LED-screen Service Prediction Using Remote Monitoring

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Abstract

In this paper, a method is researched to predict time until failure of switch mode power supplies in digital billboards. It is found in literature that temperature and humidity cause filtering capacitors, switching transistors and rectifying diodes to fail due to thermal cycling and dielectric breakdown. From the interviews with the employees at the company, the fans of the power supply are pointed out as the component that most frequently fails. This causes the power supply be unable to get rid of its generated heat and together with a high ambient temperature to go into thermal shutdown. Signs of the power supply degrading are a decreasing output power and an increasing operating temperature. The first is already monitored, for the second the DS18B20 temperature sensor is interfaced for each power supply with a one wire bus communication to the environmental management board already included in the LED panels. This data together with ambient temperature, relative humidity, time and date and ambient light intensity allow for a model to be trained. Since no run-to-failure data is available, first a degradation model is used and when multiple instances of a failing power supply are recorded, a more accurate similarity model is used.

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2. Introduction

Audio-visuals are no longer a stand-alone entity but are used as business-like tools. Businesses view them as strategic investments, they are used to realise the company's goals. In the advertising industry, the losses caused by digital billboards unable to show the commercial advertisements of its clients, are directly recoverable on the company renting out the advertising equipment. In this case, the company Hecla, a top-5 Dutch total solution provider in audiovisuals, is renting out the advertising equipment consisting of large format indoor and outdoor LED screens. Not working LED-panels or LEDs that display faulty colours result in a commercial that does not convey the message as it was intended. Next to that, it will have a negative influence on the image Hecla has in the digital advertising industry. In the current situation, when someone notices and reports a fault, Hecla knows they have to go to the screen and repair it. Of course, Hecla wants to prevent this downtime by servicing the screens just before they fail. This graduation project aims to, in order to reduce the costs and benefit all the parties, design a system that predicts and communicates the time until service of the outdoor digital billboards along the road is necessary.

In other words, it provides a way to go from reactive service to predictive service. This aim can be divided into three subjects: the identification of failure modes in the system, the acquisition method of this data and the analysis of the data.

Many papers have investigated the correlation between electrical and physical factors of LEDs and their time till failure. However, this paper distinguishes itself by investigating the failure factors in relation to LED screens and researching a suitable solution for the prediction of service of the digital billboard system as a whole. A previous paper, written for the same company, argued that the power supply is the part that fails most of the times [1]. Therefore, the focus will be on that part of the digital billboard system. To date, there is no system that can communicate the time until failure for a digital billboard power supply. The main challenge in this is to find a solution to the constraints regarding the acquisition of added relevant remotely monitored power supply data from a computer program and analyse them.

Therefore, the main objective of this paper is to provide a way on how to determine, acquire, and analyse data related to failure factors in LED-screen power supplies. With this data, the main research question:

How can remotely monitoring the billboard predict the time until failure of the digital billboard system?

To answer this question, the report will start with a state-of-the-art review of remotely monitoring electronics. Next, the methods and techniques used in the process of this paper are discussed per subject. After that, the physical and electrical quantities that allow for the proper prediction of the health of the digital billboard system are determined. In line with that, a way to measure those quantities on Hecla's system is given. Then, the acquisition method of those measurements is discussed. Finally, an appropriate platform for storing, analysis and thresholding of this data is researched, to in the end conclude with the feasibility of this design.

When the subjects discussed above are researched and a final design is known, a conclusion can be drawn about the outcome of the paper. Since this paper aims to go from reactive to predictive service a certain measure is needed to define something as predictive. This measure, in this case, is the time that failure is predicted before it the failure actually occurs. To date, service mechanics have no time scheduled for repairing the outdoor digital billboards. This is because it is yet impossible to predict when a failure occurs. Instead, when called in for service on the billboard, a high priority timeslot gets created in the mechanic's schedule and the other tasks get rescheduled at a later time. This results in mechanics being uncertain about their workday and location and clients frustrated because the mechanic has to leave in the middle of for instance an installation. All parties benefit from the fact that for at least 24 hours the schedule of the service mechanic is static. Therefore, this feasibility study is rendered successful if service on digital billboard power supplies can be predicted 24 hours before failure.

3. State of the Art on Power Supply Prognostics and Remote Monitoring

Answering these questions requires an understanding of existing solutions to similar problems. Therefore, in this section, a review of the state of the art on the prediction of the remaining useful life, prognostics, of power supplies is conducted. With this information known, the novelty of this paper can be underlined. First, the topic will be introduced. Then, information is gathered from past decade literature on power supply prognostics and remote monitoring. Finally, products providing comparable solutions to similar problems are discussed to conclude with a justification of this paper.

3.1 Topic Introduction

The IEEE standards from 2017 [2] define the remaining useful life and prognostics as the following:

Remaining useful life (RUL): The length of time from the present time to the estimated time at which the system (or product) is expected to no longer perform its intended function within desired specifications.

Prognostics: The process of predicting an object system's RUL by predicting the progression of a fault given the current degree of degradation, the load history, and the anticipated future operational and environmental conditions to estimate the time at which the object system will no longer perform its intended function within the desired specifications.

J.B. Judkins et al. [3] visualize the probability of failure with respect to certain events in the lifetime of the electronic devices as shown in the bathtub curve in Figure 1. The area of interest here is the trigger point and the remaining useful life. The prognostics for power supplies are the topic for the state of the art review. It entails the prediction of the remaining useful life by using degradation data and environmental factors.

