electric shock, as otherwise there is a danger of fatal injury. Care must be taken to ensure that UV radiation does not get in contact with people, otherwise damage to the skin or eyes may occur. In the event of lamp breakage, mercury vapour may escape, which can be inhaled and lead to poisoning. Once a UV lamp has reached the end of its useful lifetime, it must be disposed of properly so that people and the environment cannot be harmed. During the operation of the UV lamps, an adequate amount of air must be extracted, as the UV radiation of the high-pressure lamps creates ozone, which can lead to poisoning.

A further requirement for the system is that the simulated printing process is as similar as possible to the printing process of the Stratasys Objet500 Connex3. This ensures a realistic implementation and the results are based on appropriate assumptions. Therefore the same UV lamps as in the Stratasys 3D printer must be used, which guarantees that the UV lamps have the right UV intensity to cure the material. In addition, the same speed must be simulated so that the UV lamps experience the same vibration as in the print head of the Stratasys 3D printer. Also, the UV lamp must be exposed to the same temperature conditions as in the 3D printer. A temperature of 65 °C should not be exceeded close to the UV lamp, this is indicated in the Stratasys 3D printer by a heat-sensitive label, which is fixed on the cover of UV lamps. The label is a warning for overheating and changes its colour from white to black. In addition, the power supply is switched off by a heat fuse as soon as a temperature of more than 90 °C is reached around the UV lamp (Stratasys, 2018b, p. 150). The processing temperature of the printing material is approximately 25 to 30 °C to ensure a suitable flow behaviour (Gebhardt, 2016, p. 51). The cooling of the UV lamps is realised in the 3D printer with fans.

5.1.1.2 Setup

The description of the setup of the printing process simulation system includes the installation of the UV lamp, the linear working spindle with a framework, cooling fans and the cover.

The high-pressure UV lamp requires a ballast and an ignition unit for operation. The ballast converts the mains voltage from 230 V to the required 125 V of the UV lamp. At the same time, a high voltage is needed for the ignition of the gas in the UV lamp. The ignition unit generates a voltage pulse with a pulse transformer which high transforms the necessary ignition voltage to 5 kV. Figure 5-1 illustrates the wiring diagram of the UV lamp, the ballast and the ignition unit.

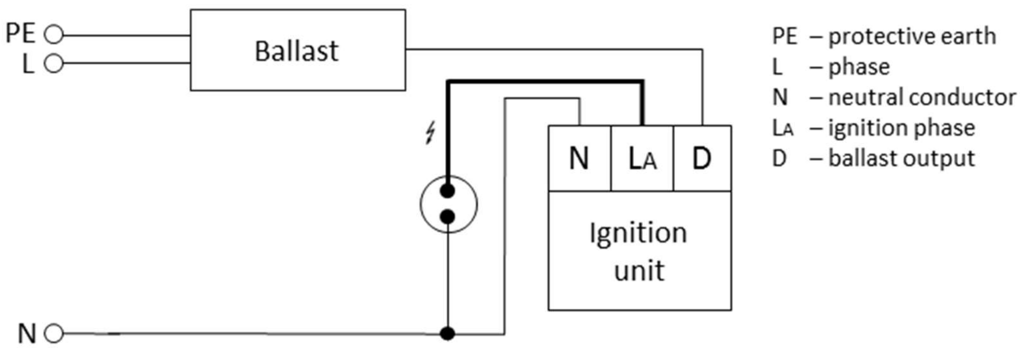


Figure 5-1: Wiring diagram of the UV lamp, ballast and ignition unit

Figure 5-2 shows the setup of the printing process simulation system. A linear working spindle simulates the movement of the print head during the printing process. The working spindle has a length of 400 mm, a height of 200 mm and a width of 100 mm. The generated rotary motion of the stepper motor is transmitted to the spindle by a clutch, which moves a slide forward and backwards. The required source code is executed on the Raspberry Pi, which transmits the electrical signal to the stepper motor by means of a driver. The rotation speed, direction and time can be set via the program code (see Appendix A).

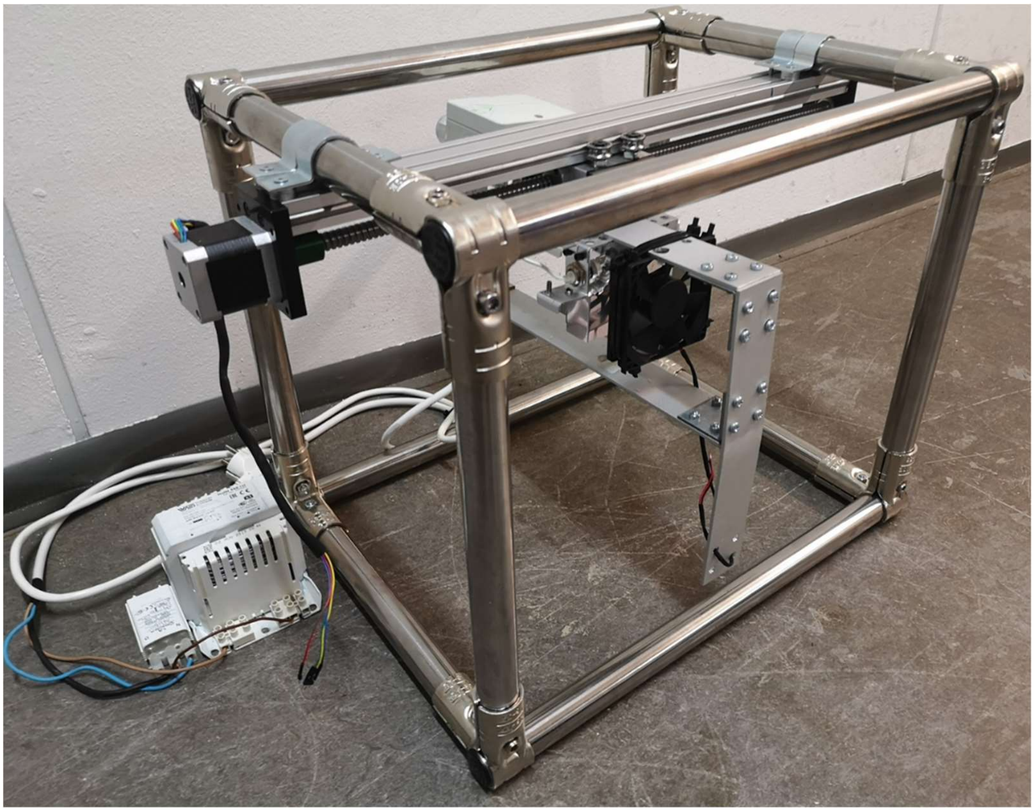


Figure 5-2: Setup of the printing process simulation system

The work spindle with a stepper motor is mounted on a frame so that the slide is at a height of 30 cm. The components of the framework are easy to assemble, stable and heat-resistant. Thus the selection fell on BeeWaTec components, which are also used in work, production and logistics processes. This is a round tube plug-in system made of steel, which can be individually designed with the help of connectors.

The UV lamp and the reflector unit are attached to the slide of the working spindle by means of an aluminium construction. In addition, a cooling fan is mounted on the aluminium construction, which blows directly onto the reflector housing to keep the temperature next to the UV lamp below 65 °C. The respective air performance of the axial fan amounts to 61.1

m^3/h, which meets the requirement for sufficient cooling of the UV lamp, which is specified with 100 m^3/h per kW power of the UV lamp.
The UV lamp must be covered due to its radiation harmful to humans. The cover is a plastic box made of polypropylene, which provides protection against UV radiation and does not conduct electricity. The dimensions of the cover are selected in such a way that the working spindle and framework fit underneath.

Six additional fans provide sufficient cooling under the cover (see Appendix A). Circular openings are drilled into the cover, which corresponds precisely to the dimensions of the diameter of the rotor blades. A total of two cooling fans are mounted at the same height in the lower area of the shorter side of the case. The blowing direction of the fans leads into the box, which means that cold air is supplied. In the inside, the air warms up by the waste heat of the UV lamp. Four further coolers are mounted at the same height in the upper part of the cover. These blow the warm air from the inside to the outside. In summary, it can be said that the air is taken in on one side in the lower area, then warmed up on the inside by the waste heat of the UV lamp and finally pulled out on the other side in the upper area.

5.2 Setup of the smart maintenance system

The following section describes the setup of the smart maintenance system with the selected hardware and software.

5.2.1 Hardware

The subsection provides an overview of the hardware setup of the smart maintenance system. It is explained which preparations are made with the Raspberry Pi in order to be able to connect the sensors. Finally, the assembled smart maintenance system is retrofitted to the printing process simulation system.
In order to facilitate the connection between Raspberry Pi and the sensors, an Adafruit T-Cobbler Plus is used, which is connected to a breadboard (see Appendix B).
Figure 5-3 shows the pins of the Raspberry Pi, which are used to connect the sensors. The red marked pin 2 is for the 5 V power supply and the black marked pin 9 is for grounding.
The orange marked pin 3 and the green marked pin 5 are for the connection with the I2C bus. These two pins are used for communication between the sensors and the Raspberry Pi.

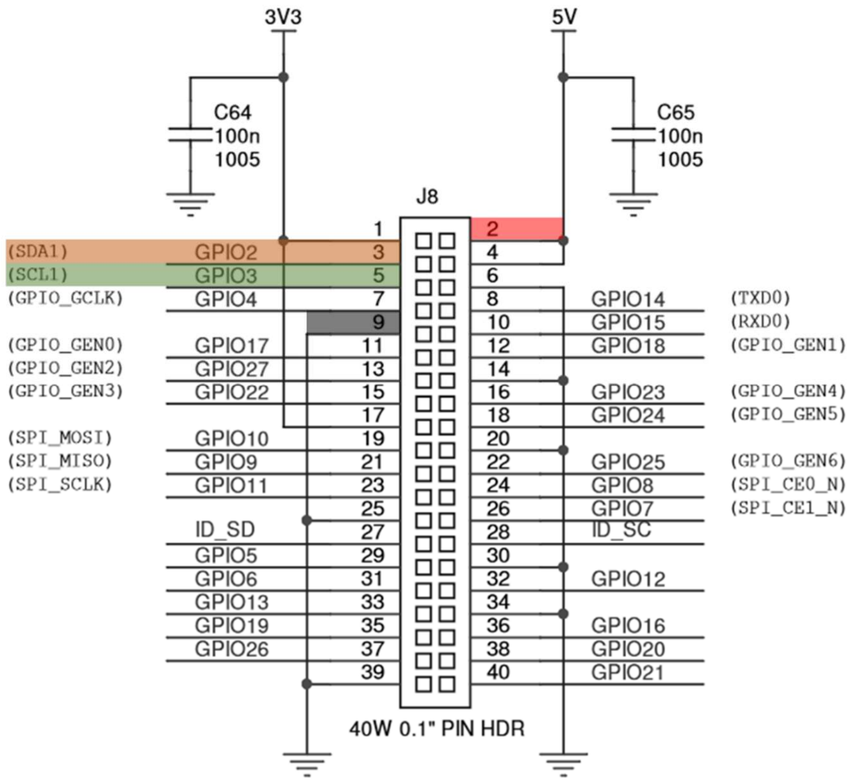


Figure 5-3: Pinout of the Raspberry Pi 3 Model B (Raspberry Pi Foundation, 2019b)

In the next step, the individual sensors are connected to the Raspberry Pi. First of all, the sensors must be prepared for their use. For this purpose, pin headers are soldered to the breakout pads of the respective sensors to ensure reliable electrical contact.

In order to be able to measure the temperature at different locations, four Adafruit MCP9808 sensors are used. The exact positions are explained at the end of this section. Figure 5-4 shows the used pins of the four Adafruit temperature sensors. The red marked pins are needed for each sensor and the unmarked Alert and A2 pin is not needed. The Vdd pin is connected to pin 2, the 5V voltage. The Gnd pin is connected to pin 9, which is responsible for grounding. The I2C data pins SCL and SDA are connected to pin 3 and 5. The green marked pins are needed sensor individually because these are used for the address assignment. For communication with several identical sensors via the I2C bus, the sensors require a unique address. This is achieved by setting different connections with the A0 and A1 pins to pin 5, the 5V voltage.

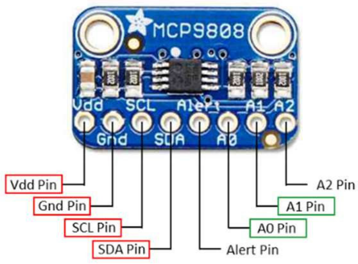


Figure 5-4: Used pins of the Adafruit MCP9808 temperature sensor (Adafruit Industries, 2019c)

Table 5-1 lists the pin assignment of the temperature sensors and the respective i2c address.

Table 5-1: Used pins of the Adafruit temperature sensor and resulting I2C address

Sensor	Used pins	I2C address
Temperature sensor 1	VDD, GND, SCL, SCA,	0x18
Temperature sensor 2	VDD, GND, SCL, SCA, A0	0x19
Temperature sensor 3	VDD, GND, SCL, SCA, A1	0x1a
Temperature sensor 4	VDD, GND, SCL, SCA, A0, A1	0x1b

The Adafruit MMA8451 accelerometer measures the vibration the lamp experiences during the printing process. For applications requiring the acceleration measurement, the pins marked in red are used, see Figure 5-5. The VIN pin is connected to pin 2, the GND pin to pin 9, the SCL pin to pin 5 and the SDA pin to pin 3. The sensor is controlled by its default address 0x1d. The pins not marked in red are not required for the acceleration measurement.

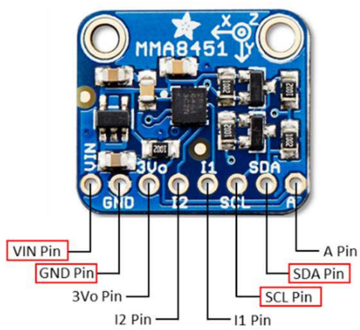


Figure 5-5: Used pins of the Adafruit MMA8451 accelerometer sensor (Adafruit Industries, 2019a)

The Adafruit VEML6075 provides the functionalities required for the smart maintenance system. The sensor enables the measurement of UV intensity as well as the UVA and UVB radiation. Figure 5-6 illustrates the required connections, which are marked in red. The VIN pin is connected to pin 2, the GND pin to pin 9, the SCL pin to pin 5 and the SDA pin to 3. The 3Vo pin is not required for the application. The sensor has a default I2C address of 0x10.

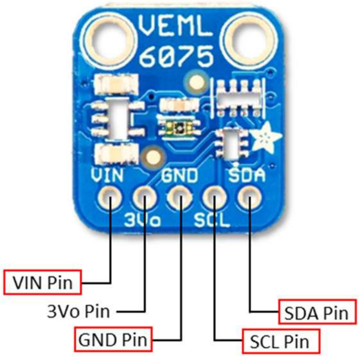


Figure 5-6: Used pins of the Adafruit VEML6075 UV sensor (Adafruit Industries, 2019b)

The power measurement is realised by a HomeMatic radio switching actuator, a radio module board and another Raspberry Pi 3. For the application, the radio module is plugged into the connections of the Raspberry Pi. The power supply for the UV lamp is plugged into the HomeMatic socket.

Several cables are required for the wiring of the various sensors, which are necessary for voltage, ground and data transmission. The individual cables of a sensor are covered with heat-shrink tubing so that the cables are isolated and protected against damage. The cables are led through the tubing and then heated to 120 °C with a hot-air gun so that the tubing shrinks and wraps around the cables.

The locations of the individual sensors on the printing process simulation system are described below. The UV sensor is placed at a distance of 5 cm directly below the UV lamp and measures continuously the UV intensity in the UVA and UVB spectrum as it moves back and forth with the construction, see Figure 5-7.

Figure 5-7: UV sensor under the UV lamp with reflector unit

A temperature sensor is mounted directly next to the UV lamp to measure the immediate ambient temperature, see Figure 5-8. The external temperature is measured with a sensor outside the cover and is directly connected to the breadboard. The measured value serves as a reference value and can provide information about the temperature supplied to the system.

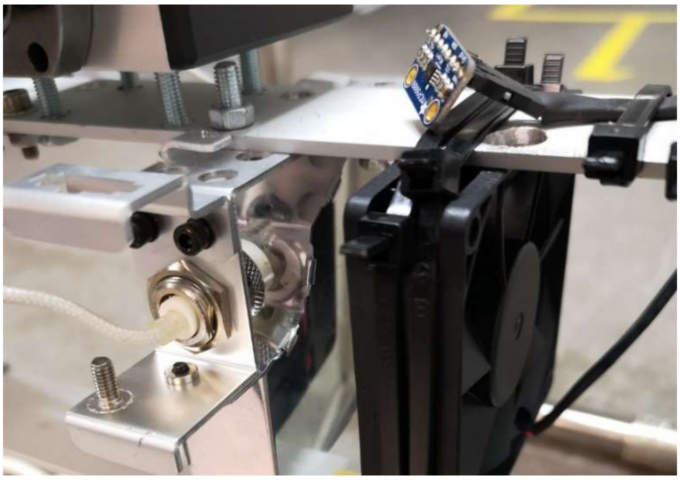


Figure 5-8: Temperature sensor next to the UV lamp

Another temperature sensor is mounted 10 cm below the UV lamp and measures the heat that a component to be printed would experience on the building platform in the 3D printer, see Figure 5-9.

Figure 5-9: Temperature sensor at the height of the building platform

The fourth temperature sensor is attached in the upper area below the cover and measures the upwards rising waste heat. In addition, the sensor moves on the same construction as the UV lamp. The acceleration sensor is attached also attached to the moving component as the UV lamp and thus measures the vibration the lamp experiences, see Figure 5-10.