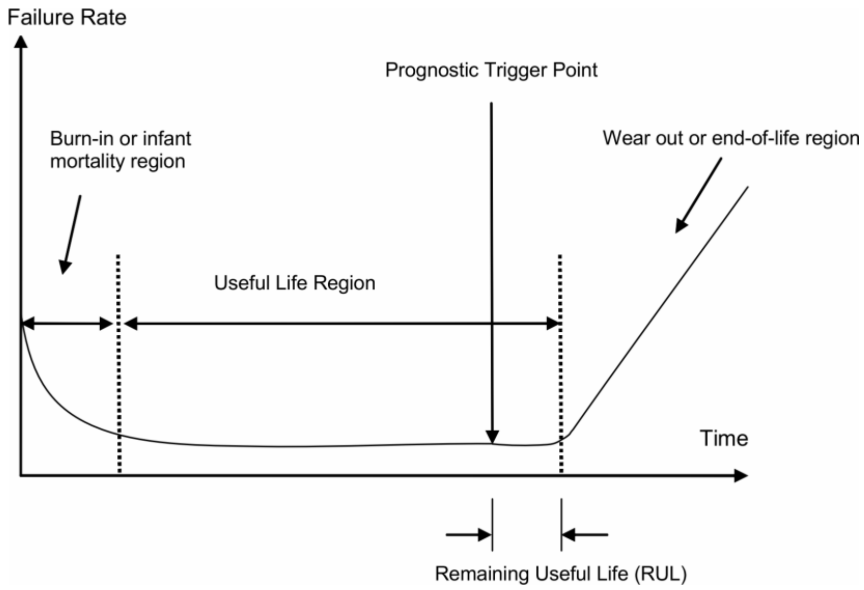


Figure 1: Reliability Curve or Bathtub Curve showing the remaining useful life and the prognostic trigger point [3].

3.2 Current Thinking in the Field

First, from the literature the level of development of this technique, used methods and current thinking in the field are found. For this, the fields of prognostics and remote monitoring are investigated. This is done because, for the first, this is the overarching theme of the paper. For the second field, this is the method used to obtain data for prognostics. They are discussed below in this respective order.

3.2.1 Prognostics

For the prognostics, it can be seen that the development of the technique for power supplies is focussed on designing accurate algorithms for calculating the remaining useful life while the methods for obtaining the data remain the same. Moreover, although components become more reliable, the current thinking in the field still sees a need for prognostics in power supplies. The reason for the data acquisition methods to still use the same sensors to acquire information is elaborated on by A.J. Boodhansingh et al. [4]. They state that the trade-off in prognostics is if you want more data to predict the remaining useful lifetime or if you want a reliable system. J.B. Judkins et al. [3] support the first claim by arguing that the fault coverage could theoretically add up to 100%. However, they criticise the usefulness of this by stating that with a large number of sensors, the system becomes inherently less reliable. In line with this, one can argue that when sensors are added, components are added, these sensor components can fail to cause a different electrical performance and thus other components to fail. The current thinking in the field, therefore, is to monitor power supplies with non-invasive methods to keep the system reliable.

3.2.2 Remote Monitoring

The above-mentioned monitoring has to be done remotely. A literature review on as to what is remote monitoring, the goals in use contexts of this technique and used methods of communication was conducted to elicit a suitable technique for this project. However, since the focus of this paper lays on power supply prognostics, only a concise summary of the review will be presented from hereon. The full review can be found in Appendix A.

From the literature, the definition of remote monitoring was distilled as the process of wirelessly obtaining scalable sensor information of a remote system or device to cost-effectively monitor the health of it. With regards to the goals in use contexts of remote monitoring, it was concluded that the technology serves three goals: provide system safety, act on device failures and prevent events from happening. The latter is the goal that is pursued in this paper as well. The prevention of an event is done by communicating prognostic data to a server where it is analysed. From the review, for the communication methods, a distinction can be made between using the internet or using existing communication methods and use public or private networks. What became clear from the review in this field, is that the current thinking leaves a decision on which method to use depending on the context. Using existing infrastructures offer easy connectivity but, other than using internet connectivity, can be limited in data transmission rates. In short, remote monitoring is the technique that allows for power supply prognostics seen its goals and use contexts. Its use contexts need to be determined though.

3.3 Product Review

Next, as of devices using the prognostics technology, there is just one company found to date that offers plug and play products. The RidgeTop Group Inc. [5] uses acquired sensor data in a prediction method to find the state of health and the remaining useful life. They use an algorithm that will update these two time-variables after each new sensor point. They also offer a product [6] that will obtain data by looking at the response of the power supply to source or sudden load changes introduced by the product. The response of the power supply changes due to components wearing out because of stress or ageing. The response will be in the form of a ringing waveform like the one shown in Figure 2 which reveals clues about the system’s health. The health can be determined by first establishing a baseline with a properly functioning power supply and comparing measured responses with it. However, this product is used for static loads while the digital billboard has a different power demand between day and night. This is discussed in chapter 7 and 8.

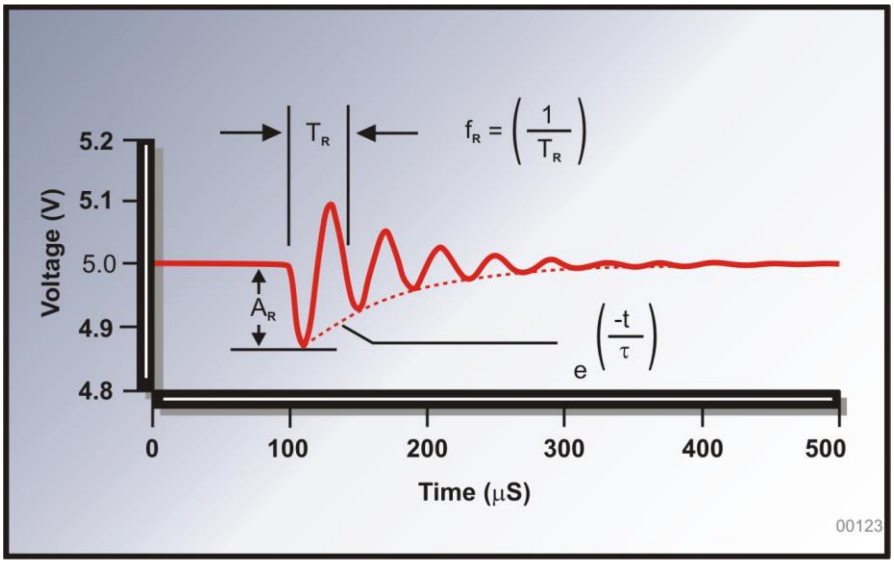


Figure 2: Damped sinusoid response or ringing signal in response to a load change [6]

To conclude, the novelty of this paper is justified because of the specific problem and challenges. The problem is aimed at power supplies in digital billboards which are at an outdoor remote location. Conditions can be harsh and thus quantities to be monitored should be adequately chosen with environmental factors in mind. As for the challenges, this paper investigates if the already existing system can be used to give prognostics on the power supplies. For this, the specifics of this kind of power supply are important. Moreover, the failures found in these power supplies might differ from the information found in literature and dealt with in the existing prognostics solutions. In short, there is to the author's knowledge no existing answer to the question if by remotely monitoring the digital billboard's system, the time until failure can be predicted.

4. Methods and Techniques

To answer the concluding sentence of the state of the art review, which is at the same time the research question of this paper, a clear working method is needed. With this working method, the focus is kept on the relevant subjects. Although the method gives structure to the way research is conducted, each type of question requires a different kind of approach. All of which will be relatable to 'A Creative Technology Design Process' presented by A. Mader and W. Eggink [7]. This schematic overview of a design process is presented in Appendix B. Therefore, in this section, for each of the subjects complementary to the research question, the methods and techniques used are discussed.

4.1 Failure Modes

To find the failure modes in power supplies, the way they break down, a fairly straight forward approach is used. First, conversations and interviews are conducted with employees to get to know the system better. This is done for the reason that in further research findings can be quickly placed into context, ideas can be generated by possibly using other parts of the system and the affected systems can be taken into account when implementing a possible solution. Second, the view is narrowed down into a part of the system, the power supply, and relevant literature is reviewed. This is done to get an understanding of the common failure modes found in power supplies, how they arise, what the causes are and what the effect and occurrence is. Third, to be case-specific, the failure modes found in Hecla's power supplies are researched. This is done by interviews conducted in present time as well as interviews conducted at the company by a previous student in 2018. Also, this student's analysis of maintenance records is taken into account to point out the relevant parameters for the power supplies' prognostics. Finally, the part will be concluded with a list of the found critical quantities that will need monitoring for service prediction. So, overall, this follows a structure that narrows down and goes from ideation to specification.

4.2 Measurements on the System

From this specification phase, naturally, the realisation phase is next. Again by interviews with employees and research into relevant parts of the system and software, the found solutions are integrated. In this section, a structure with multiple iterations is used to finetune the solution. The structure iterates through the implementation of the sensors, the accuracy of the sensors and the relevant thresholds. For the first two factors, their datasheets are investigated to interface the sensors correctly. Also, for accuracy, a thorough test on the sensors is conducted. Finally, via conversations with employees and experiments with the power supplies, the thresholds are determined when its health becomes critical. All in all, this section follows a structure of iterative implementation and evaluation.

4.3 Data Transportation

When the sensors operate correctly, they are read from a distant location. In this section, the current way of communication between the previous mentioned Lighthouse Control Master, LCM, and Hecla's head office are investigated to get an idea how the data can be read from the new sensors. This involves interviews with the developer of the LCM software and an adaption of the current software. An important question in the interviews is the refresh rate of data as that might influence the predictability of failure. Another important task is the extraction of the data from the software to a database where it can be used for analysis. For this, the possible ways are investigated and the software developer is asked questions regarding a possible permanent solution. The test setup again consists out of the LED panels available at the company connected to an LCM and the data extraction software running on a separate device. Synthetically a failure mechanism is applied to the power supply to acquire degradation data. The structure in this section is fairly explorative as the author is less acquainted with this field.

4.4 Analysis Framework

While the data is being extracted the framework for the analysis is researched. In this section similar to the previous section, the structure is explorative. First, possible frameworks are investigated by researching solutions with similar datasets. Then, by taking the stakeholders and limitations into account, one of them is chosen. This choice is based upon what data is relevant for the stakeholders, e.g. temperature, voltage or just remaining useful life. Another important factor is the question as to what is possible, seen the data that is available. One analysis tool might require more input than others. In the end, a suitable and accurate framework is proposed. The accuracy of the framework depends on the availability of data and if this data is representative for the real degrading power supplies. In the scope of this project, it is not possible to do extensive testing on the accuracy in real-world application because the chances of power supplies breaking down in this time are low. In short, this part has an explorative structure and with regards to the overall structure of the report, it follows three phases: ideation, specification and realisation to come to a conclusive product. It starts with broad investigations and narrows down possibly applicable solutions.

5. Failure Modes

As stated in the introduction, the power supply, turns out to be the main cause of failure. Therefore, investigation as to what are the physical and electrical quantities that allow for the proper prediction of the health of the digital billboard system will focus on the power supply. First, as an introduction, a schematic overview of the LED-panel is given and explained. Second, the failure modes in a power supply found from literature are presented. Third, an analysis of the failure modes found by employees of Hecla is conducted to finally conclude with the electrical and physical quantities that should be measured in the power supplies or digital billboard system as a whole.

5.1 Overview of the LED-panel

The digital billboards' screen can be up to 110m^2 big. The screen is made up out of smaller panels of a little less than 1m^2. A closer look will be taken into these smaller panels because that is the area of interest concerning the power supplies. In Figure 3, a close up from the smaller panels can be found.