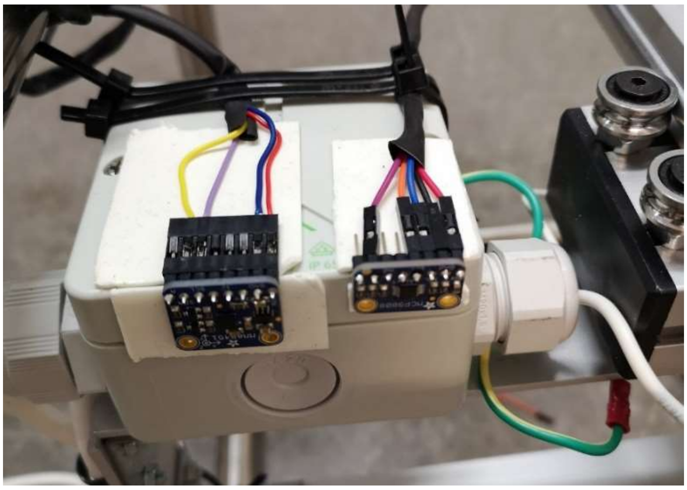


Figure 5-10: Acceleration and the temperature sensor in the upper part of the printing chamber (from left to right)

5.2.2 Software

The section introduces the software used for the Raspberry Pi 3 Model B and the preparations to be made to integrate the sensors. The source code is partially described for the applied sensors to provide an overview of the source code structure. This is followed by a description of the connection to the IoT platform and the development of the dashboard. Finally, the connection between the HomeMatic radio switching actuator to the IoT platform is outlined. The entire source code is in Appendix B. All implementations are based on the defined requirements and the functional model.

The first step is to install the open-source operating system Raspbian on a SD card of the Raspberry Pi. The I2C bus on the Raspberry Pi must be activated to enable the integration of the sensors. The serial bus is enabled by entering the command *sudo raspi-config* into the terminal and the I2C driver is activated within the extended options. The complete programming takes place on the Raspberry Pi in the development environment Thonny. The next step is to import the required libraries to integrate the sensors and the IoT platform Losant, see Listing 1.

```
import smbus
import time
import Adafruit_MCP9808.MCP9808 as MCP9808
import adafruit_mma8451
from losantmqtt import Device
from sys import argv, exc_info
from time import sleep
from smbus import SMBus
import board
import busio
```

Listing 1: Required libraries to integrate the sensors

The integration of the Adafruit MCP9808 temperature sensors is exemplarily shown by one sensor. The individual sensor is defined as `sensor18 = MCP9808.MCP9808(address=0x18, busnum=1)`that accesses the library. The I2C address of the sensor is specified, as well as the bus number via which the sensor communicates with the Raspberry Pi. For the other temperature sensors, the respective address and the same bus number are used. The command `sensor18.begin()` initialises the sensor. The function of the temperature measurement is executed with `temp18 = sensor18.readTempC()`.

```
sensor18 = MCP9808.MCP9808(address=0x18, busnum=1)
...
sensor18.begin()
...
while True:
    global data
    data = ""
    temp18 = sensor18.readTempC()
...
```

Listing 2: Structure of the source code of the Adafruit MCP9808 temperature sensor

The Adafruit MMA8451 is defined as `sensor =adafruit_mma8451.MMA8451(i2c)` and accesses the library. The sensor initialises itself with `x, y, z = sensor.acceleration` and at the same time measures the acceleration values in three axes with the command.

```
sensor = adafruit_mma8451.MMA8451(i2c)
...
    x, y, z = sensor.acceleration
...
    print(data)
    device.loop()
    if device.is_connected():
...
        print("x={0:0.3f}m/s^2".format(x))
        print("y={0:0.3f}m/s^2".format(y))
        print("z={0:0.3f}m/s^2".format(z))
```

Listing 3: Structure of the source code of the Adafruit MMA8451 accelerometer

A separate class exists for the Adafruit VEML6075 UV sensor. The class `veml6075` starts with the first function `__init__(self, address)`, which creates an instance. The `setADCSettings(self, i)` converts analog input signals into digital data. The `error(self, message)` function indicates when an error has occurred during data transmission. A connection to the sensor is established by the function `readDeviceID(self)`. The last function `readUV(self, sensitivity)` measures the required parameters of the UV lamp.

```
class veml6075:
...
    def __init__(self, address):
...
    def setADCSettings(self, i):
...
    def error(self, message):
...
    def readDeviceID(self):
...
    def readUV(self, sensitivity):
```

Listing 4: Structure of source code of the Adafruit VEML6075 UV sensor

A connection is established between the Raspberry Pi and the IoT platform Losant to send the status of the device. The communication between the device and the IoT platform is implemented as shown in Listing 5. To establish the connection, the Raspberry Pi ID, the access key and the access secret are required.

```
device = Device("5d5e647427db81000672993c", "1fbbe29d-cb7f-451a-921e-552bbc548ff1",
"44244444fa8ce78a78c3f8178e2c5c6c308fc4b2961727eefbcf5c11f6c58520")
```

Listing 5: Raspberry Pi ID, access key and access secret

Figure 5-11 illustrates the reported state of the individual sensors transferred to the IoT platform but without the UV lamp being switched on. Each reported state is provided with a timestamp. In addition, a second UV sensor is implemented to determine a valid reference value for UV intensity.

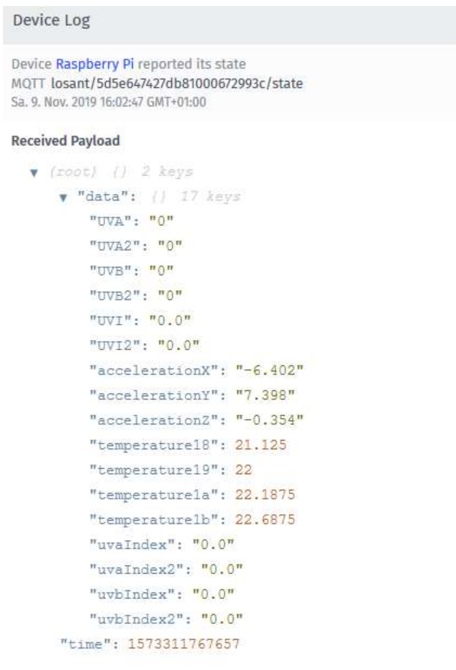


Figure 5-11: Reported state of the Raspberry Pi to the IoT platform

The transfer interval of the measurements is approximately one second, see Figure 5-12. A shorter interval cannot be implemented because the initialisation and the measuring process of the UV sensor requires a certain time interval.

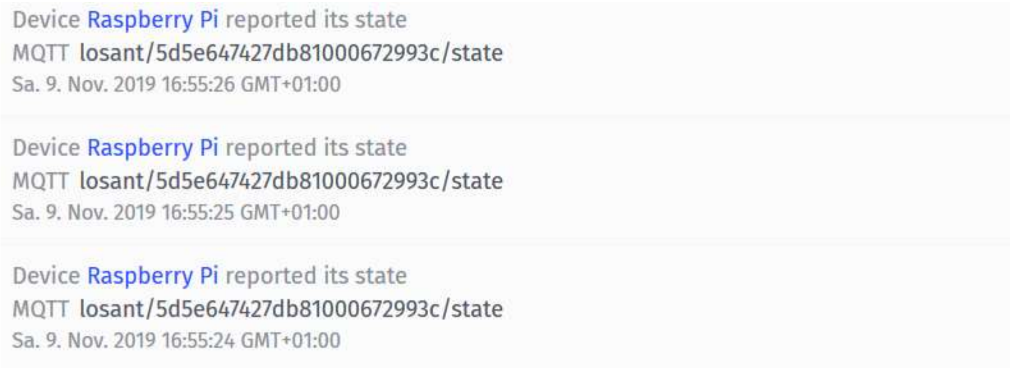


Figure 5-12: Transfer interval of reported states

After the acquisition and processing of the required sensor values, as well as the communication to the IoT platform, were enabled, this section describes the analysis, categorisation and presentation of the measured values. The elaborated functionalities of the smart maintenance system are realised in the graphical user interface of the IoT platform. The Losant IoT platform provides a modular design of the dashboard, which the maintenance staff can customise according to his requirements.

Figure 5-13 shows the implementation in the dashboard of the ranges defined in Section 4.2 as an example for the temperature sensor mounted directly next to the UV lamp. The defined temperature ranges are defined with conditional expressions. Analogue to this, the implementation for the other temperature sensors and the UV intensity values are carried out (see Appendix B).

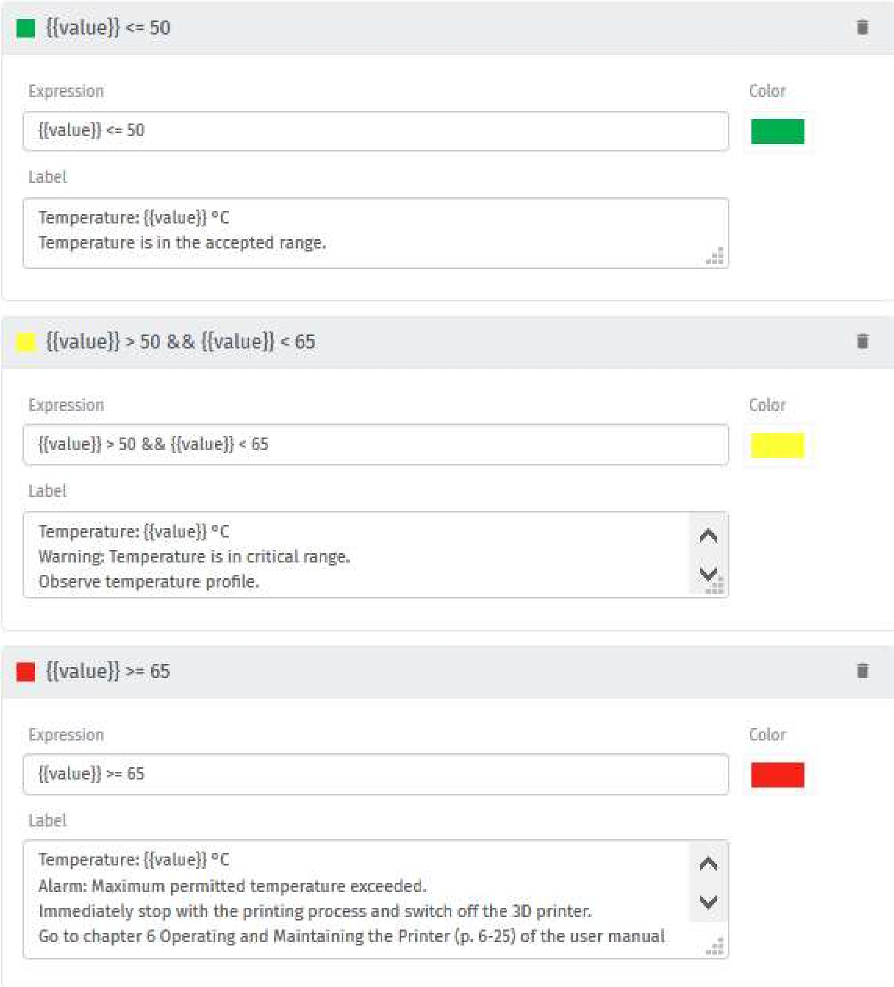


Figure 5-13: Implementation of the conditions in the dashboard of the Losant IoT platform as an example for the temperature sensor mounted directly next to the UV lamp.

In addition to the display of the measured values in the dashboard, an SMS and email with status information and context-based maintenance measures are also sent. Figure 5-14 demonstrates the workflow of the smart maintenance system for the analysis and categorisation of status information as well as the suggestion of context-based maintenance measures sent by email and SMS. As an example, the implementation is explained using the measured value UV intensity in the UVA spectrum. Analogously, the workflow is also created for the other measured values (see Appendix B).

At the beginning of the workflow is the device that sends the current state of the sensors to the IoT platform and thus allows a flow. The analysis and categorisation of the measured value take place in the condition node. The node compares two defined conditions.

If the UV intensity is above 80 % of the initial value, the condition is true and it follows the right path. The value is therefore within the acceptance range, which corresponds to the debug node in the workflow. The node outputs the value in the workflow and stores as a log. If the UV intensity is below 80 % of the initial UV intensity, the condition is false and it follows the left path. Another condition node follows, which analyses the value between the critical and rejected range. If the values are above 75 % of the initial UV intensity, the condition is true and the value is categorised as critical. Here the flow meets a throttle node which throttles the output on the left path and is not throttled on the right path. The flow is reduced to one message per ten minutes. The event record pops up in the dashboard and an email and SMS will be sent that the temperature is in the critical range every ten minutes. The unthrottled flow takes the right path and ends at the debug node where the data are logged. If the value is below 75 % of the initial UV intensity, the condition is false and the flow takes the left path. The following node throttles the left path to one message per minute, while the right path is unthrottled. The left path displays the log in the dashboard, sends an SMS and an email with an alarm message and context-based maintenance measures. The right path continuously logs the values from the rejection range.

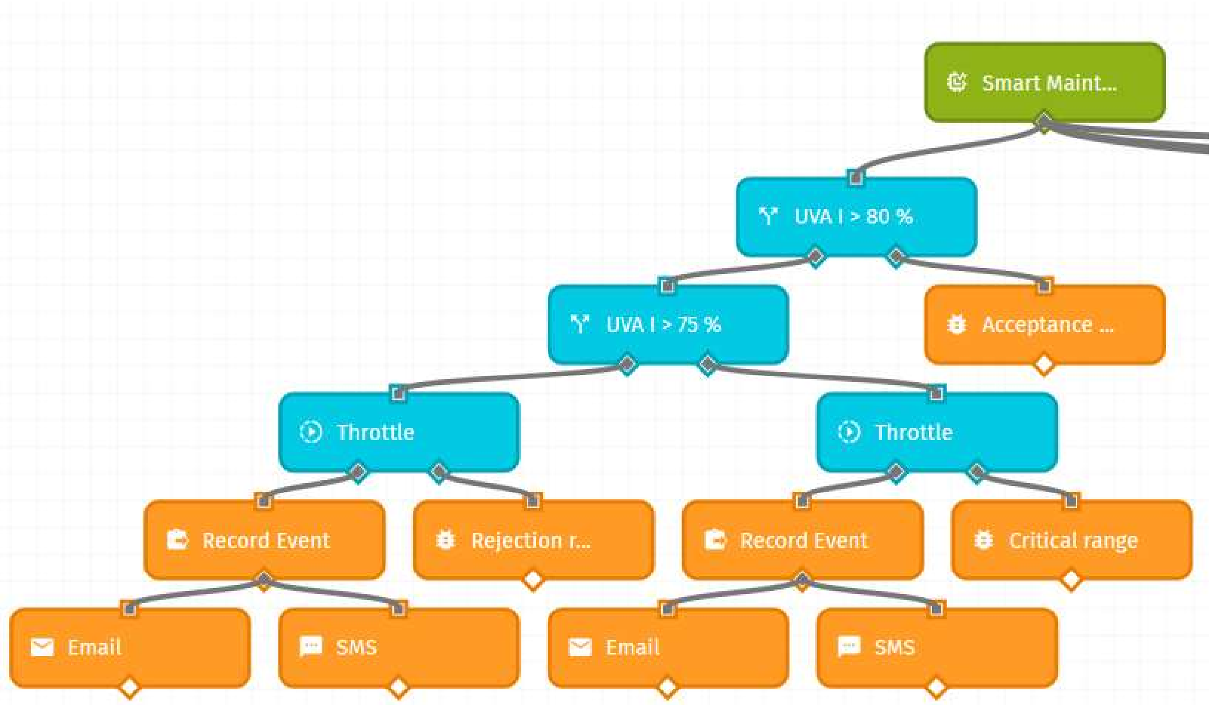


Figure 5-14: Workflow of the relative UVA intensity monitoring including an alarm function and context-based maintenance measures

In the next step, the graphical user interface of the power measurement including the actuator is set up to meet the requirements of the smart maintenance system. The manufacturer of the HomeMatic provides a GUI for displaying the measured values, switching the socket on and off, and setting limit values. The measured values displayed in the GUI are taken with a remote procedure code and transmitted to the IoT platform Losant (see Appendix B).

In the last step, the function is introduced, which determines the remaining lifetime of the UV lamp. The measured values of the current, which have a timestamp, serve as the basis. As soon as a current is measured, which is an indicator that the UV lamp is in operation, the timestamp is recorded. The time of the current flowing corresponds to the burning time of the lamp and is subtracted from the initial lifetime of 600 hours. Furthermore, a counter is integrated, which registers the number of switch-on operations within the last 24 hours. For each count greater than or equal to four, half an hour is subtracted from the remaining useful lifetime (see Appendix B).

5.3 Design of experiments

The section describes the design of experiments, which is oriented towards the statistical design of experiments, even if the experiment carried out here are not statistical experiments. In order to obtain a statistically meaningful result, a higher number of UV lamps would have to be tested. However, due to the stated useful lifetime of the UV lamps of 600 hours, this can only be accomplished over a long period of time. Furthermore, experiments in which several UV lamps are used at the same time could only be realised at a high cost. For each UV lamp, the hardware of the smart maintenance system, a reflector and the electrical ballast with the ignition unit would have to be provided. Nevertheless, the experimental design is defined in such a way that a statistical series of experiments can be conducted once the challenges mentioned have been removed.

5.3.1 Definition of system boundaries and quality characteristics

Figure 5-15 illustrates the schematic representation of the investigated system. The blue arrow describes the input variables that can be changed by the user of the 3D printer. The red arrow indicates the input variables that cannot be changed by the user or are unknown. The green arrow indicates the output of the UV lamp. The individual sizes are explained in more detail below.

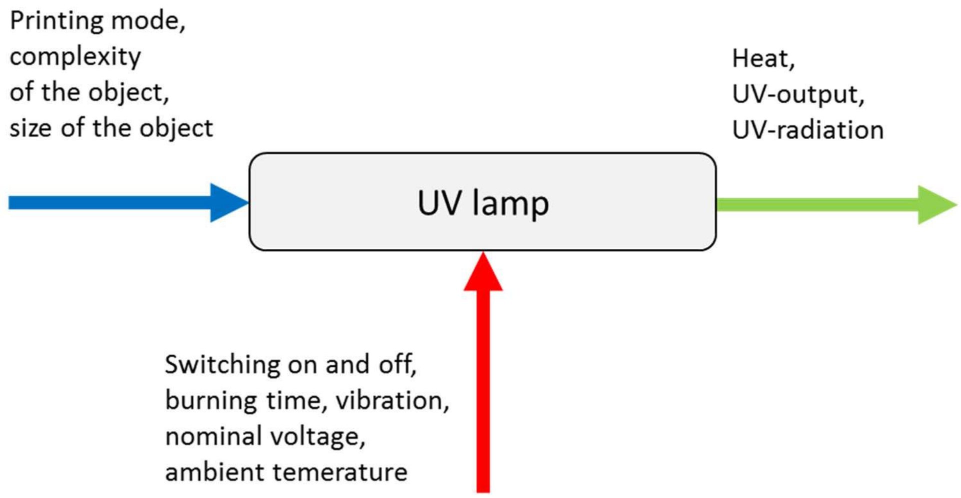


Figure 5-15: Schematic representation of the investigated system, own representation based on Siebertz, van Bebber, and Hochkirchen (2017, p. 3)

The variables that can be changed by the user are the printing mode, the complexity and size of the printed object. The printing mode can be selected between high-speed mode, high-quality mode and digital printing mode. The complexity is determined by the user-created object to be printed as well as the size of the object. All the variables mentioned have an impact on the length of the printing time and therefore influence the lifetime of the UV lamp.

The variables on which the user has no influence are the switching on and off and the burning time of the lamp. Furthermore, the user has no direct influence on the vibration experienced by the lamp. Also, the voltage and the ambient temperature of the lamp cannot be changed by the user.

The outcomes of the UV lamp is heat, UV intensity and UV radiation, which are necessary for the curing of the printing material. The outcomes reflect the functions of the system and form the quality characteristics that are measurable. Quality characteristics must be continuous quantities, otherwise no effect calculation is possible. (Siebertz et al., 2017, p. 4).

In the following, the quality characteristics of the system are defined in measurable values. The ambient temperature in the direct vicinity of the UV lamp must remain below 65 °C. In addition, the temperature below the lamp must be between 25 to 30 °C to ensure the optimum processing temperature of the resin, as described in Section 2.3. The UV intensity of the UV lamp is 104 W/cm^2 and should not fall below 50 % of the value in order to guarantee complete curing.

5.3.2 Definition of factors and levels

The quantity of all input variables in a system is termed as a parameter. The parameters that have a large influence on the system according to the available information are selected for the experimental design and are named factors. The factors must be set in a targeted and reproducible manner during the execution. Different combinations of settings are provided in the design of the experiment and it is important that the combinations cannot be mutually exclusive (Siebertz et al., 2017, p. 5).

The defined factors of the system are the printing mode, the complexity and the size of the object to be printed. The factors can be simulated with the help of the printing process system and are reproducible. A combination of the factors is excluded since these are chosen independently of each other.

The next step is to define the settings of the factors named levels. Each factor is tested on two different levels, whereby the effect of a factor depending on the distance between the levels. Especially in the early phase of an investigation, large level distances are advisable. Low-level distances lead to small effects which are physically justified. The level distances are limited by the demand for a functional system and the printing process system (Siebertz et al., 2017, p. 6).

Table 5-2 defines the factors and levels applied in the experiment. All selected factors and levels affect the printing time and therefore also the burning time of the UV lamp. All three factors in the first level result in the shortest printing time, whereas all factors in the second level result in the longest possible printing time. The high-speed mode produces objects twice as fast as the high-quality mode. The third printing mode digital material printing is deliberately omitted, as it requires the same printing time as the high-quality mode. The size of the object is specified in two levels and simulated by the printing process system with the linear motion of the work spindle. An object with high complexity requires twice the printing time for the same object size, in contrast to an object with low complexity.

Table 5-2: Defined factors and levels applied in the experiment

Factor	1^{st} level	2^{nd} level
Printing mode	High-speed mode	High-quality mode
Size	50 mm	100 mm
Complexity	Low	High

Subsequently, all the factor levels are coded and displayed compactly, see Table 5-3. Each factor is tested in two different settings and the two levels are coded with - and +. A total of eight tests make it possible to test all combinations. The principle applies that only one influencing variable may be changed at a time, while the other influencing variables remain constant. This allows the effects to be clearly assigned. (Siebertz et al., 2017, p. 7).

Table 5-3: Experimental design (Siebertz et al., 2017, p. 7)

A	*B*	*C*	*y*
-	-	-	y_1
+	-	-	y_2
-	+	-	y_3
+	+	-	y_4
-	-	+	y_5
+	-	+	y_6
-	+	+	y_7
+	+	+	y_8

Figure 5-16 illustrates the graphical representation of the experimental design. Point y1 means high-speed printing mode, small size and low complexity of the printed object. This results in the following printing time, which at the same time corresponds to the burning time of the UV lamp during the experiment:

$$y1 = High\ speed\ mode\ x\ 50\ mm\ x\ low\ complexity\ = 1\ x\ 0.5\ h\ x\ 1 = 0.5\ h$$

The printing time at point y8 is calculated as follows:

$$y8 = High\ quality\ mode\ x\ 100\ mm\ x\ high\ complexity = 2\ x\ 1h\ x\ 2 = 4\ h$$

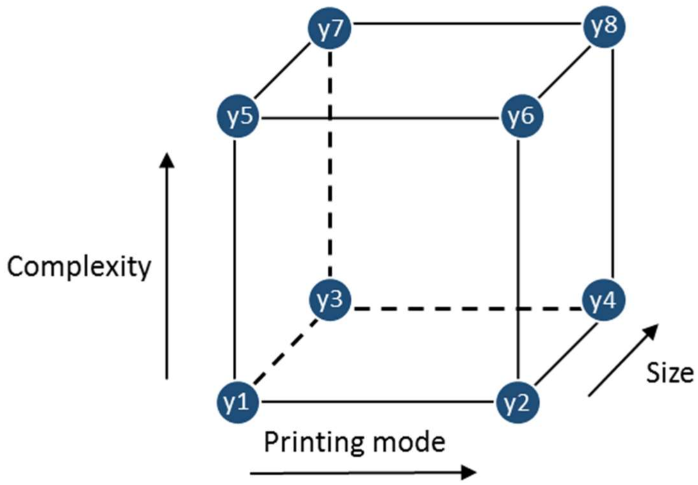


Figure 5-16: Graphical representation of the experimental design, own representation based on Siebertz et al. (2017, p. 8)

5.3.3 Procedure for evaluation

This subsection describes the basic procedure for evaluating the experimental design. Descriptive functions are derived from the experimental results and illustrated in standardised representations such as effect diagrams and interaction diagrams.

The factors have an impact on the system and are identified as an effect. The effect is calculated from the difference between two mean values for the setting + and – (Grove & Davis, 1992). The effect, therefore, quantifies the mean registered change in the quality characteristic when changing the factor setting from – to +. For the effect calculation of the factors the same experimental data are used but in a different grouping. The effect of the factors print mode is calculated (Siebertz et al., 2017, p. 12):

$$E_{Printing\ mode} = \frac{y2\ + y4\ + y6\ + y8}{4} - \frac{y1\ + y3\ + y5\ + y7}{4}$$

The effect calculation of the factor size is determined as follows:

$$E_{Size} = \frac{y3\ + y4\ + y7\ + y8}{4} - \frac{y1\ + y2\ + y5\ + y6}{4}$$

The factor complexity also results in the same way:

$$E_{Complexity} = \frac{y5\ + y6\ + y7\ + y8}{4} - \frac{y1\ + y2\ + y3\ + y4}{4}$$

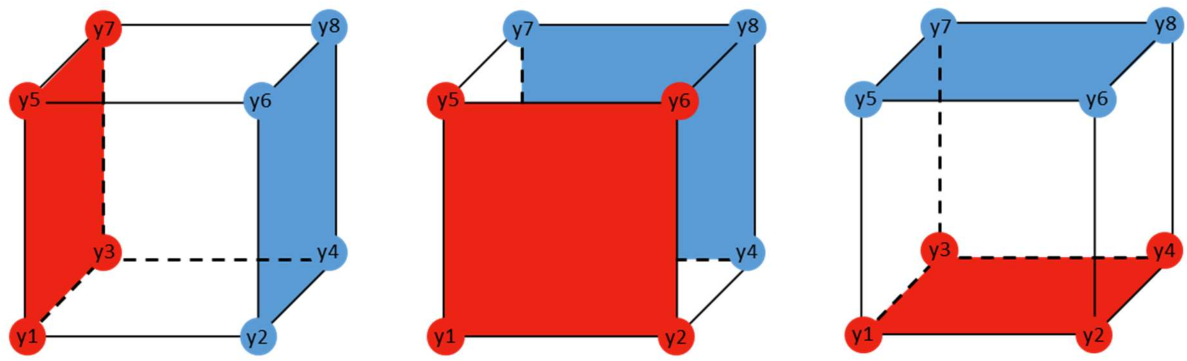


Figure 5-17: Graphical representation of the effect calculation, own representation based on Siebertz et al. (2017, p. 13)

In addition, interactions are considered, since it cannot be excluded whether there is a dependency on the initial state, see Table 5-4. An interaction exists when the effect of one factor depends on the setting of another factor. New columns are created to calculate interaction effects. For better differentiation, the effects of the factors are now called main effects. The interaction columns indicate whether the factors are at the same (+) or different (–) level. If the interaction effect has the same sign as the main effects, the interaction has an intensifying effect, e.g. in the fourth column: A (+), B (+) and A × B. If the interaction effect has different signs like the main effects, the interaction has a weakening effect, e.g. in the first column: A (–), B (–) and A × B (Siebertz et al., 2017, p. 15).

Table 5-4: Interaction columns of the experimental design, own representation based on Siebertz et al. (2017, p. 19)

A	*B*	*C*	*AB*	*AC*	*BC*	*ABC*	*y*
-	-	-	+	+	+	-	y_1
+	-	-	-	-	+	+	y_2
-	+	-	-	+	-	+	y_3
+	+	-	+	-	-	-	y_4
-	-	+	+	-	-	+	y_5
+	-	+	-	+	-	-	y_6
-	+	+	-	-	+	-	y_7
+	+	+	+	+	+	+	y_8

The interaction between the Printing mode × Size and Printing mode × Complexity illustrates Figure 5-18. The points of the same sign lie on a diagonal in the plane Printing mode and Size, see the left cube. Likewise, the points of Printing mode and Complexity are on a diagonal in-plane, see the right cube.

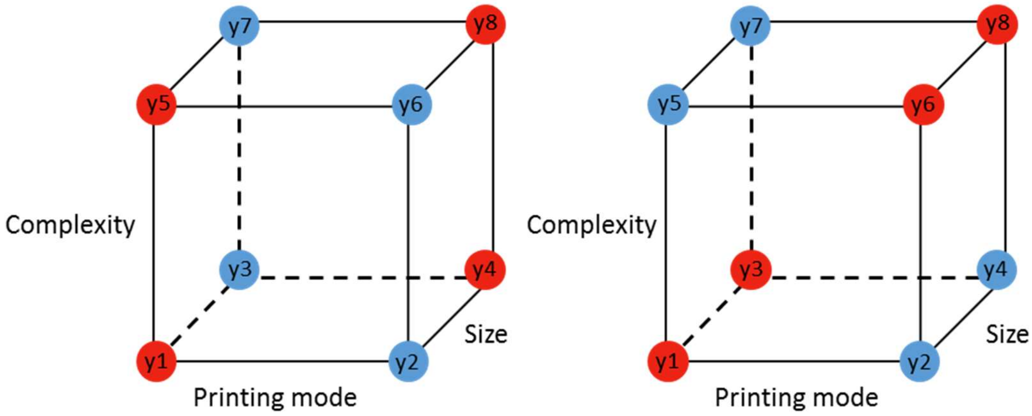


Figure 5-18: Graphical representation of the interactions Printing mode × Size and Printing mode × Complexity, own representation based on Siebertz et al. (2017, p. 20)

Figure 5-19 shows the interactions between Size × Complexity and Printing mode × Size × Complexity. Also, in this case, the dots of the same sign are on a diagonal in the plane Size and Complexity, see the left cube. In the right cube, the dots with the same sign form a tetrahedron.

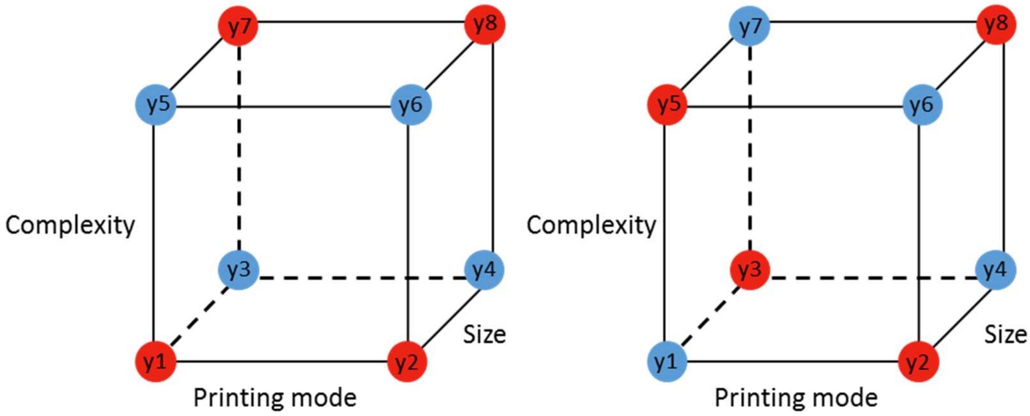


Figure 5-19: Graphical representation of the interactions Size × Complexity and Printing mode × Size × Complexity, own representation based on Siebertz et al. (2017, p. 20)

Finally, a linear description model is developed, which quantifies the effect of the main effects and interactions on the quality characteristic. The result is a descriptive equation that quantifies correlations. A linear description model for the present case is as follows:

$$y = c_0 + c_1x_1 + c_2x_2 + c_3x_3 + c_{12}x_1x_2 + c_{13}x_1x_3 + c_{23}x_2x_3 + \varepsilon$$

For each combination of the input variables $x_1 = Printing\ mode,\ x_2 = Size$ and $x_3 = Complexity$, the model provides an approximation of the quality characteristic y. The seven model constants are $c_0 \ldots c_{23}$ and the deviation is ε. With a suitable model, the deviation is small compared to the variation of the quality characteristic (Siebertz et al., 2017, p. 21).

5.3.4 Test cycle

In this subsection, the actually applied test cycle is presented, which is based on the design of experiments. The test cycle has a total of eight different settings, which are executed sequentially. A pause is made between each setting until the temperature sensor next to the UV lamp has the same temperature as the temperature sensor that measures the outside temperature. This ensures that the UV lamp is completely cooled down. Table 5-5 lists the individual settings.

Table 5-5: Applied test cycle

Printing mode	Size [mm]	Complexity	Printing time [h]	Setting number
High-speed mode	50	Low	0.5	1
High-quality mode	50	Low	1	2
High-speed mode	100	Low	1	3
High-quality mode	100	Low	1	4
High-speed mode	50	High	2	5
High-quality mode	50	High	2	6
High-speed mode	100	High	2	7
High-quality mode	100	High	4	8

The following explains the effects of the individual settings on the printing process simulation system, which has three adjustable parameters. The speed of the linear spindle, the length of the distance to be moved and the burning time of the UV lamp can be set. When the high-speed mode is set, the linear spindle moves at a 6.67 % faster speed than in high-quality mode. That is because of high-speed mode prints with a layer thickness of 30 micrometres, while high-quality mode prints with a layer thickness of 16 micrometres and twice the printing time.

If an object with a size of 50 mm is printed, the linear spindle moves 50 mm in one direction and 50 mm in the other direction. Analogously, the linear spindle moves with an object of a size of 100 mm. The complexity of the object has an influence on the printing time and thus on the burning time of the UV lamp. High complexity objects are created with slower-moving printheads and require twice the printing time compared to a low complexity object. The speed of the work spindle is halved for highly complex objects, while it remains the same for less complex ones. The burning time of the UV lamp is preset for each setting with the HomeMatic radio switching actuator. Appendix A contains the program code for the work spindle in which the different speeds, times and moving lengths are defined as well as the burning times set via the HomeMatic.

Chapter 6 Validation of the system

The chapter contains the validation of the smart maintenance system on the printing process simulation system. The objective is to validate the functional capability of the smart maintenance system. The validation procedure is performed on the basis of the test cycle described in Subsection 5.3.3. During the validation of the system, it will be investigated whether there are further accepted, critical and rejected ranges for the factors influencing the lifetime of the UV lamp. It is tested until the UV intensity is no longer sufficient for the curing of the printing material and the useful lifetime is used up. The data collected is compared with data of an existing lifetime model. Finally, the fulfilment of the requirements is evaluated.

First of all, an overview of the dashboard of the smart maintenance system in operation is given, which indicates the condition values of the UV lamp. Figure 6-2 shows the upper part of the dashboard where all categorised measurands are displayed live in a green, yellow or red window depending on their value. The information about the remaining useful lifetime is placed on the left side. To the right is the categorised UV intensity in the UVA and UVB spectrum. In addition, each UV intensity is plotted with the current and past values in a diagram. The values of the four temperature sensors are also reported in categorised colour-coded windows.