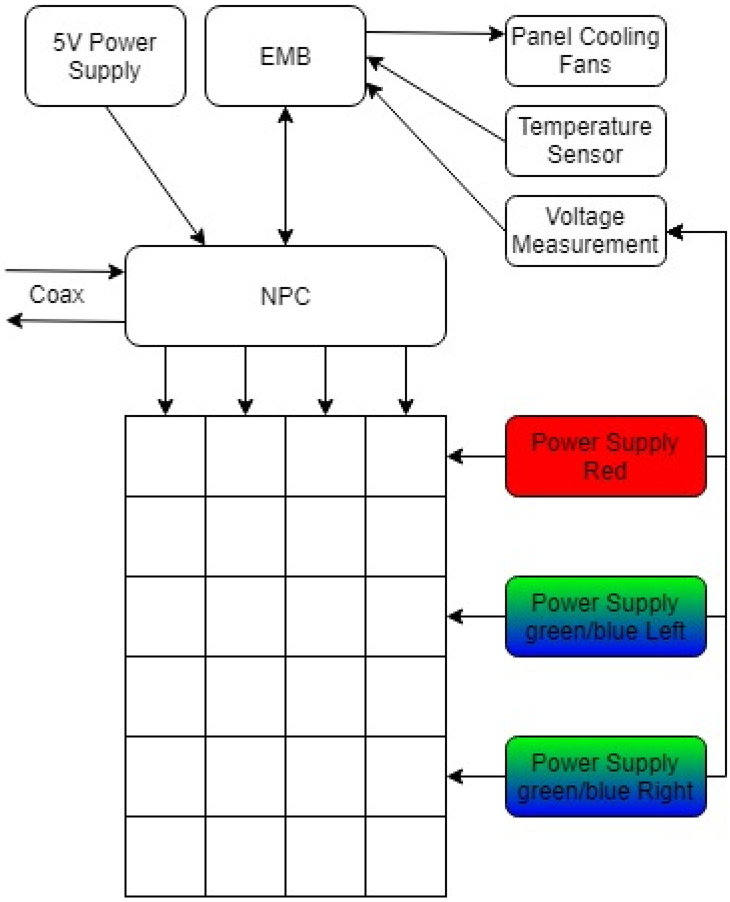


Figure 3: Schematic overview of the LED-panel

As seen in the overview above, a panel consists of 4x6 tiles. These tiles contain 12x12 RGB LEDs. These tiles are controlled by the NPC, the New Panel Controller. The NPC distributes the input signal from the coax cable to the tiles. The NPC is powered by a 5V power supply. The tiles are powered by 3 power supplies of 2 different kinds. One 3.3V power supply for the red LEDs and two 5V power supplies for the green and blue LEDs. These 3 power supplies are found to be the ones that fail most often. The output voltage of these power supplies is measured and send to the EMB, the Environmental Management Board. To this board also a temperature sensor is connected and so it can regulate the panel cooling fans. The information from this EMB can be read via the NPC and a VPN-connection with a device called the LCM, the Lighthouse Control Master. This device is connected to all the NPCs of the smaller panels in the complete digital billboard. A detailed overview is given in chapter 7. Next to the output power and temperature, it can also detect which tile is defective. Furthermore, the EMB has room for two more sensors to be placed on them. This topic is discussed in chapter 6. If from the failure analysis in power supplies it becomes clear that certain electrical or physical quantities need to be measured, there is room in the existing system for that.

5.2 Failure Modes in SMPS: a Literature Review

To determine if and what sensors need to be added, a deeper look is taken into the failure modes in power supplies. More specifically, the physics of failure in 300W 3.3V and 5V switch mode power supplies are of interest. A generic overview of the discussed power supply is shown below in Figure 4.

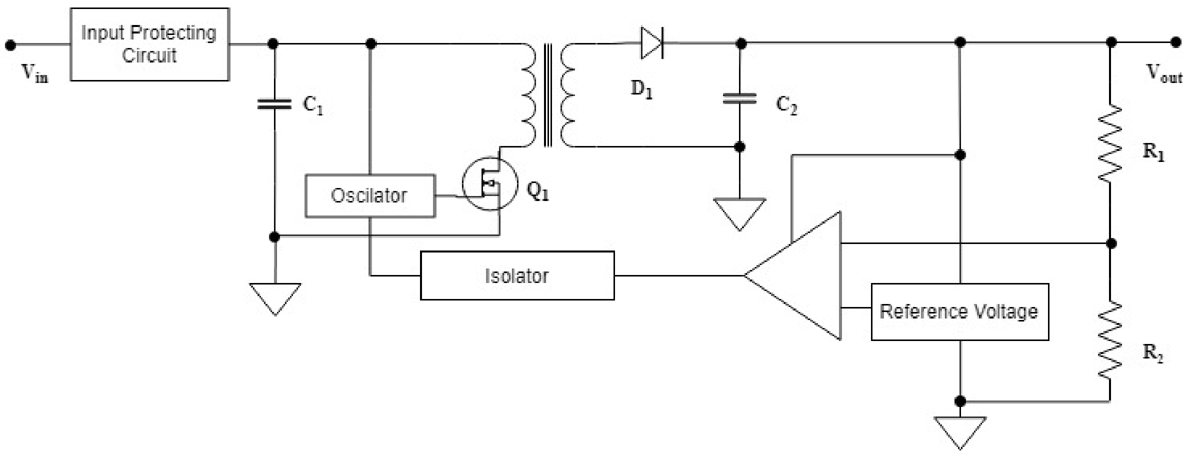


Figure 4: Simplified block diagram of the SMPS

On the input side, there is a protection circuit that controls the current through the capacitor C_1 when the power is applied for the first time. R. Orsagh et al. [8] point out that this capacitor is, in combination with other components, part of a filter that blocks radio frequency interference. The oscillator is connected to the MOSFET Q_1 and sends a PWM signal to it. During a PWM cycle, the current through the input side of the transformer goes up when the signal turns Q_1 on. When later in the cycle Q_1 turns off, the voltage across C_2 rises because the output side of the transformer tries to maintain the current. The reference voltage as a fraction of the output voltage V_{out} determines the duty cycle of the PWM of the oscillator. Furthermore, there is a fan included in the power supply to cool all the electronics. All in all, the transformer is at the heart of the switch mode power supply, alongside some arbitrary components, it transforms the 220V AC to 5V DC.

In literature, it is pointed out that it is mainly those arbitrary components that are the cause of failure in SMPS. R. Orsagh et al. [8] list the components into three different categories: Switching Transistors, Filtering Capacitors and Rectifying Diodes. These components are also mentioned by D. Li and X. Li [9] as the critical components that cause performance degradation. R. Orsagh et al. also argue that 80% of the failures might be due to 20% of the components (Pareto Principle). The failure statistics D. Li and X. Li [9] and H. Li et al. [10] refer to, support this statement by showing that in 72.9% of the system failures in a certain switch mode power supply it was due to component failures. In those statistics, they mention deficiencies during installation, design errors and Personnel error and inadequate maintenance as other causes of failure. However, since they only account for 22.63% of the failures and are immeasurable from a remote location, they are not be considered in the physics of failure of the power supplies. They also mention the operating environment as a cause of failure, but only for 1.68% of the times. In other literature, the operating environment is tested thoroughly and is relatable to 70% - 87.5% of the failures [8], [10], [11]. Therefore, it is wise to investigate the three categories identified by R. Orsagh et al. how they are influenced by environmental factors.

5.2.1 Switching Transistors

For the switching transistors, metal-oxide semiconductor field-effect transistors (MOSFETs) are commonly used in SMPS. Environmental factors including temperature and humidity are causes of failure for this component. R. Orsagh et al. [8] point out gate oxide breakdown resulting from thermal cycling as a failure mode with a high probability of occurrence for MOSFETs where the environmental temperature is listed, amongst others, as a possible cause. The gate oxide breakdown can lead to leakage current and eventually can short circuit the component. R. Moazzami et al. [12] show that at an operating temperature of 25°C the component lasts 1000 years while at 75°C it only lasts 47 years. This is due to the dielectric material breaking down. According to D. Li and X. Li [9], this degradation can also be seen in the gate-source threshold voltage, this value decreases with a rise in temperature and thus decreasing dielectric film. Next, For humid environments, J. Flicker et al. [11] mention corrosion as failure mode and point out that humidity is a common stressor in accelerated life tests. However, according to R. Orsagh et al. [8], the probability of occurrence is low. But when it occurs, there are no signs of degradation J. Flicker et al. [11] point out. They also mention that this is true for the two other components, capacitors and diodes, as well. All in all, the temperature is a cause of failure and can be detected over time while long-time exposure to humidity can cause sudden failure of components and thus the power supply.

5.2.2 Filtering Capacitors

The corroding effect of humidity is the same for the filtering capacitors and, again, also temperature plays a role in the degradation of capacitors. In the switch mode power supplies the primary purpose of the output filter capacitors, labelled as C_2 in Figure 4, is to handle the noise of the transformer. The voltage ripple coming from this depends amongst other factors on the ambient temperature. This can again cause the dielectric to break down. Dielectric break down can also be caused by thermal fatigue according to R. Orsagh et al. [8]. They state that thermal fatigue damage occurs every time a component experiences an environmental temperature cycle and during power-up and power-down and can cause cracks in the dielectric film. In the electrolytic capacitors, this gradual breakdown can be detected. D. Li and X. Li [9] propose to measure capacitance as it can indicate failure. In their research, they show the effect of high ambient temperatures on the capacitance of electrolytic capacitors. At 80°C, they found a regression coefficient of -0.01736 regarding capacitance and sampling times. Although J.K. Mann et al. [13] argue that the equivalent series resistance, ESR, can be used for degradation measurement, they support D. Li and X. Li for measuring capacitance as the absolute regression coefficients for the capacitance are higher than for the ESR. In short, the capacitance is most notably influenced by the ambient temperature cycles and humidity, and measuring it reveals information about its current health.

5.2.3 Rectifying Diodes

Finally, regarding the rectifying diodes, the same corrosion failure mode is a cause of failure for this component. Furthermore, contact migration resulting, again, from thermal cycling is a failure mode caused by environmental temperature. When contact material in the in SMPS commonly used Schottky diode diffuses with the silicon region it can cause leakage current and a spike that can short the PN-junction. In addition, D. Li and X. Li [9] point out that thermal cycling due to ambient temperature can speed up this process by increasing the junction temperature. R. Orsagh et al. [8] show in their accelerated life test that the output voltage suddenly drops when contacts migrate, however, the power supply still works. They also point out that in the time before the diode failure the power supply seems to have difficulties keeping the output voltage constant and the efficiency seems to decrease over time. In sum, also temperature and humidity are environmental factors that are causes of failure for diodes. Failure of this component can be detected over time by measuring output voltage and efficiency.

Regarding the failure modes in switch mode power supplies found in literature, it is found that mainly arbitrary components are the cause of failure. Those components are filtering capacitors, switching transistors and rectifying diodes. All investigated literature mention ambient temperature and humidity as factors of degradation for those components. They also state that for most of the failure modes, degradation over time can be measured and thus a prediction could be made.

5.3 Failure Modes in Hecla's SMPS

Taking these found failure modes into account, the failure modes reported by Hecla employees are investigated to see if they correlate. For this, interviews and maintenance records are consulted. The particular interviews were conducted by H. Bierma [1] in 2018. The AV technician Support & ICT at Hecla, T. ten Hove, verified in a conversation that the failure modes reported by H. Bierma remained the same in 2019. From the maintenance records between 2014 and 2018 it was found that defective tiles and power supply failure are most prevailing, 34,66% and 26,56% respectively. The next most prevailing failure modes are undetermined- and other modes. Then the New Panel Controller, NPC, is most seen with 4,8%. This a relatively low occurrence, therefore those and components or modules with even lower occurrences will not be investigated. All in all, defective tiles and power supply failures are the failure modes that occur most often in the digital billboards of Hecla.