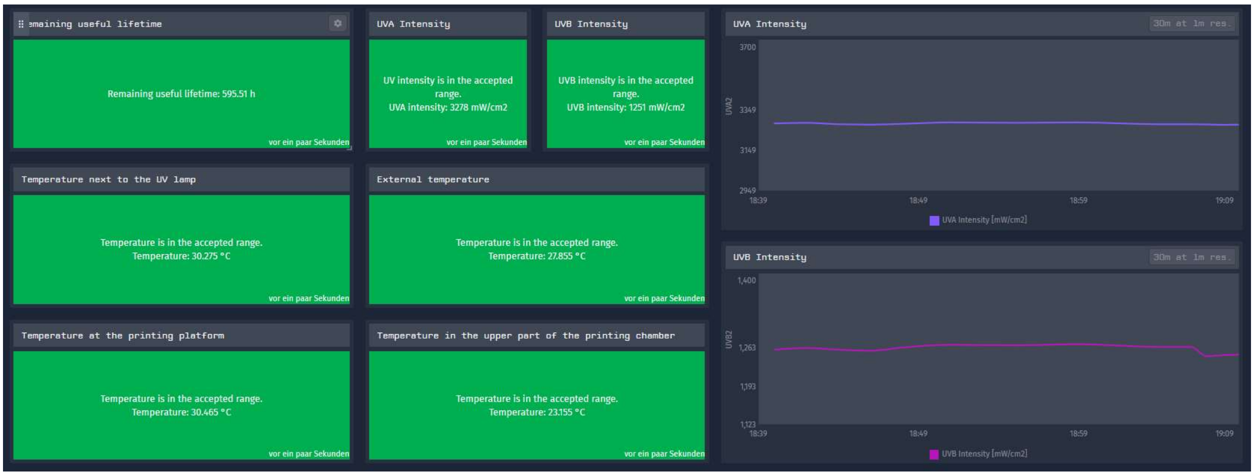


Figure 6-1: Upper part of the dashboard

In the middle area of the dashboard on the left side are the courses of the individual measured temperatures, as shown in Figure 6-2. On the right side, the measured values of the power measurement are given in individual diagrams.

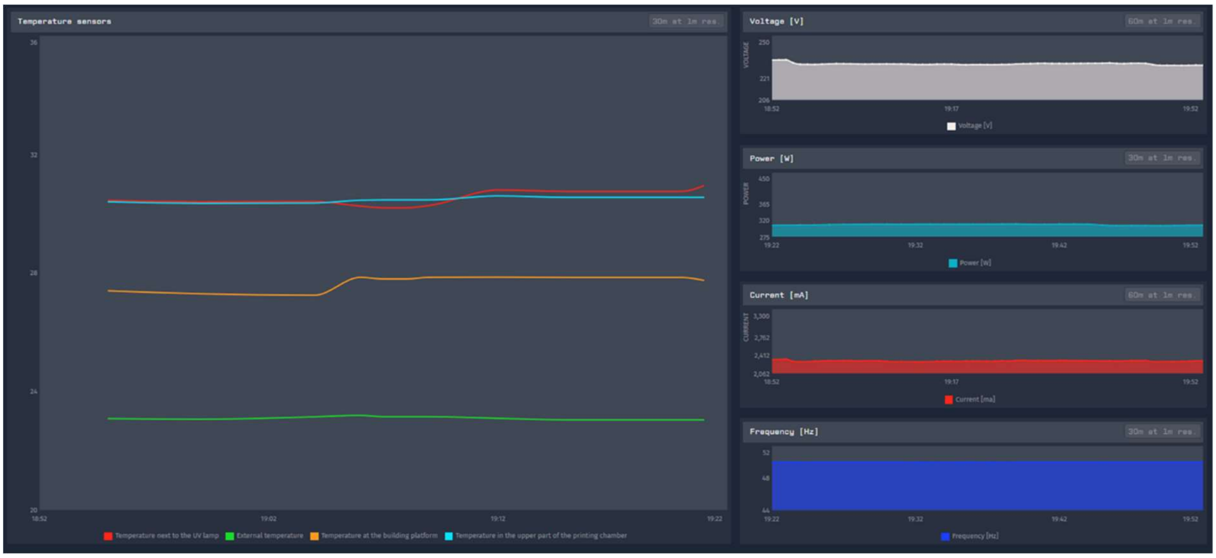


Figure 6-2: Middle part of the dashboard

The acceleration values in x-, y- and z-axes as well as the energy consumption are visualised in the lower part of the dashboard, see Figure 6-3.

Figure 6-3: Lower part of the dashboard

6.1 Measured values

The following section provides the values of the sensors measured during the validation of the system. First, the course of the measured values for each measurand during a printing process is shown as an example on test cycle setting five. The mentioned printing process simulates the setting ‘high-speed mode, an object size of 50 mm and a high complexity. This results in a printing time of two hours, which corresponds to the same burning time of the UV lamp. The measured values of the printing process are from the initial phase of the experiment and are the first values obtained in this print setting.

In the next step, the measured values of each sensor are displayed in the time interval of the useful lifetime. Therefore the values of the UV intensity are presented first. This is followed by the values of the various temperature sensors, the acceleration sensor and the power measurement. Finally, the measured UV intensity is compared with the existing lifetime model.

6.1.1 UV intensity

The subsection presents the measured values of the UV intensity in the UVA and UVB spectrum in test cycle setting five and afterwards over the entire useful lifetime of the UV lamp. Figure 6-4 illustrates the measured UV intensity in the UVA spectrum during a two-hour simulated printing process. The UV lamp has a starting phase of approximately three minutes until the lamp releases its full UV intensity. After that, all measured values are within an interval of 3292 mW/cm^2 to 3260 mW/cm^2 until the lamp is switched off again. The UV intensity is sufficient for the curing of the printing material over the entire simulated printing process.

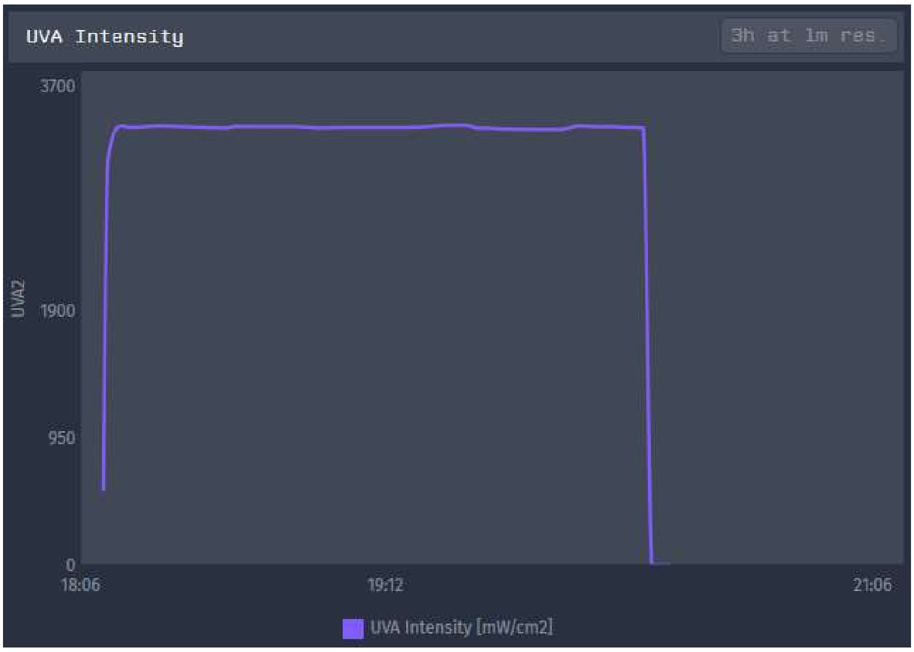


Figure 6-4: Measured UV intensity in the UVA spectrum in test cycle setting five

In order to achieve full UV intensity in the UVB spectrum, the UV lamp also needs a start-up phase of three minutes, see Figure 6-5. All values measured afterwards are within an interval of 1241 mW/cm^2 to 1266 mW/cm^2. The measured UV intensity is as well sufficient for the curing of the printing material.

Figure 6-5: Measured UV intensity in the UVB spectrum in test cycle setting five

The measured initial values of the UV intensity in the UVA spectrum amounts to 3280 mW/cm^2. Sufficient curing of the printing material is guaranteed up to 75 % of the initial value. The diagram shows the absolute values of the UV intensity with a stray area of -1 % to +1 %, see Figure 6-6. After a burning time of 474 hours and 43 minutes, a UV intensity of 2460 mW/cm^2 was measured for the first time, which is 25% less than at the beginning. From this point, the UV intensity is no longer sufficient for the complete curing of the printing material. A total of 284 single test settings were carried out until the UV intensity fell below for the first time at test setting seven after 1.72 h.

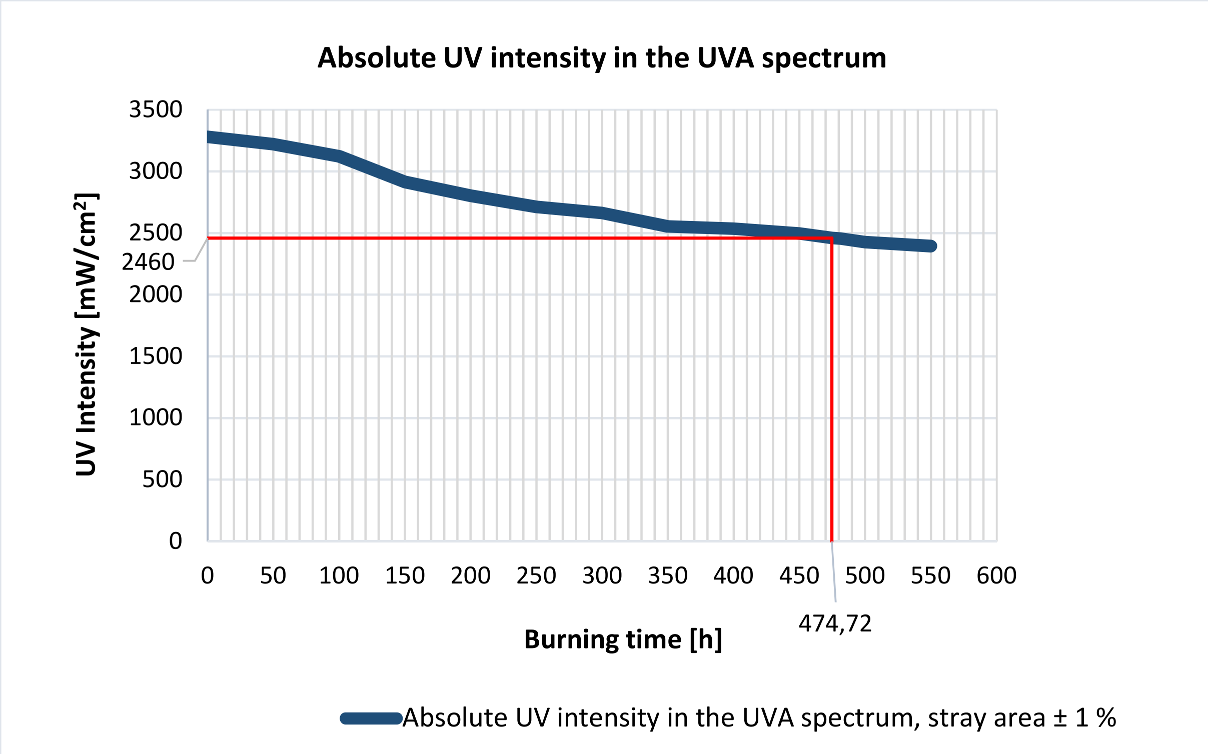


Figure 6-6: Absolute UV intensity in the UVA spectrum of the UV lamp

Figure 6-7 shows the relative UV intensity in the UVA spectrum. The relative UV intensity is composed of the division of the UV intensity measured at the respective time and the initial UV intensity.

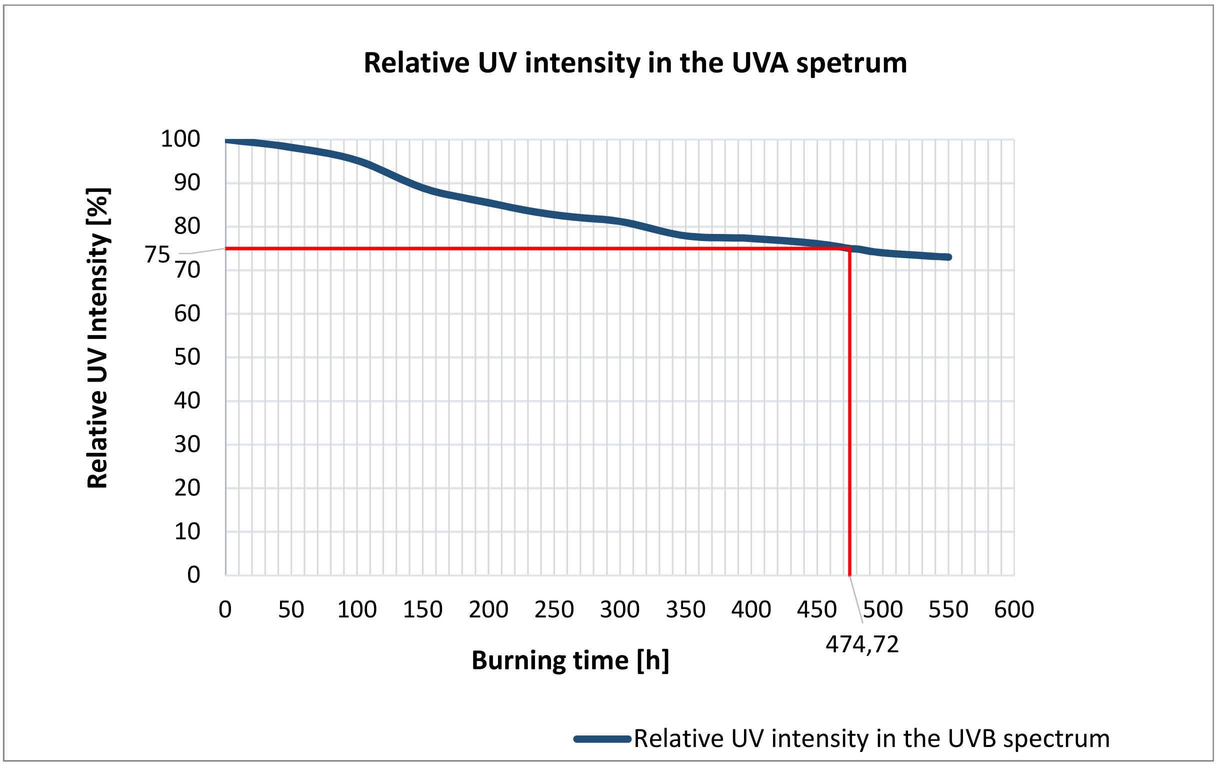


Figure 6-7: Relative UV intensity in the UVA spectrum of the UV lamp

Figure 6-8 shows the absolute values of UV intensity in the UVB spectrum in a stray area of -1 % to +1 %. The measured initial UV intensity in the UVB spectrum is 1250 mW/cm^2. In order to enable sufficient curing of the printing material, a UV intensity in the UVA spectrum of at least 937.5 mW/cm^2 is required, which is equivalent to 75 % of the initial value. After a burning time of 481 hours and 22 minutes, the specified limit value is reached. A total of 288 test settings have been performed until the UV intensity in the UVB spectrum fell below the required value at test setting three after 1.87 h.

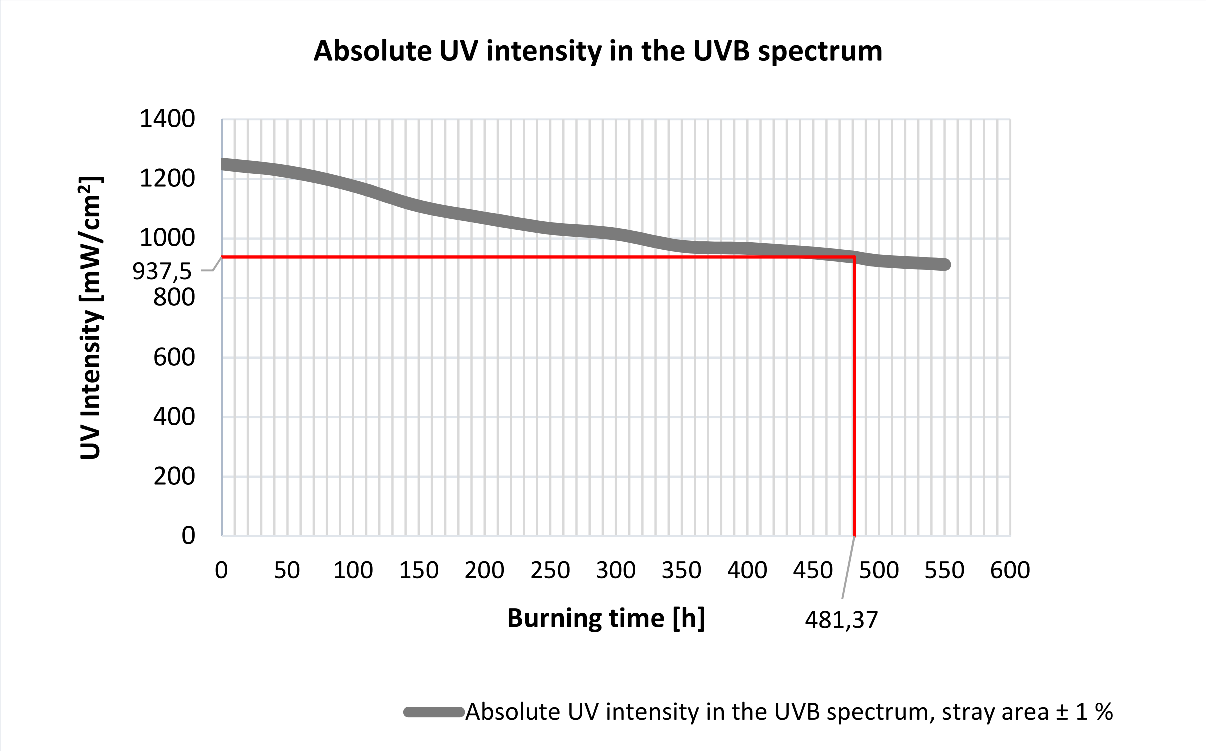


Figure 6-8: Absolute UV intensity in the UVB spectrum of the UV lamp

The relative UV intensity in the UVB spectrum is calculated by dividing the UV intensity measured at the respective time by the initial UV intensity, see Figure 6-9.