For the tiles, Jan Löbker, Senior Operational Project Manager, mentions damage by the environmental factor of water for ±90% as the cause of the failures. Failures include single pixel failure, pixels displaying faulty colours and complete tile failure. This happens by water entering the tiles via leakages in the gaskets placed between the tiles and the 'chassis.' H. Bierma mentions a water detecting sensor can be placed in every tile. However, as seen in Figure 3, one panel consists out of 24 tiles, a billboard can consist out of 120 panels, so that would be 2880 water sensors in one billboard. H. Bierma rightfully states that the costs for this outweighs the benefits. However, other than H. Bierma claims, it was found that in the current software Hecla uses for checking billboards, there is an option available for checking the status of the single LEDs. However, this requires the system to communicate a state for all 414720 LEDs in the 120 panel billboard. Due to bandwidth constraints this is not possible as becomes clear in chapter 7. All in all, failure of single LEDs cannot be communicated with the current hardware, also prediction of failure in tiles is not beneficial.

The other often occurring failure is in the power supply for the LEDs. For this, the failure modes found by employees have also been recorded by H. Bierma and are presented here onwards. What becomes clear from the interviews is that the cooling fan in the power supply seems to be the main failure mode in the power supplies. Moreover, H. Bierma reports cooling fan failures to be ~99% of the failure modes according to the interviewed service mechanics. They report rubbing corroded fans and breaking soldering joints in the fans as causes and mention corroded vent meshes as an indication. Corrosion occurs when there is moisture present and high temperatures cause the relative humidity to rise. For the rubbing fans, as H. Oh et al. [14] point out that corrosion can affect the ball bearings in the motor. Moreover, they state that the oxidation products from the corroded ball bearings can cause wear and tear on other materials used in the fans as well. For Hecla, eventually the fans will seize, the power supplies will get hot, some components might fail and otherwise, it will go in thermal shutdown. This can also be seen in the current draw of the fans. Fans are set to maintain a constant speed, when the load, in this case the friction due to corrosion, increases, the fan needs more current to maintain the same speed. This again can be measured in the power supplies. Therefore it can be predicted when a fan fails. So, the fan is yet the only mentioned failure mode, it's health related to friction can be measured in the current hardware.

The other plausible cause is the breaking soldering joints. Jan Löbker, senior operational project manager at Hecla, mentioned in a conversation that it is the soldering joint corroding and then suddenly disconnecting joints inside the fan. He argues the corrosion occurs due to the fan sucking warm humid air through its own internal circuit. The corroding meshes behind the fan are most likely also related to the same humid air that disconnects the soldering joints. This information leads to the debate whether it is friction or soldering joints or both that cause the failure of the fans. Because to date, there is no corroded power supply fan available at Hecla, the assumption is that both causes are present as failure modes. In the previous part, it was found that friction can be determined from the current passing through the fan. For the sudden solder disconnection, it cannot priory be measured over time by a sensor. Elaborating on the fan failure, Mr. Löbker points out that when the power supply's fan fails, the power supply is not dead at the same instance. He argues that when the ambient temperature is about 25°C, the power supplies are prone to go in thermal shutdown. H. Bierma [1] showed a supporting graph that correlates power supply failures to ambient temperature and finds that in the summer, more power supplies fail than during the winter period. The datasheet of the power supplies [15] shows that the supplies operate at 100% until 50°C that is their self-generated heat. However, at 65°C, it specifies a derating of 50%. The same datasheet specifies that temperature as the maximum operating temperature before it goes into thermal shutdown. Although no data is available on the time between complete fan failure, temperature and complete power supply failure, this failure mode is still important because with the right sensors data can be gathered and relations can be found.

Regarding the failure modes found by employees of Hecla, it can be concluded that the prediction of a faulty power supply is much higher in the current situation with the current software than the failure prediction of a LED tile. Furthermore, it is less sensors are needed for this.

5.4 Critical Electrical Quantities for SMPS Service Prediction

From the literature, the failure modes in SMPS were relatable to arbitrary components such as capacitors, MOSFETs and diodes while in Hecla's power supplies the fan turned out to be the component that causes failure. In literature regarding failure modes in power supplies, fan failure was never mentioned. But since this seems to be the main cause of failure it has to be taken into account in the determination of electrical and physical quantities that have to be taken into account when predicting the time until failure of the power supply. As stated, the current of the fan indicates its health with regards to friction due to, in this case, corrosion. The discussed literature does mention that ageing of components can be measured at the output voltage of the power supply, others suggest measuring efficiency as that will also decrease over time. Furthermore, temperature and humidity are environmental factors that are of influence of the health of the components and thus should be monitored. Next to that, the temperature is also a result of the fan failure and thus the temperature of the power supply itself is an important factor to be monitored. One might argue to monitor electrical quantities like the capacitors, MOSFETs and diodes inside the power supplies, however, from a conversation with the Innovation Manager L. Kuipers and J. Löbker, it became clear that a plug and play solution is desirable. If it turns out that it is impossible to accurately predict service on power supplies based on a plug and play solution this statement needs readdressing.

6. Measurements on the Test Setup

With the quantities to be measured known, the sensors able to perform such measurements are determined, tested, implemented and evaluated for accuracy and system reliability. In this part, first, the sensors are interfaced with regards to the already implemented Environmental Management Board, EMB. Second, the used sensors and their accuracy are determined. An overview of the tests can be found in chapter 4 Methods and Techniques.

6.1 Environmental Management Board

In the chapter about failure modes, the environmental management board, EMB, was already briefly discussed. In this section, a closer look is taken at the board to understand its working and to enlist features that are useful for implementing a prognostics system based on the EMB. As a start, an overview of the EMB is presented alongside the connections to and from the board that are currently used in the billboards. Then, not used features on the board are discussed and with the previously found quantities in mind, their possible usage in the prognostics system is determined.

The EMB is responsible for managing the screen internal environmental conditions and communicating with the new panel controller, NPC. As seen in Figure 5 and in Figure 3 in chapter 5 the board is a hub for communication and information passing through the digital billboard system. Thus it is wise to investigate the functions and the possibilities for extending its usage.