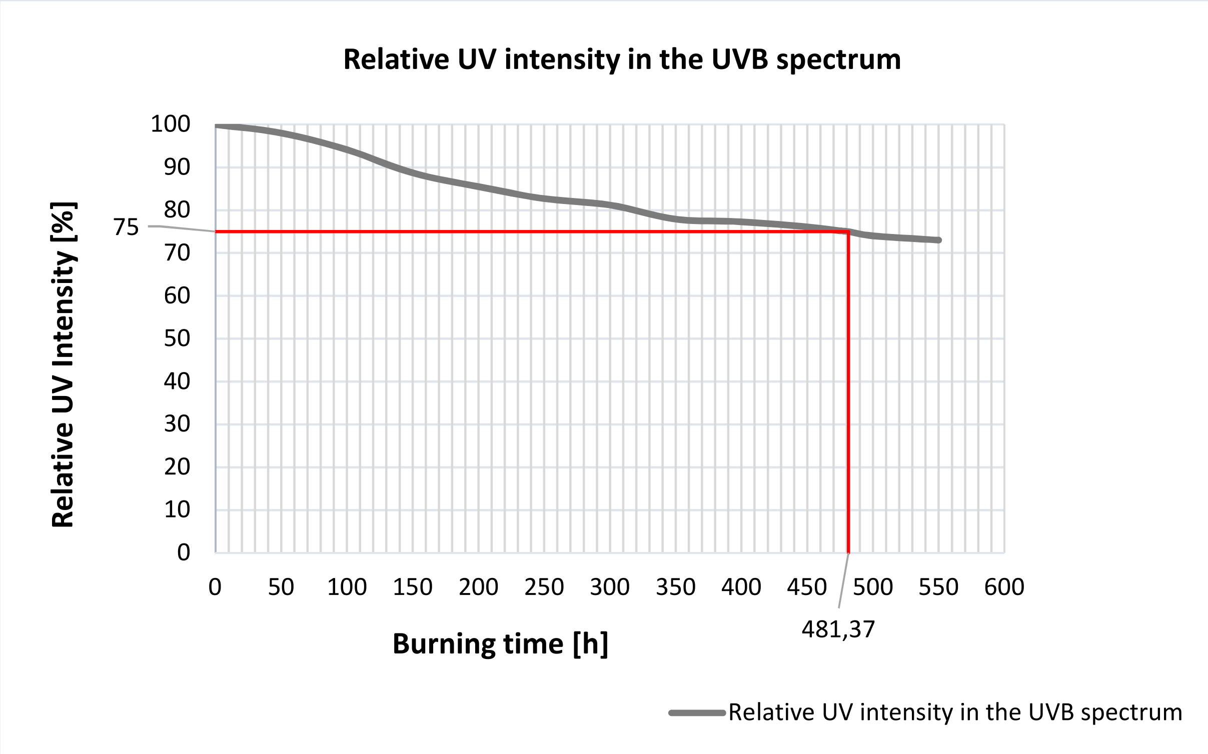


Figure 6-9: Relative UV intensity in the UVB spectrum of the UV lamp

6.1.2 Temperature

The measured temperature values of the individual sensors are described in this section.

First, the course of the temperature values during the printing process is shown on the test cycle setting five. This is followed by the temperature curves over the entire useful lifetime of the UV lamp.

Figure 6-10 illustrates the temperature curves during the simulated printing process in setting five.

The red curve of the temperature sensor in the direct vicinity of the lamp increases from 23 °C to 30 °C within five minutes after the UV lamp starts. The temperature never exceeds 32.5 °C at any time, which in turn means that the temperature is within the recommended range. The green curve of the external temperature sensor remained constant at about 23 °C over the entire operating time and is accordingly in the accepted range. The orange curve indicates the measured temperature values, which an object to be produced experiences on the building platform.

The temperature is within the temperature range of 25 °C to 30 °C during the entire printing process, that is required for curing.

The turquoise curve indicates the temperature in the upper part of the printing chamber. The highest measured temperature of the sensor is about 31 °C, which is in the accepted range as well.

Figure 6-10: Measured temperatures in the test cycle setting five

The measured temperatures over the entire useful lifetime are in the same range as the values measured within the test cycle setting five. The measured temperature next to the UV lamp and the external temperature are consistently in the accepted range. The temperature measured on the building platform is at all times within the required temperature range of 25 °C to 30 °C. Also, the temperature in the upper area of the printing chamber was consistently within the accepted range.

6.1.3 Acceleration

The acceleration values are given in x-, y- and z-axis and have the unit m/s^2. The x-axis indicates the vibration orthogonal to the working spindle. The measured values are between -0.7 m/s^2 and 0.7 m/s^2. The measured values in the y-axis are between 8.5 m/s^2 and 11 m/s^2 because in this case, the y-axis of the sensor points to the centre of the earth. The values of the z-axis describe the acceleration in of the linear movement of the working spindle.

6.1.4 Power measurement

The power measurement sensor provides the current, voltage, frequency, and effective power as well as power consumption. First, the measurements of the test cycle setting five are introduced. Next, the values are described over the entire useful lifetime of the UV lamp.

Figure 6-11 depicts the current of the UV lamp in the starting phase as well as during operation. A current of 2845 mA flows to the ballast to ignite the UV lamp. During operation, a current of 2270 mA to 2339 mA flows.

Figure 6-11: Measured current in the test cycle setting five

In the following, the further values that were measured during the operation of the UV lamp are presented. The measured voltage is within a range of 229.7 V to 234.8 V.

The frequency is consistent in an interval of 49.96 Hz and 50.02 Hz. The measured electrical power to operate the UV lamp is within the interval between 306.1 W to 316.2 W. The specified electrical power of the UV lamp amounts 250 W. This leads to the conclusion that approximately 65 W to 75 W is lost in the ballast and ignition unit, for example as waste heat. As a result, electricity consumption is 0,31 kWh.

The measured values over the entire useful lifetime are in the same range as the measured values from the previously described test cycle setting five. There is no difference in the measured values between a start phase of the UV lamp at the beginning or at the end of the useful lifetime. Similarly, there were no differences in the values during the operation of the UV lamp between the beginning and the end of the useful life.

6.2 Comparison with existing lifetime model

In this subsection, the obtained data on the UV intensity is compared with an existing lifetime model of a UV lamp with a mercury spectrum. The lifetime model is valid on the condition that the UV lamp is started a maximum of three times a day. Otherwise, half an hour will be deducted from the remaining useful lifetime each time the lamp is switched on.

The UV lamp used in the test has a useful lifetime of 600 hours, as specified by the manufacturer. The test is performed according to the defined test cycle. The UV lamp has been switched on a total of 284 times until the required UV intensity in the UVA spectrum was fallen below, of which 149 were turn-ons, which were considered as a fourth start or more per day. This results in additional wear of 74.5 hours, which is equivalent to a useful lifetime of 525.5 hours. However, the actual useful lifetime is 474.72 hours. A start of the UV lamp carried out for the fourth time or more often on the same day, subtracts in this case 0.84 hours instead of 0.5 hours from the useful lifetime. For this purpose, the useful lifetime, specified by the manufacturer, is subtracted from the actual useful lifetime and divided by the number of starts per day performed as the fourth start or more. The UV intensity in the UVB spectrum is fallen below the limit value after 6.65 hours after the UVA intensity in the UVA spectrum has been undershot. This results in a useful lifetime in the UVB spectrum of 481.37 hours. In this case, the UV lamp has been switched on 288 times, of which 153 starts were performed, counting as fourth start or more per day. This also results in additional wear of 0.77 hours as soon as the UV lamp is switched on more than three times a day.

The curve of the decrease of the relative UV intensity in both spectra has similarities with the existing lifetime model. In this case, the influencing factor for additional wear of the useful lifetime of half an hour is set too low and must be adjusted to 0.84 h in the UVA spectrum and 0.77 h in the UVB spectrum.

6.3 Fulfilment of the requirements

The section describes on the basis of the test cycle performed whether the defined requirements are fulfilled. The degree of fulfilment is divided into 'integrated' and 'non-integrated'. If the functional capability of the requirement is fulfilled, the degree of fulfilment is considered as ‘integrated’. If the functional capability of a requirement is not demonstrated during the validation, the degree of fulfilment is classified as ‘non-integrated’.

Table 6-1 indicates the degree of fulfilment of the defined requirements of the smart maintenance system based on the data recorded during the validation process.

Table 6-1: Degree of the fulfilment of the requirements for the smart maintenance system

Requirements				Target type	Degree of fulfilment
1. Data collection	Relative UV intensity [%]	UV intensity of the UV lamp in UVA spectrum		Must	Integrated
		UV intensity of the UV lamp in UVA spectrum		Must	Integrated
	Temperature (0°C – 120 °C)	Temperature next to the UV		Must	Integrated
		External temperature		Must	Integrated
		The temperature at the building platform		Wish	Integrated
		An additional sensor in the printing chamber		Wish	Integrated
	Accelerometer (-15 m/s^2 – +15 m/s^2)	Movement of the lamp in the x-axis		Must	Integrated
		Movement of the lamp in the y-axis		Must	Integrated
		Movement of the lamp in the z-axis		Must	Integrated
	Power measurement	Voltage (0 V – 250 V)		Must	Integrated
		Current (0 A – 10 A		Must	Integrated
		Frequency (49 Hz –51 Hz)		Must	Integrated
		Effective power (0 W – 3000 W)		Wish	Integrated
		Energy consumption (0 kWh – 3 kWh)		Wish	Integrated
2. Data processing	Complete			Must	Integrated
	Transfer interval [s]	Temperature values	2	Must	Integrated
		Accelerometer values	2	Must	Integrated
		UV intensity values	2	Must	Integrated
		Power measurement values	2	Must	Integrated
3. Data analysing and categorising	Temperature values			Must	Integrated
	UV intensity values			Must	Integrated

Requirements		Target type	Degree of fulfilment
	Calculation of remaining useful lifetime of the UV lamp based on manufacturer specifications	Must	Integrated
	Counting of the turn-on frequency of the UV lamp	Must	Integrated
4. Data visualisation	Measured values	Must	Integrated
	Analysed and categorised values	Must	Integrated
	Context-related maintenance measures for categorised temperature values, UV intensity values and remaining lifetime	Must	Integrated
	Notification function for categorised temperature values, UV intensity values and remaining lifetime by email or SMS	Must	Integrated
	Availability of historical values	Must	Integrated
5. Data access and security	Access by PC, smartphone and tablet	Must	Integrated
	Location-independent	Must	Integrated
	Authorised	Must	Integrated
	Encrypted data transfer	Must	Integrated
6. Modular expandability	Software: Integration of IT systems such as ERP-systems, production planning systems or advanced planning	Wish	Integrated
	Hardware: Integration of additional sensors and actors	Wish	Integrated
7. Setup of the final system	System retrofittability within one hour	Wish	Integrated
8. Cost of the system	As cost-effective as possible: < 1000 Euro or 16,000 Rand	Wish	Integrated
9. Safety of the system	No potential danger from the system for humans or the environment	Must	Integrated

The validation demonstrates that all defined system requirements are met. The functional capability of the smart maintenance system is proven.

6.4 Further fields of application

The subsection examines if the functioning smart maintenance system can be applied in the context of other UV lamps. The requirements of the UV lamps from the industrial applications described in Section 2.3 serve as an initial situation.

The existing system monitors the influencing factors of the lifetime of the UV lamps as well as the factors that are decisive for the process result. Consequently, the influencing factors for the lifetime of the components already known since the components to be monitored are also UV lamps. The lifetime can be determined on the basis of the existing lifetime model and adapted to the lifetime specified by the manufacturer of the UV lamp to be applied. If a lifetime model of the UV lamp applied is available, this model can be used as a basis. Furthermore, the factor which has an influence on the process result of the application must be known. For instance, for an application with a certain required UV intensity, a reference value must be first defined. The reference measurement is carried out with the UV sensor at the same distance to the UV lamp as the sensor is integrated within the later application. The defined reference value is set in relation to the values determined during the operation of the application. Subsequently, the respective limit values for the application have to be determined, such as the required UV intensity or external temperature.

The smart maintenance system developed can be used for further applications with UV lamps under the condition that limit values such as temperature and UV intensity are adjusted to the requirements of the new application.

Chapter 7
Summary, conclusions and recommendations

The chapter provides the reader with a brief overview of the thesis. First, a summary of each chapter is given, describing the research content and approach. This is followed by a description of how the defined research questions were approached and how they were answered within the context of the research work. Finally, the limitations and recommendations for future research projects are outlined.

7.1 Research summary

The subsection summarises the individual chapters to give an overview of the research study. Chapter 1 introduces the research topic and starts with background information on smart maintenance systems. The research problem and questions are defined as well as the research objectives and contributions are directed. The research methodology and design are then constituted. The ethical considerations, as well as the delimitations and limitations of the research, are regarded. The thesis structure is outlined at the end of the chapter.

The literature review in Chapter 2 provides insights into smart maintenance, the structure of cyber-physical systems and applications of UV lamps as well as the specific UV lamp to be investigated.

An overview of research approaches and established applications that belong to the adjacent research area of smart maintenance systems is given in Chapter 3.

Chapter 4 determines the concept of the smart maintenance system. The requirements for the system are based on the findings of the literature review and defined from the projects in adjacent research areas. The functional model of the smart maintenance system architecture is created, whose functionalities are geared to the defined requirements. Based on the requirements and the function model, the hardware and software are selected.

Chapter 5 describes the development of the smart maintenance system. First, the printing process simulation system is presented, on which the smart maintenance system is validated. Next, the hardware is assembled and retrofitted to the printing process simulation system. The development and functionality of the source code and the IoT platform is explained.

Finally, the test cycle for the validation process is presented, which is based on the statistical design of the experiment.

The validation of the smart maintenance system on the printing process simulation system is conducted in Chapter 6. The objective is to validate the functional capability of the smart maintenance system. Subsequently, it is investigated whether the existing lifetime model can be used to determine the lifetime of the present UV lamp.

7.2 Research conclusions and contribution

This section summarises the results of the secondary research questions and answers the primary research question. The key findings of each research question are presented below.

SRQ 1	What are the characteristics and requirements of a smart maintenance system?	Chapter 2 & Chapter 4

The main characteristic of a smart maintenance system is the preservation of the operating conditions, which contains to ensure the availability and reliability of machines and plants. Through the application of cyber-physical systems, condition data about critical components in machines is collected. The data are analysed and compared with existing wear models of the components to provide a load-dependent prognosis of the remaining useful lifetime of the components. Based on this data, predictive maintenance strategies can be derived and maintenance relevant information can be provided.

The first requirement for a smart maintenance system is that the system supports the selection of the maintenance strategy decision for machines and plants. The decision-making process should consider object-related as well as the complete value creation network. Furthermore, the maintenance planning must be accelerated by integrating the data from the cyber-physical systems immediately in the maintenance planning module. Search times must be reduced by providing the required information and the application of a planning assistant. The maintenance staff must be provided with context-related maintenance measures to improve usability. IT systems must be able to be flexibly networked to the smart maintenance system to implement additional software solutions such as an enterprise resource planning system or an advanced planning and scheduling system. Moreover, the smart maintenance system must be modularly expandable to enable fast adaptability to application-specific cases such as the monitoring of further critical components.

SRQ 2	How can cyber-physical systems improve maintenance?	Section 2.1

Cyber-physical systems are systems with embedded software, which have abilities of identification, data storage, and data processing, as well as the possibility of interaction and communication. In the context of maintenance, cyber-physical systems can be applied to monitor the condition of critical components or assembly groups which could lead to machine and plant breakdowns. The developed systems enable to collect physical data of the condition using sensors. Integrated actuators allow executing physical processes to preserve the operating condition. The systems are able to store and process data in order to analyse the captured data if certain limit values are reached or deviation to the normal state are given. Cyber-physical systems have human-machine interfaces to provide information such as maintenance relevant information about the condition and the remaining lifetime of a component. The systems are connected to other networks to share their maintenance-relevant information. For instance, the share of information with a spare part supplier in order to have the part ready at the right time.

SRQ 3	What factors are described in the literature that influences the lifetime of UV lamps?	Section 2.3

The literature search has revealed the following influencing factors for UV lamps. The actual burning time of the UV lamp leads to wear. The switch-on and switch-off operations result in a decreasing lifetime. A manufacturer of UV lamps specifies in a lifetime model that a start of the UV lamp carried out for the fourth time or more often on the same day, subtracts the remaining lifetime by half an hour. An increased ambient temperature, which can be attributed to insufficient cooling of the lamp, has a negative effect on the lifetime of the UV lamp. Another factor that has an influence on the lifetime is the vibration of the UV lamp experiences.

SRQ 4	How can lifetime models be developed for components and systems?	Section 2.1

Lifetime models of components and systems are the foundation of predictive maintenance. Collected condition data of a component is compared with the respective lifetime model of the component to provide a prognosis for the remaining lifetime.

There are three different approaches to develop lifetime models for components or systems. The models differ in the range of the later applicability in the costs for the development as well as in their accuracy. Models with a wide range of applicability can be cost-efficient developed by using experienced-based methods such as component failure history assessment. However, the models have a low prediction accuracy. The evolutionary or trending methods such as comparison of measured values of condition describe features with already known reference values, neural networks, Hidden Markov models, or modelling of physical correlations. The models can be applied to several components, have a medium accuracy and can be developed with adequate costs. The model-based prognostics have the highest prediction accuracy and development with intermediate costs. The physical models developed can be used for a limited range of applications.