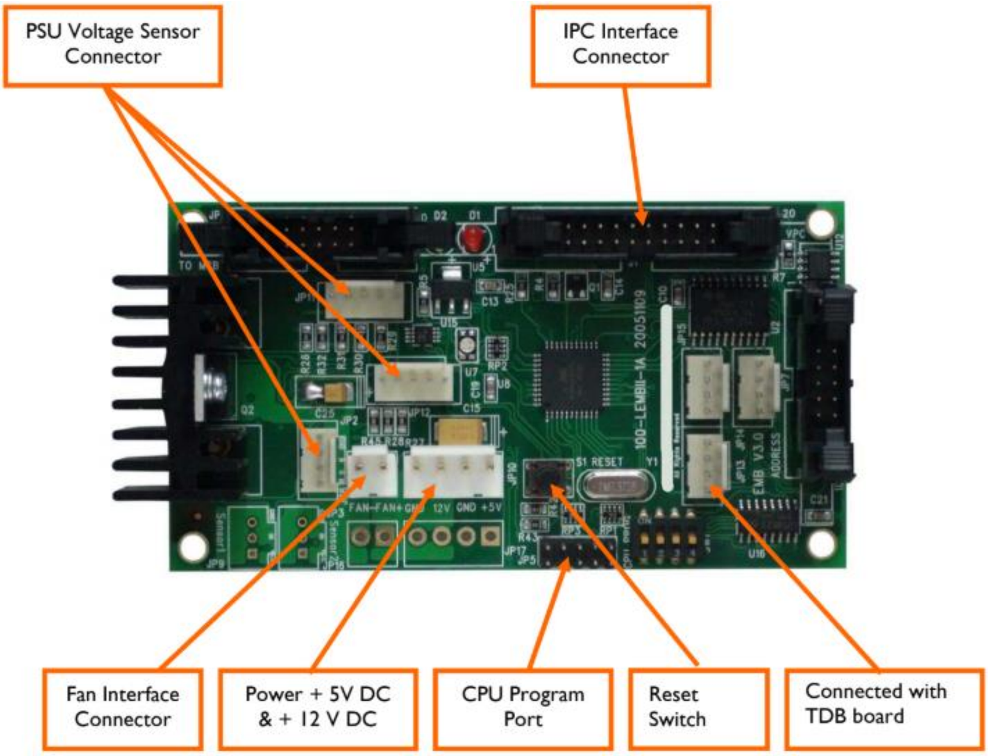


Figure 5: Main connections on the Environmental Management Board 2 [16]

The functions shown above are self-explanatory. The output voltages of the power supplies are measured by the EMB by using a voltage divider for each of the outputs. As seen in Figure 5 there are three voltage sensor connectors, however, only one is used for the measurement of the three different power supply output voltages. One power supply provides the ground and an output wire while the other two only provide their output wire. Also, a voltage divider is incorporated for the not further discussed 12V DC power supply. Similarly, a connector that enables the EMB to register whether the panel fans are operating or not is also not discussed for the reason that this paper aims to resolve the failure modes around the power supplies. The IPC interface connector is connected to the NPC and via that board, the EMB can request information about tiles. The amount of available information, however, is low. Currently, it can communicate whether a tile functions properly or not and further information about what could be the cause takes a lot of bandwidth to be communicated. H. bierma [1] even reports visible colour deficiencies on the output image when this information is requested. The connection with the temperature data board, TDB, enables the EMB to get the current temperature. The TDB is based around a temperature IC placed on the side of the 5V power supply. This IC measures the ambient temperature in the LED panel.

This results in the following list shown in Table 1 of the connections that are not used but can house a useful feature for the prognostics system. These features are discussed hereonwards.

Table 1: Available connections on the EMB

Connection Type	Amount	Intended Function	Possible Function
5-pin JST	1	PSU Voltage Sensor	Measure output currents to determine efficiency.
4-pin JST	1	PSU Voltage Sensor	Measure PSU fan currents to determine if there is friction or a disconnection.
4-pin JST	2	5V TDB connection	Connect TDB for outside temperature measurements.
3-pin open	2	5V Sensor connection	Connect humidity sensor Connect temperature sensor to each of the PSUs and gain info via 1 data line.

As discussed in the previous chapter, a decreasing efficiency with regards to input power versus output power indicates a failing power supply. Measuring output currents and voltages enables the prognostics system to calculate the power. By relating that to the power the power supply was designed for a statement can be made on the power supply's health state. However, input power measurements would require every power supply to be opened in order to incorporate voltage and current sensors. This is not in line with the idea of designing a plug and play solution to the power supply prognostics. Therefore, the comparison of input and output power is no option for power supply prognostics. The same reason is applicable for measuring the fan currents, the power supply has to be opened, wires cut and stripped, connections soldered and new data lines to be inserted in order to accomplish this. In short, the critical electrical quantities for power supply failure prediction that are efficiency and fan current are discarded for the reason that they are not easily implementable.

Temperature and humidity sensors, however, can be placed outside the power supplies and still fulfil their purpose and provide relevant data. As J. Löbker mentioned in the previous chapter, the outside temperature is related to power supply failures, so is the temperature of the power supply itself. He pointed out that the thermal shutdown is not instantaneously at 25°C ambient temperature, but can take up to 3 days to occur or not occur at all. AV technician Support & ICT at Hecla, T. ten Hove supports this and additionally points out that derating is shown in output voltage and a rise in power supply temperature at the critical ambient temperature mark. However, the rate of change in the temperature is not high and thus he suggests a temperature value every ten minutes is suitable for prediction this then does not stress the bandwidth that is available. Future tests on the exact time have to be conducted on this to be certain. One might think that that time depends on the billboard's position relative to the sun, however, H. Bierma [1] shows in a plot that there is no relation. Inside the panel, the sensor for sensing the power supply temperature can be placed near a heat source in the power supply on the outside metal casing and still sense temperature rise in case of fan failure. The rise in temperature can then be related to the outside temperature to verify fan failure. Therefore, three temperature sensors are added. However, only two sensor connections are available at the EMB. Luckily, for the connection of temperature sensors to the power supplies, only one data bus is needed. Via this bus, the temperature of each of the power supplies is collected by addressing each sensor with his own serial number [17]. In order to incorporate more data for prognostics, the other available sensor space is reserved for a humidity sensor. As found from the literature and the failure modes discussed with employees, humidity in the LED panels causes component degradation and corroding equipment. The placement does not pose a problem as the humidity is fairly equal in the panel. All in all, three sensors for measuring each power supply's temperature and one sensor for measuring humidity are added to the EMB and are read every ten minutes.