PRQ	Can a smart maintenance system be developed for the use case of UV lamps?	Chapter 4, 5 & 6

In the area of predictive maintenance, there is no system developed to monitor the condition of UV lamps and predict their remaining lifetime. The present research work describes if such a system can be developed.

The smart maintenance system monitors the influencing factors for the lifetime of UV lamps. For this purpose, the burning time, the number of the switch-on and switch-off operations per day, the temperature in the direct vicinity to the UV lamp as well as the vibration that the UV lamp experiences is captured. Furthermore, the relative UV intensity of the UV lamp is determined since the UV intensity influences the process result of the present UV application. For the implementation, the measurands are temperature, acceleration, relative UV intensity as well as power measurands such as current and voltage. The measured values are categorised into an acceptable, critical and rejected range on the basis of prescribed limit values in order to preserve the operating condition of the UV lamp and adhere to the required process factors. The visualisation of the measured and categorised values are displayed in a dashboard. In the event of reaching a critical and rejected range, a notification is issued and context-related information is provided to preserve and restore the operating condition of the UV lamp.

The developed smart maintenance system is validated on a system, which simulates the application process of the UV lamp. The process simulates the additive manufacturing of a 3D printer that uses the present UV lamp to cure the printing material. The validation process is carried out according to a defined test cycle, which is based on the different possible settings of the 3D printer.

The performed validation reveals that the functional capability of the smart maintenance system is given. The system is able to provide information about the condition and the remaining useful lifetime of the UV lamp by using an existing lifetime model. As soon as measured values are in critical or rejected ranges, measures are initiated to preserve the operating condition of a UV lamp such as the provision of context-related information.

SRQ 5	Can the developed smart maintenance system also be applied in the context of other UV lamps?	Section 7.2

For the application of the smart maintenance system for other UV lamps, the influencing factors of the components to be investigated are already known. The lifetime can be determined on the basis of the existing lifetime model and adapted to the lifetime specified by the UV lamp manufacturer. If a lifetime model of the UV lamp applied is available, this model can be used as a basis. Furthermore, the factor which has an influence on the process result of the application must be known. For an application with a certainly required UV intensity, a reference value must be first defined. The reference measurement is carried out with the UV sensor at the same distance to the UV lamp as the sensor is integrated within the later application. The defined reference value is set in relation to the values determined during the operation of the application. Subsequently, the respective limit values for the application have to be determined, such as the required UV intensity or external temperature.

7.3 Recommendation for further research

Further research is needed to provide more accurate predictions about the remaining useful lifetime of the UV lamp. Also, with regard to the influence of vibration on the UV lamp, further research work needs to be done.

The approach of the statistical design of experiments described in Section 5.3 serves as the basis for the creation of a more accurate lifetime model. The developed printing process simulation system can be used for the execution of further experiments.

The statistical experiments are carried out to obtain the precise wear of the UV lamp depending on the load which is derived from the size and complexity of the objects to be printed as well as the printing mode setting.

The objective is to develop a model that calculates the remaining useful lifetime taking into account the experienced, current and expected load of the UV lamp. The experienced load reflects the wear caused by the prints already performed, whereas the current load is the live wear during the printing process. The expected load represents the wear of the UV lamp, which is predicted due to the characteristics of the object to be printed and the printing mode settings.

In addition, the expected load on the wear of the UV lamp of the following objects to be printed can be considered. In this way, the objects to be printed can be individually evaluated according to their expected load on the wear of the UV lamp and the objects can be preferred for which the remaining lifetime is still sufficient.

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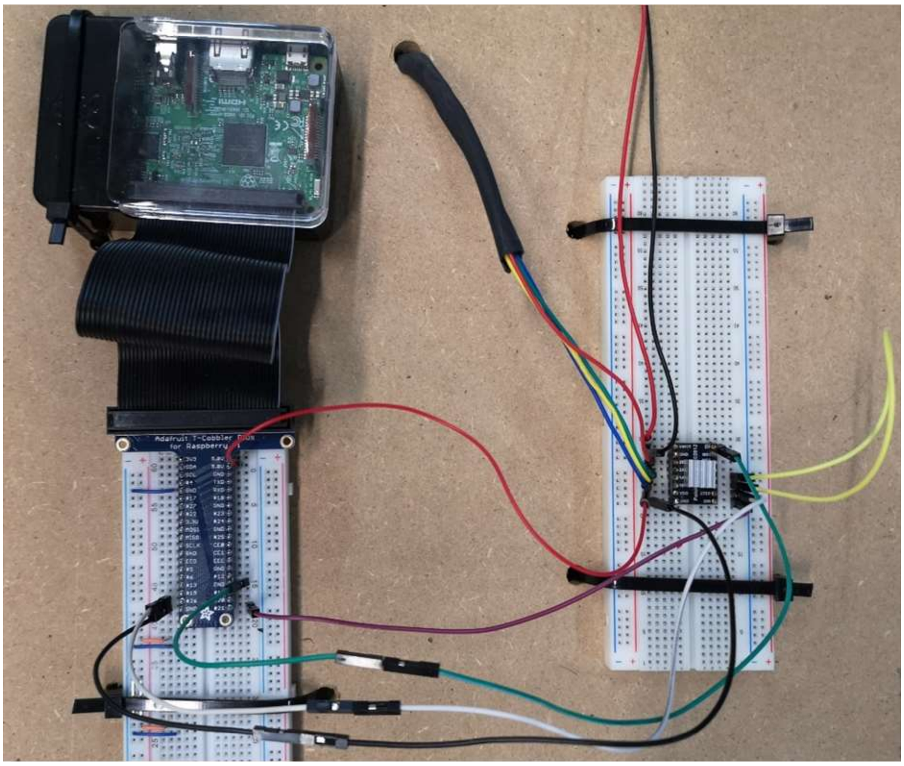
Appendix

Appendix A
Printing process simulation system

Appendix A shows the required hardware and developed software to operate the printing process simulation system. Finally, a list is provided, which contains all parts used to implement the printing process simulation system.

A1 Hardware setup

Appendix 1 shows the wiring of the driver of the stepper motor with the Raspberry Pi.

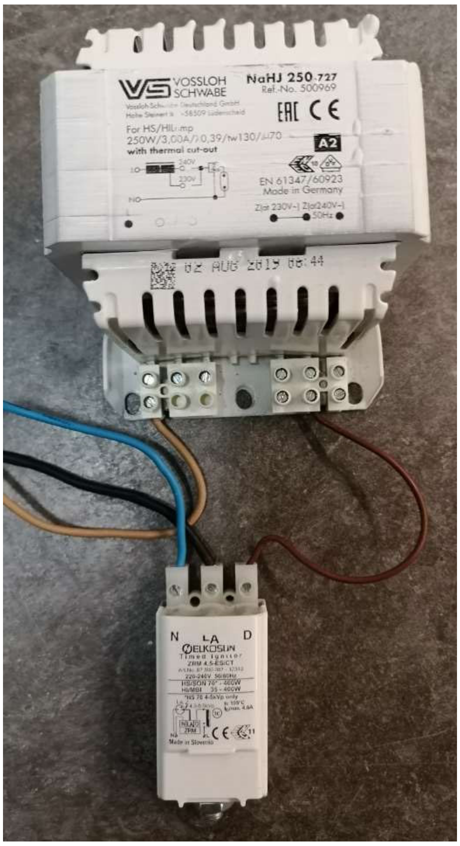


Appendix 1: Wiring of the stepper motor driver with the Raspberry Pi

Appendix 2 illustrates the cover for the printing process simulation system that protects against UV radiation. A total of six cooling are integrated into the cover to provide cooling for the UV lamp.

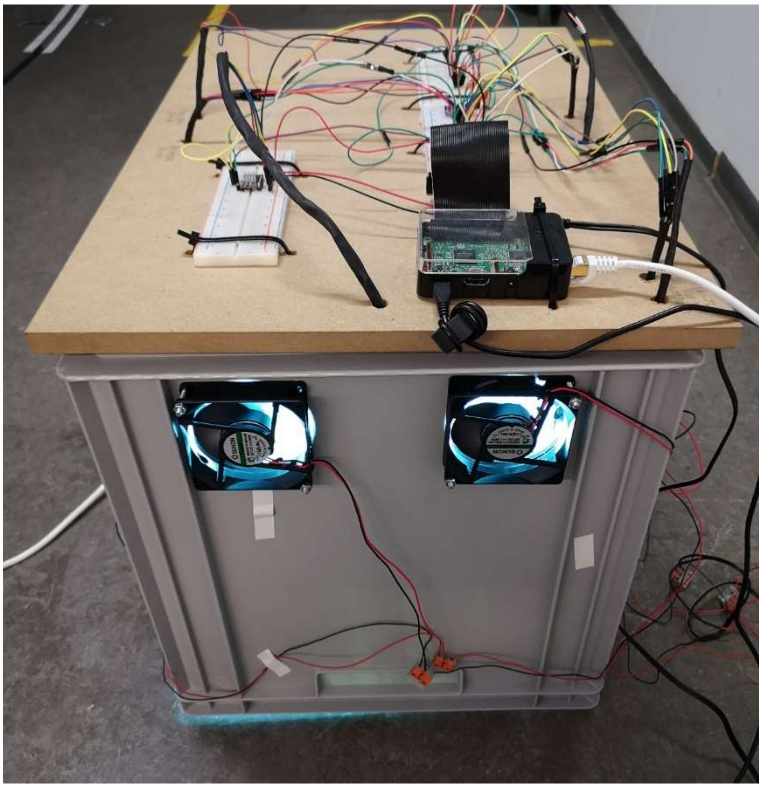
Appendix 2: Cover with integrated cooling fans

The ballast and the ignition unit are responsible for the power supply of the UV lamp, see Appendix 3.



Appendix 3: Ballast and ignition unit to start the UV lamp

Appendix 4 illustrates the smart maintenance system and the printing process simulation system in operation.



Appendix 4: Smart maintenance system and printing process simulation system in operation

A2 Software setup

Appendix 5 shows the source code to control the stepper motor to move the linear spindle.

```
//Imports
const Gpio = require('pigpio').Gpio;
const sleep = require('sleep')

//Motor variables
const time = 3 ; //Time to drive in one direction [s]
const cycles = 300; //Number of repetitions
var dir = 1;  // Direction: 0 = towards motor ; 1 = away from motor
const us = 500; // Time between single steps [µs]

//Wiring to Raspberry Pi
const direction = new Gpio(21, { mode: Gpio.OUTPUT});
const step = new Gpio(26, { mode: Gpio.OUTPUT});

for(var i=0; i<cycles; i++){

    var end = Date.now() + time*1000;
    dir = 1;
    direction.digitalWrite(dir);
//Away from motor
    while(Date.now() <= end){
       step.digitalWrite(1);
       sleep.usleep(us);
       step.digitalWrite(0);
       sleep.usleep(us);
    }
    end = Date.now() + time*1000;
    dir = 0;
    direction.digitalWrite(dir);
//Towards motor
    while(Date.now() <= end){
       step.digitalWrite(1);
       sleep.usleep(us);
```

```
        step.digitalWrite(0);
        sleep.usleep(us);
    }

```

Appendix 5: Source code for the stepper motor

Appendix 6 shows the in Stepper motor variable settings for the individual test cycle settings.

Printing mode	Size [mm]	Complexity	Printing time [h]	Setting number	Motor variables		
					Const time [s]	Const cycles	Constant us
High-speed mode	50	Low	0.5	1	3	300	500
High-quality mode	50	Low	1	2	3.2	562	533
High-speed mode	100	Low	1	3	6	300	500
High-quality mode	100	Low	1	4	6.4	562	533
High-speed mode	50	High	2	5	6	600	1000
High-quality mode	50	High	2	6	6.4	920	1067
High-speed mode	100	High	2	7	12	300	1000
High-quality mode	100	High	4	8	12.8	562	1067

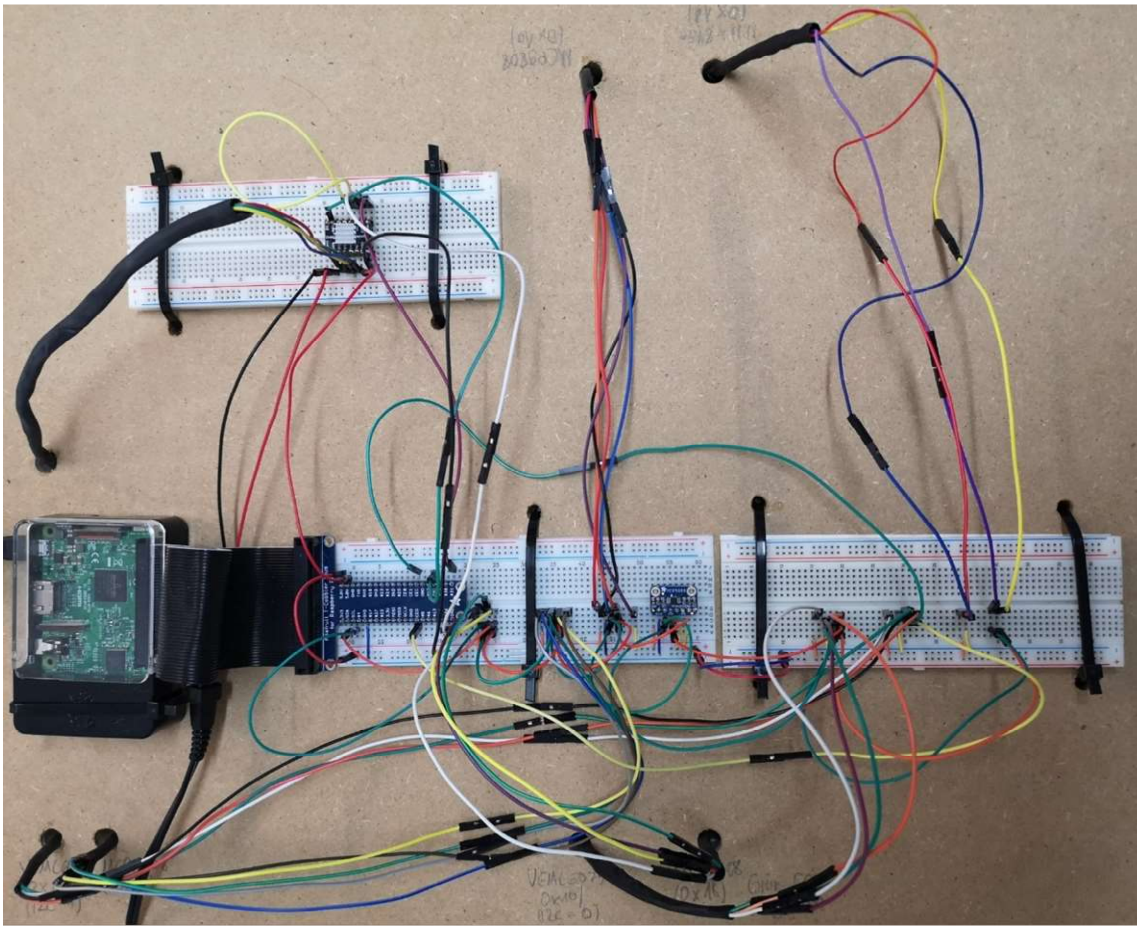
Appendix 6: Stepper motor variable settings for the individual test cycle settings

Appendix B Smart maintenance system

Appendix B contains the hardware and software setup of the smart maintenance system.

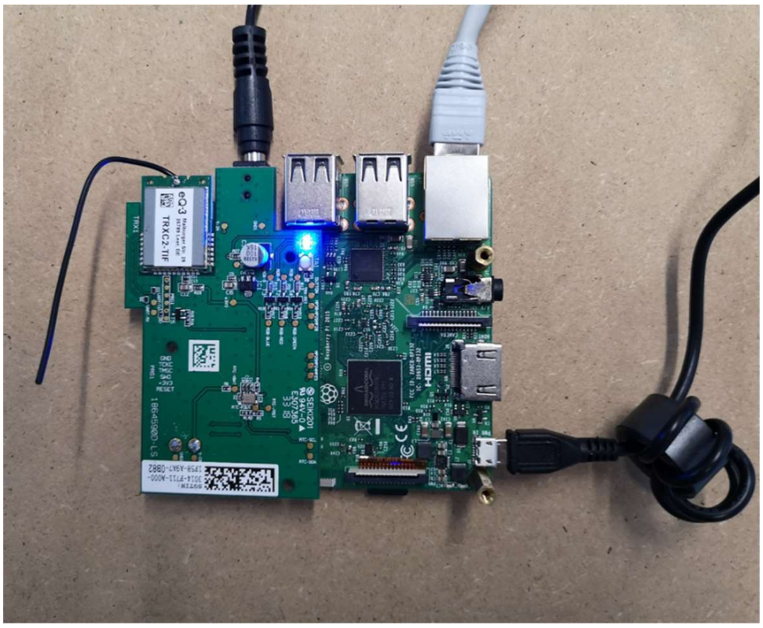
B1 Hardware setup

Appendix 7 shows the wiring of the sensors with the Raspberry Pi and the breadboards.



Appendix 7: Wiring of the sensor to the Raspberry Pi

Appendix 8 illustrates an additional Raspberry Pi 3 Model B with a radio module to capture the data of the Homematic radio socket.



Appendix 8: Raspberry Pi with radio module in operation

B2 Software setup

The software setup contains all required program codes, the implementation of the analysis and categorisation of the measured values on the IoT platform as well as the workflow to provide context-based information.

Appendix 9 shows entire source code to integrate the temperature sensors, the acceleration sensor and the UV sensors.

```
import smbus
import time
import Adafruit_MCP9808.MCP9808 as MCP9808
import time
from losantmqtt import Device
from sys import argv, exc_info
from time import sleep
from smbus import SMBus
import time

import board
import busio

import adafruit_mma8451
a1=0
b1=0
c1=0
d1=0
e1=0

# Initialise Adafruit MMA8451 acceleration sensor
bus = SMBus(1)
# Initialise I2C bus.
i2c = busio.I2C(board.SCL, board.SDA)
sensor = adafruit_mma8451.MMA8451(i2c) # Acceleration sensor
class veml6075: # Adafruit VEML6075 UV sensor
    # Register Addresses
    regUVConf = 0x00
    regUVA = 0x07
```

```
    regUVB = 0x09
    regUVComp1 = 0x0A
    regUVComp2 = 0x0B
    regID = 0x0C
    # Config Register Bit Masks
    powerOn = 0x00
    powerOff = 0x01
    triggerMeasurement = 0x04
    highDynamic = 0x08
    normalDynamic = 0x00
    integTime50 = 0x00
    integTime100 = 0x10
    integTime200 = 0x20
    integTime400 = 0x30
    integTime800 = 0x40
    integStrings = {0x00 : "50ms", 0x10 : "100ms", 0x20 : "200ms", 0x30 : "400ms", 0x40 : "800ms"}
    # UV Coefficents, Responsivity
    A = 2.22  # UVA visible
    B = 1.33  # UVA infrared
    C = 2.95  # UVB visible
    D = 1.74  # UVB infrared
    UVAresp = 0.001461
    UVBresp = 0.002591
    # Conversion Factors (VEML6075 Datasheet Rev. 1.2, 23-Nov-16)
    UVACountsPermWcm = 0.93
    UVBCountsPermWcm = 2.10

    def __init__(self, address):
        self.address = address
        self.integTimeSelect = 0x00
        self.dynamicSelect = 0x00
        self.waitTime = 0.0
        self.divisor = 0
   def setADCSettings(self, i):
        if i == 0:
            self.integTimeSelect = veml6075.integTime800  # Most Sensitive
            self.dynamicSelect = veml6075.normalDynamic
            self.waitTime = 1.920
            self.divisor = 16
        elif i == 1:
            self.integTimeSelect = veml6075.integTime400
            self.dynamicSelect = veml6075.normalDynamic
            self.waitTime = 0.960
            self.divisor = 8
        elif i == 2:
            self.integTimeSelect = veml6075.integTime200
            self.dynamicSelect = veml6075.normalDynamic
            self.waitTime = 0.480
            self.divisor = 4
        elif i == 3:
            self.integTimeSelect = veml6075.integTime100
            self.dynamicSelect = veml6075.normalDynamic
            self.waitTime = 0.240
            self.divisor = 2
        elif i == 4:
            self.integTimeSelect = veml6075.integTime50
            self.dynamicSelect = veml6075.normalDynamic
            self.waitTime = 0.120
            self.divisor = 1
        elif i == 5:
            self.integTimeSelect = veml6075.integTime800
            self.dynamicSelect = veml6075.highDynamic
            self.waitTime = 1.920
            self.divisor = 16
        elif i == 6:
            self.integTimeSelect = veml6075.integTime400
            self.dynamicSelect = veml6075.highDynamic
            self.waitTime = 0.960
            self.divisor = 8
        elif i == 7:
            self.integTimeSelect = veml6075.integTime200
            self.dynamicSelect = veml6075.highDynamic
            self.waitTime = 0.480
            self.divisor = 4
        elif i == 8:
            self.integTimeSelect = veml6075.integTime100
            self.dynamicSelect = veml6075.highDynamic
            self.waitTime = 0.240
            self.divisor = 2
        elif i == 9:
            self.integTimeSelect = veml6075.integTime50  # Least sensitive
            self.dynamicSelect = veml6075.highDynamic
            self.waitTime = 0.120
            self.divisor = 1
```

```
        else:
            self.error("ADC Configuration, Unkown Sensitivity Option")

    def error(self, message):
        print("Error: Failed "+ message)  # print error with message argument passed to function
        print(exc_info())  # print system exception info (type, value, traceback)
        raise SystemExit

    def readDeviceID(self):
        try:
            deviceID = bus.read_word_data(self.address, veml6075.regID)
            print ("Device ID | 0x{:04X}" .format(deviceID))
        except:
            self.error("Device ID Read")

    def readDeviceID(self):
        try:
            deviceID = bus.read_word_data(self.address, veml6075.regID)
            print ("Device ID | 0x{:04X}" .format(deviceID))
        except:
            self.error("Device ID Read")
    def readUV(self, sensitivity):
        self.setADCSettings(sensitivity)
        bus.write_byte_data(self.address, veml6075.regUVConf,
        self.integTimeSelect|self.dynamicSelect|veml6075.powerOn)
        # Write Dynamic and Integration Time Settings to Sensor
        # Write Dynamic and Integration Time Settings to Sensor
        sleep(self.waitTime)  # Wait for ADC to finish first and second conversions, discarding the first
        bus.write_byte_data(self.address, veml6075.regUVConf, veml6075.powerOff)  # Power OFF

        rawDataUVA = bus.read_word_data(self.address,veml6075.regUVA)
        rawDataUVB = bus.read_word_data(self.address,veml6075.regUVB)
        rawDataUVComp1 = bus.read_word_data(self.address,veml6075.regUVComp1)  # visible noise
        rawDataUVComp2 = bus.read_word_data(self.address,veml6075.regUVComp2)  # infrared noise

        scaledDataUVA = rawDataUVA / self.divisor
        scaledDataUVB = rawDataUVB / self.divisor
        scaledDataUVComp1 = rawDataUVComp1 / self.divisor
        scaledDataUVComp2 = rawDataUVComp2 / self.divisor

        compensatedUVA = scaledDataUVA - (veml6075.A*scaledDataUVComp1) - (veml6075.B*scaledDataUVComp2)
        compensatedUVB = scaledDataUVB - (veml6075.C*scaledDataUVComp1) - (veml6075.D*scaledDataUVComp2)

        if compensatedUVA < 0:  # Do not allow negative readings which can occur in no UV light environments
            compensatedUVA = 0
        if compensatedUVB < 0:
            compensatedUVB = 0
        UVAmWcm = compensatedUVA/ veml6075.UVACountsPermWcm  # convert ADC counts to mWcm^2
        UVBmWcm = compensatedUVB / veml6075.UVBCountsPermWcm

        UVAIndex = compensatedUVA * veml6075.UVAresp
        UVBIndex = compensatedUVB * veml6075.UVBresp
        UVI = (UVAIndex + UVBIndex) / 2
        print ("{} Integration Time, {} Dynamic" .format(veml6075.integStrings[self.integTimeSelect],
        "High" if self.dynamicSelect else "Normal"))

        print ("\nADC Counts:")
        print ("UVA ---------- {}" .format(rawDataUVA))
        print ("UVB ---------- {}" .format(rawDataUVB))
        print ("UVComp1 ------ {}" .format(rawDataUVComp1))
        print ("UVComp2 ------ {}" .format(rawDataUVComp2))

        print ("\nADC Counts Scaled to 50ms Integration Time:")
        print ("UVA ---------- {}" .format(int(scaledDataUVA)))
        print ("UVB ---------- {}" .format(int(scaledDataUVB)))
        print ("UVComp1 ------ {}" .format(int(scaledDataUVComp1)))
        print ("UVComp2 ------ {}" .format(int(scaledDataUVComp2)))

        print ("\nADC Counts Compensated for Visible and Infrared:")
        print ("UVA ---------- {}" .format(int(compensatedUVA)))
        print ("UVB ---------- {}" .format(int(compensatedUVB)))

        print ("\nUVA|UVB Radiation:")
        print ("UVA (mWcm) --- {}" .format(int(UVAmWcm)))
        print ("UVB (mWcm) --- {}" .format(int(UVBmWcm)))

        print ("\nUVA|UVB Index:")
        print ("UVA Index ---- {}" .format(round(UVAIndex, 2)))
        print ("UVB Index ---- {}" .format(round(UVBIndex, 2)))
        print ("UVI ---------- {}" .format(round(UVI, 2)))
        print ("\nUVA|UVB Index:")
        print ("UVA Index ---- {}" .format(round(UVAIndex, 2)))
        print ("UVB Index ---- {}" .format(round(UVBIndex, 2)))
        print ("UVI ---------- {}" .format(round(UVI, 2)))
```

```

        return "{}" .format(int(UVAmWcm)),"{}" .format(int(UVBmWcm)),
        "{}" .format(round(UVAIndex, 2)),"{}" .format(round(UVBIndex, 2)),"{}" .format(round(UVI, 2))
#        device.send_state({"UVA": "UVA (mWcm) --- {}" .format(int(UVAmWcm))})
#        device.send_state({"UVB": "UVB (mWcm) --- {}" .format(int(UVBmWcm))})
#        device.send_state({"uvaIndex": "UVA Index ---- {}" .format(round(UVAIndex, 2))})
#        device.send_state({"uvbIndex": "UVB Index ---- {}" .format(round(UVBIndex, 2))})
#        device.send_state({"UVI": "UVI ---------- {}" .format(round(UVI, 2))})

# Construct device
device = Device("5d5e647427db81000672993c", "1fbbe29d-cb7f-451a-921e-552bbc548ff1",
"44244444fa8ce78a78c3f8178e2c5c6c308fc4b2961727eefbcf5c11f6c58520")

def on_command(device, command):
    print("Command received.")
    print(command["name"])
    print(command["payload"])

# Listen for commands
device.add_event_observer("command", on_command)

# Connect to IoT platform Losant
device.connect(blocking=False)

def c_to_f(c):
    return c * 9.0 / 5.0 + 32.0

sensor18 = MCP9808.MCP9808(address=0x18, busnum=1)  # Temperature next to the UV lamp
sensor19 = MCP9808.MCP9808(address=0x19, busnum=1)  # Temperature at the building platform
sensor1a = MCP9808.MCP9808(address=0x1a, busnum=1)  # Temperature in the upper part of the printing chamber
sensor1b = MCP9808.MCP9808(address=0x1b, busnum=1)  # Temperature outside the system

sensor18.begin()
sensor19.begin()
sensor1a.begin()
sensor1b.begin()

print('Press Ctrl-C to quit.')
while True:
    global data
    data = ""
    temp18 = sensor18.readTempC()
    temp19 = sensor19.readTempC()
    temp1a = sensor1a.readTempC()
    temp1b = sensor1b.readTempC()
    print('Temperature18: {0:0.3F}*C'.format(temp18, c_to_f(temp18)))
    print('Temperature19: {0:0.3F}*C'.format(temp19, c_to_f(temp19)))
    print('Temperature1a: {0:0.3F}*C'.format(temp1a, c_to_f(temp1a)))
    print('Temperature1b: {0:0.3F}*C'.format(temp1b, c_to_f(temp1b)))

    x, y, z = sensor.acceleration
    print(data)
    device.loop()
    if device.is_connected():
        temp = 100

        print("x={0:0.3f}m/s^2".format(x))
        print("y={0:0.3f}m/s^2".format(y))
        print("z={0:0.3f}m/s^2".format(z))
        if len(argv) >= 2:  # if the user has passed in an argument use it as the script option
            scriptOption = int(argv[1])
        else:  # else default to most sensitive ADC setting
            scriptOption = 0

        uv = veml6075(0x10)  # instantiate VEML6075 class with address 0x10
        uv.readDeviceID()
        a,b,c,d,e = uv.readUV(scriptOption)

###Code for the second UV sensor which uses the other I2C Bus due to the same I2C address of the sensors
        bus=SMBus(0)

        if len(argv) >= 2:  # if the user has passed in an argument use it as the script option
            scriptOption = int(argv[1])
        else:  # else default to most sensitive ADC setting
            scriptOption = 0

        uv = veml6075(0x10)  # instantiate VEML6075 class with address 0x10
        uv.readDeviceID()
        a1,b1,c1,d1,e1 = uv.readUV(scriptOption)

        bus = SMBus(1)

### Individual sensor values sent to the IoT platform

```

```
        device.send_state({"temperature18": temp18,"temperature19": temp19,
        "temperature1a": temp1a,"temperature1b": temp1b,
        "accelerationX": "{0:0.3f}".format(x),"accelerationY": "{0:0.3f}".format(y),
        "accelerationZ": "{0:0.3f}".format(z),
        "UVA":a,"UVB":b,"uvaIndex":c,"uvbIndex":d,"UVI":e,
        "UVA2":a1,"UVB2":b1,"uvaIndex2":c1,"uvbIndex2":d1,"UVI2":e1})

    time.sleep(0.5)
```

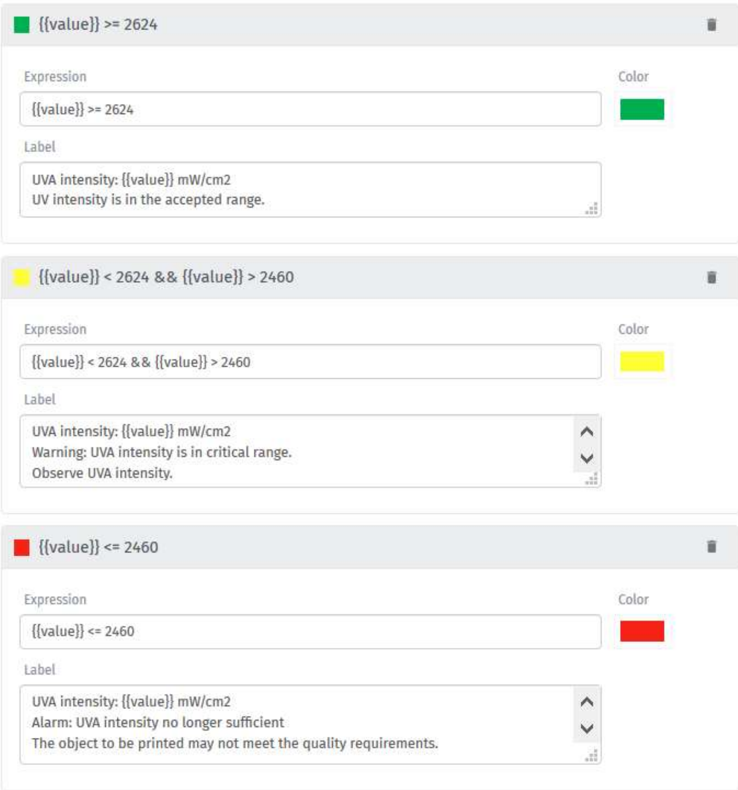
Appendix 9: Entire source code for integrating the temperature sensors, acceleration sensor and UV sensors

Appendix 10 shows the source code for the transfer of the power measurement data from the manufacturer-specific GUI to the IoT platform Losant.

```
const url = 'http://134.103.112.220/'

const request = require('request');
var parseString = require('xml2js').parseString;
setInterval(getValues,2000);
function getValues(){
request(url+'addons/xmlapi/state.cgi?device_id=1394', { json: true }, (err, res, body) => {
if (err) { return console.log(err); }
parseString(body, function (err, result) {
    //console.log(result.state.device[0].channel[0].$.name);
    var channels = result.state.device[0].channel;
    var ch = channels.find((channel) => {
        return channel.$.name === 'HM-ES-PMSw1-Pl PEQ0415171:2'
    })
    var json = {
        values:{
            ENERGY_COUNTER: 0,
            POWER: 0,
            CURRENT:0,
            VOLTAGE:0,
            FREQUENCY:0
        },
        timestamp:0
    }
    for(var name in json.values){
        var point = ch.datapoint.find((elem) => {
            return elem.$.type === name
        })
        json.values[name] = parseFloat(point.$.value)
        json.timestamp = parseInt(point.$.timestamp)
    }
    json.values.TIMESTAMP = json.timestamp
    console.log(json);
    pushJson2Losant(json)
});
});
}
// losant stuff
var api = require('losant-rest');
var client = api.createClient();

function pushJson2Losant(json){
    client.auth.authenticateDevice({ credentials: {
        deviceId: '5dcaa34bbc7127000646f795',
        key: '420634aa-4be3-4910-a6bd-a13b90ea524c',
        secret: '477f72f328c3ec4901d1adfd902774afbefd1df996cc7bcae781e323519995f0'
    }}).then(function (response) {
        client.setOption('accessToken', response.token);
        var appId = response.applicationId;

        var state = { data: json.values };
        return client.device.sendState({
        deviceId: '5dcaa34bbc7127000646f795',
        applicationId: appId,
        deviceState: state
        });
    })
    .then(function (response) {
        console.log(response); // { success: true }
    })
    .catch(function (error) {
        console.error(error);
    });
}
```

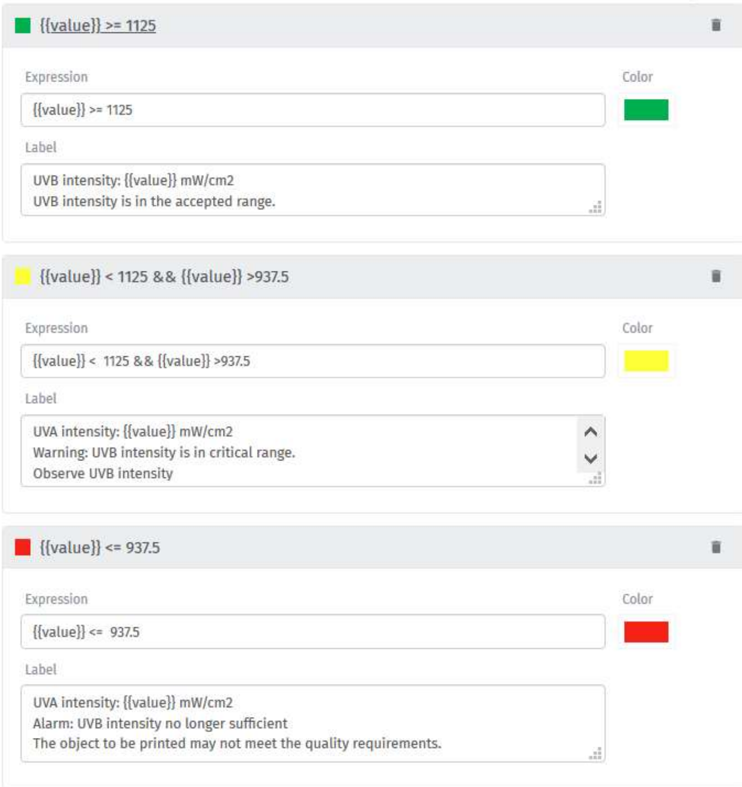
Appendix 10: Source code for the transfer of the power measurement data from the manufacturer-specific GUI to the IoT platform Losant

In the following, the analysed and categorised values are implemented by means of conditional expressions. All values are shown in a colour-coded field in the dashboard with their respective location of measurement. Appendix 11 shows the conditional expressions set up to analyse and categorise the UV intensity in the UVA spectrum



Appendix 11: Analysing and categorising of the UV intensity in the UVA spectrum

Appendix 12 shows the determined conditional expression to analyse and categorise UV intensity in the UVB spectrum.

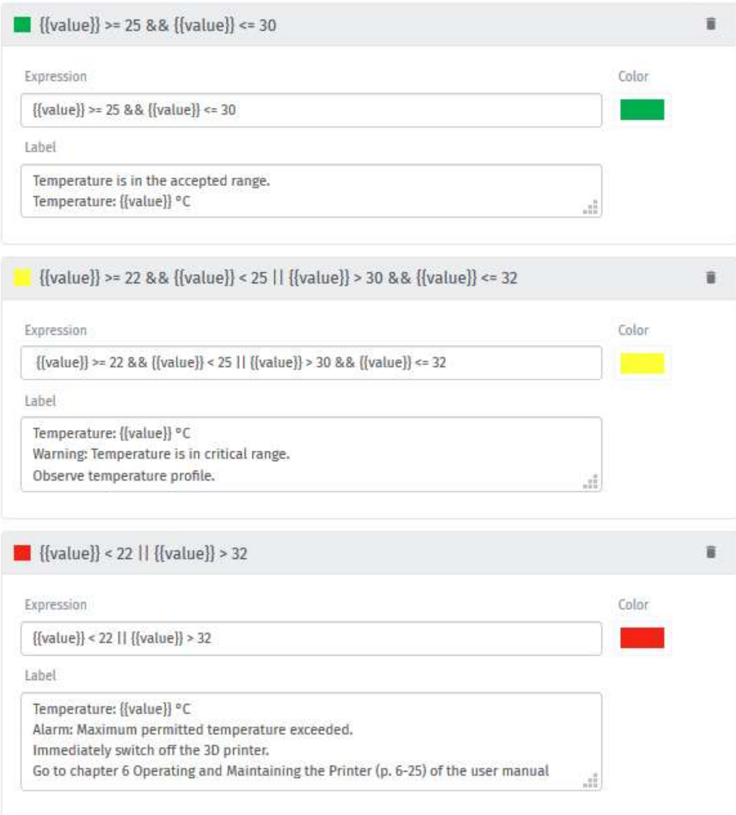


Appendix 12: Analysing and categorising of the UV intensity in the UVB spectrum

Appendix 13 shows the determined conditional expression to analyse and categorise UV intensity in the UVB spectrum.

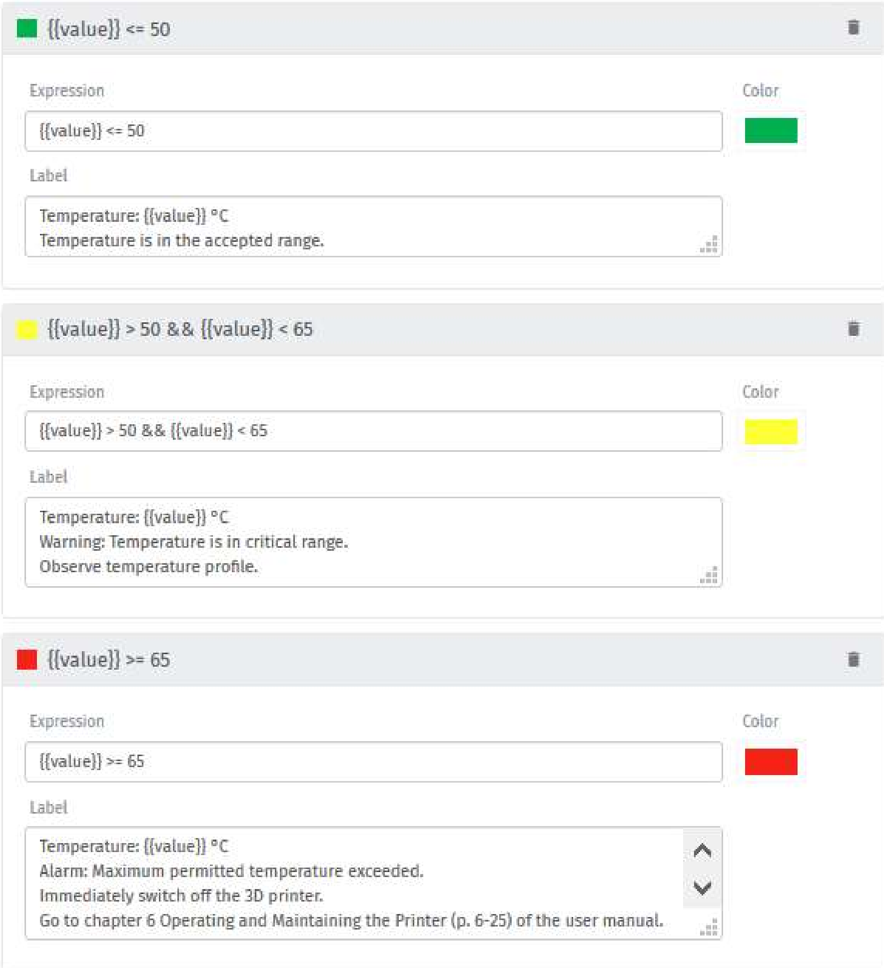
Appendix 13: Analysing and categorising of the external temperature

Appendix 14 illustrates the analysing and categorising of the temperature on the printing platform.



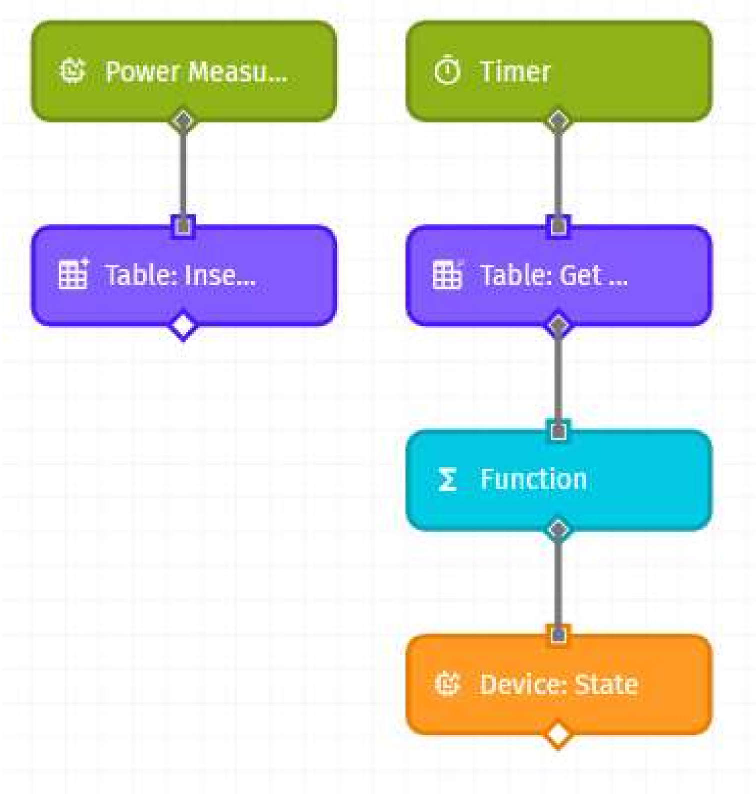
Appendix 14: Analysing and categorising of the temperature on the printing platform

Appendix 15 depicts the conditional expression to analyse and categorise the temperature next to the UV lamp.



Appendix 15: Analysing and categorising of the temperature next to the UV lamp

Appendix 16 illustrates the workflows of the calculation of the remaining lifetime of the UV lamp. In the right workflow, the measured data of the power measurement are stored in a table. In the second workflow, a timer triggers the data readout. The function calculates the remaining useful lifetime by using the current as of the reference value for switching on and off.



Appendix 16: Workflows of the power measurement to calculate the remaining lifetime

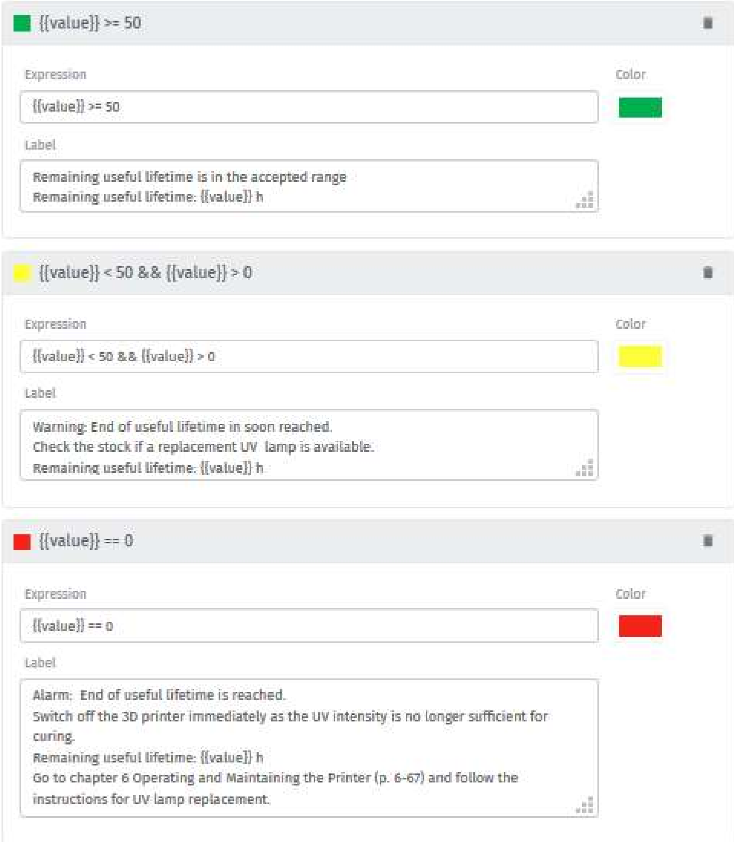
Appendix 17 shows the source code of the developed function, which calculated the remaining useful lifetime of the UV lamp based on the lifetime specified by the manufacturer and an existing lifetime model of UV lamps.

```
// Useful lifetime specified by the manufacturer
var max = 600;

// itemsRaw contains all records, including duplicate records
var itemsRaw = payload.data.payload.items;
// dieses Array ist nachher für die gefilterten Datensätze
var items = [];

// In this loop duplicate items are sorted out and stored in items
for(let i=1;i<itemsRaw.length; i++){
  if(itemsRaw[i].Timestamp !== itemsRaw[i-1].Timestamp){
    let obj = {
      "current":parseFloat(itemsRaw[i].Current),
      "timestamp": parseInt(itemsRaw[i].Timestamp)
    }
       items.push(obj);
  }
}

// onTime are the seconds of the AN-TIME
var onTime = 0;
//countOnTime is the number of switch-on operations
var countOnTime = 0;
// Auxiliary variable to measure time interval
var countOnTimeFirstTimestamp = 0;
//Number of wear deducted in the time interval of 24 hours
varhalfHours = 0;
console.log(items);

// Loop through the filtered items
for(let i=0;i<items.length-1; i++){
  // if ON, add the time interval to the next record to onTime
  if(items[i].current > 0){
    onTime = onTime + (items[i+1].timestamp - items[i].timestamp);

```

```
    // If it was off before, it was a switch-on operation
    if(i>0 && items[i-1].current == 0){
      // Then increment the counter for the switch-on operation
      countOnTime = countOnTime + 1;
      if(countOnTime == 1){
        //Dann startzeit saven
        countOnTimeFirstTimestamp = items[i].timestamp;
      }
      // If the lamp is switched on more than 3 times within 24 hours, add one half hour each.
      if(countOnTime >= 4){
        halfHours = halfHours +1;
      }
      // The counter is reset when 24 hours have passed since the first switch-on operation
      if(items[i].timestamp > countOnTimeFirstTimestamp + 86400){
        countOnTimeFirstTimestamp = 0;
        countOnTime=0;
      }
    }

  }

}
console.log(halfHours)

// Calculation of the remaining lifetime of the UV lamp
var rlt = (max - (onTime+1800*halfHours)/3600)
//mache zahl auf 2 nachkommastellen
rlt = rlt.toFixed(2)


//console.log(rlt);
//console.log(onTime)

//returne das Ergebniss
return {"rlt":rlt};
```

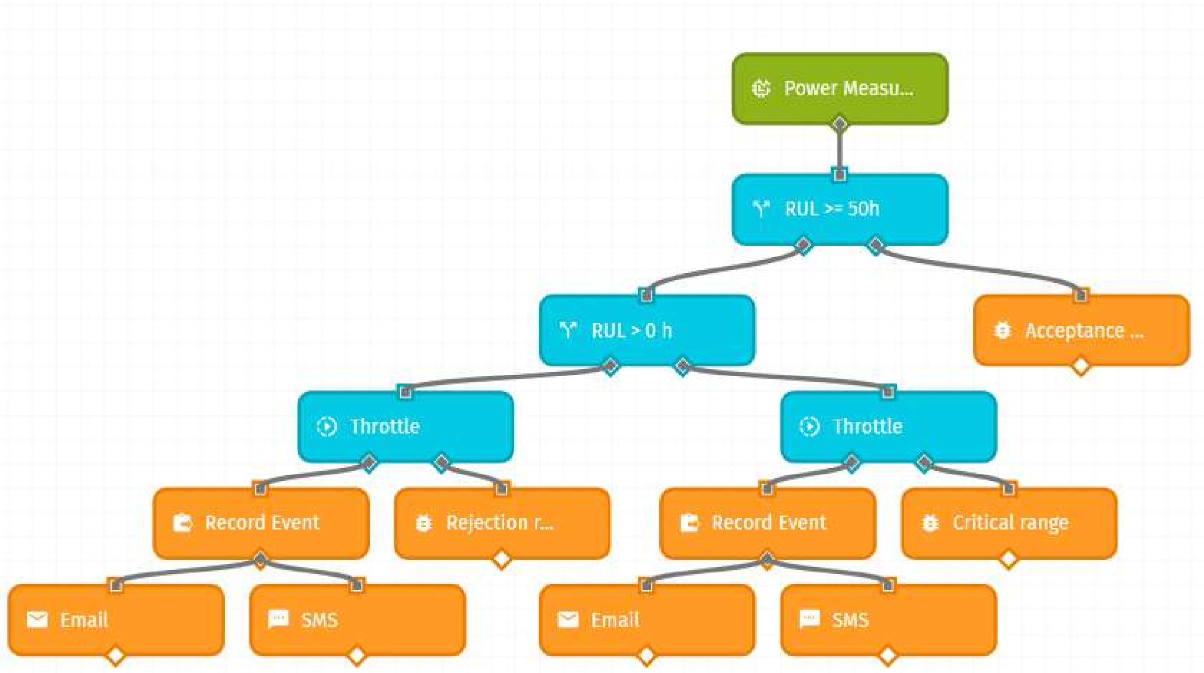
Appendix 17: Source code for the calculation of the remaining useful lifetime

Appendix 18 shows the analysing and calculation of the calculated remaining useful lifetime of the UV lamp.



Appendix 18:Analysing and categorising of the calculated remaining useful lifetime

Appendix 19 depicts the workflow of the calculated remaining useful lifetime. As soon as the remaining lifetime is in the critical or rejected range, a notification, among other things, is sent by mail.



Appendix 19: Workflow of the calculated remaining useful lifetime including an alarm function and context-based maintenance measures

Appendix 20 shows the email notification, which is sent as soon as the end of the useful lifetime is reached. The email contains situation-based information and context-related maintenance measures that can be accessed via a link.

```
<!doctype html>
<html>
  <head>
    <title></title>
    <meta name="viewport" content="width=device-width" />
    <meta http-equiv="Content-Type" content="text/html; charset=UTF-8" />
  </head>
  <body>
    <div>
     <p>Alarm:  End of useful lifetime is reached.</p>

      <p>Switch off the 3D printer immediately as the UV intensity is no longer sufficient for curing.</p>

     <p> Remaining useful lifetime: {{data.rlt}} h</p>

      <p>Open the link and follow the maintenance instructions:</p>
     <p> https://www.dropbox.com/s/ze94rmwz60p3opp/UV%20lamp%20replacement%20instruction.pdf?dl=0</p>
      </div>
  </body>
</html>
     }
```

Appendix 20: Source code of email as soon as the end of the useful lifetime is reached

Appendix 21 shows the received email notification as soon as the end of the remaining lifetime is reached.

5d5e61199998f3000689d7c8@workflows.losant.com

Alarm: End of useful lifetime is reached

An Böhm, Max

Alarm: End of useful lifetime is reached.

Switch off the 3D printer immediately as the UV intensity is no longer sufficient for curing.

Remaining useful lifetime: 0 h

Open the link and follow the maintenance instructions:

https://www.dropbox.com/s/ze94rmwz60p3opp/UV%20lamp%20replacement%20instruction.pdf?dl=0

Appendix 21: email notification as soon as the end of the remaining lifetime is reached