6.2 The Sensors

To determine whether a sensor is suitable for the system, a set of requirements is made. This set of requirements specifies in what ranges the sensors have to operate, their required input voltage, the accuracy and resolution. These requirements are shown below in Table 2. The accuracy and resolution requirements are based upon their importance in the prognostics system, however the real requirement for them is to be as good as possible. Therefore, the required value shown here is the minimum rating that the sensor has to meet.

Table 2: Requirements for the sensors in the prognostics system

Parameter	**Unit**	**Required**
Voltage	V	5 [16]
Temperature Range	°C	-30-85 [15]
Temperature Accuracy	°C	≤±1.0
Temperature Resolution	°C	≤±0.5
Humidity Range	%RH	54-89 [26]
Humidity Accuracy	%RH	≤±2.0
Humidity Resolution	%RH	≤±0.5

Before the sensors are implemented, the right sensor for the job has to be chosen. For the temperature sensor, this is the DS18B20 [17] because a lot of documentation is available on this sensor on how to set up the communication over one wire [18]–[20]. In addition, many have proven its accuracy and resolution [19], [20]. So, verifying these properties is of no use since this has been done extensively by other authors. The specifics are listed below in Table 3.

Table 3: DS18B20 temperature sensor properties

Parameter	**Unit**	**Rated value** [17]	**Meets requirement**
Voltage	V	5	Yes
Max current	mA	1.5	N/A
Temperature Range	°C	-55-125	Yes
Temperature Accuracy	°C	±0.5	Yes
Temperature Resolution	°C	0.5 (max.: 0.0625)	Yes
Sampling Rate	Hz	10.5 (max.: 13.33)	N/A

Therefore, in this part, the working of different types of humidity sensors are discussed. First, relevant information concerning the humidity sensors is given. Then, the types of sensors and their workings are discussed to finally conclude with the sensor that is going to be used. With this sensor a test to verify its specified accuracy and range is conducted.

Humidity is the environmental factor that is measured by these sensors. Humidity is defined as "the amount of water present in the surrounding air." [21]. A humidity sensor measures relative humidity. This is the ratio of water vapour pressure in the air at a temperature relevant to the maximum water vapour pressure possible in the air at that same temperature [22]. Absolute humidity does not take temperature into account when measuring the ratio. Because the temperature and moisture content in the air of importance in the degradation of the components and corrosion of the fan, the relative humidity sensing sensors are used. In short, the sensor measures air temperature and water vapour present in the air.

6.2.1 Analysis

There are two different ways to measure relative humidity based on capacitance and resistance. Capacitive humidity sensors like the one shown in Figure 6 work based on the changing dielectric permittivity due to change in relative humidity. The advantages are that the output voltage is near linear, a large sensing range and stable results over long time usage [23]. A limitation is a limited distance from the sensor to the circuit, meaning that signals can get lost due to voltage losses [21].

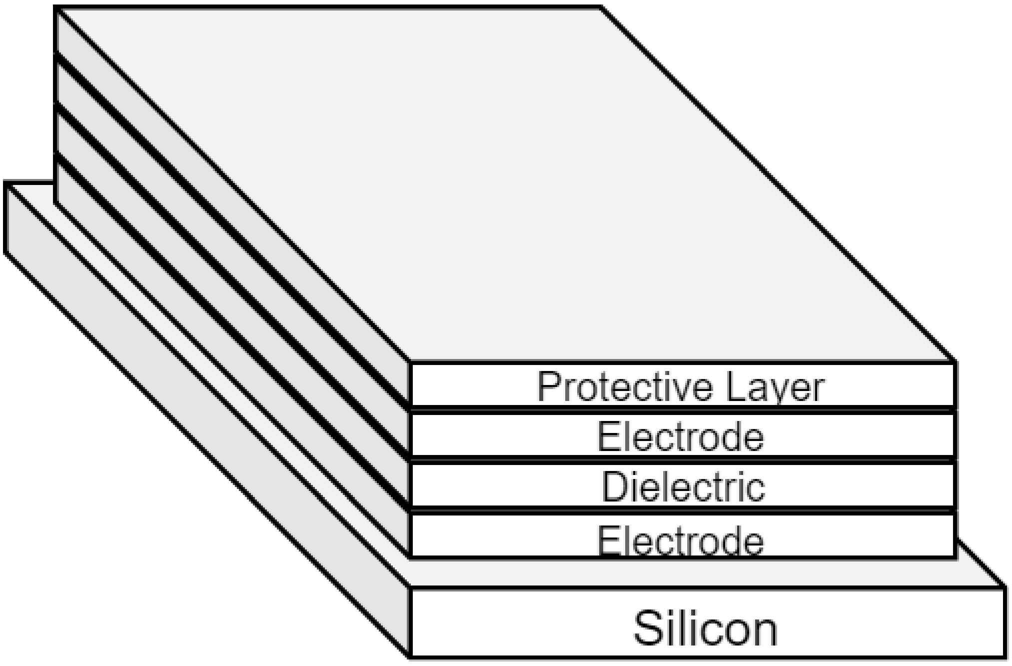


Figure 6: Schematic of the capacitive relative humidity sensor

The second way to measure humidity is based on the change in conductivity in non-metallic conductors due to water content. These sensors of which a representation is shown in Figure 7, are made of materials with very low resistance that changes when exposed to humid conditions. Their relation is inverse exponential. This type of sensor is widely used in industrial, commercial and residential applications for their low cost, small size and interchangeability as they require no calibration standards. Disadvantages, however, are their sensitivity to chemical vapours and shifting readings when used with water soluble products [21], [23].

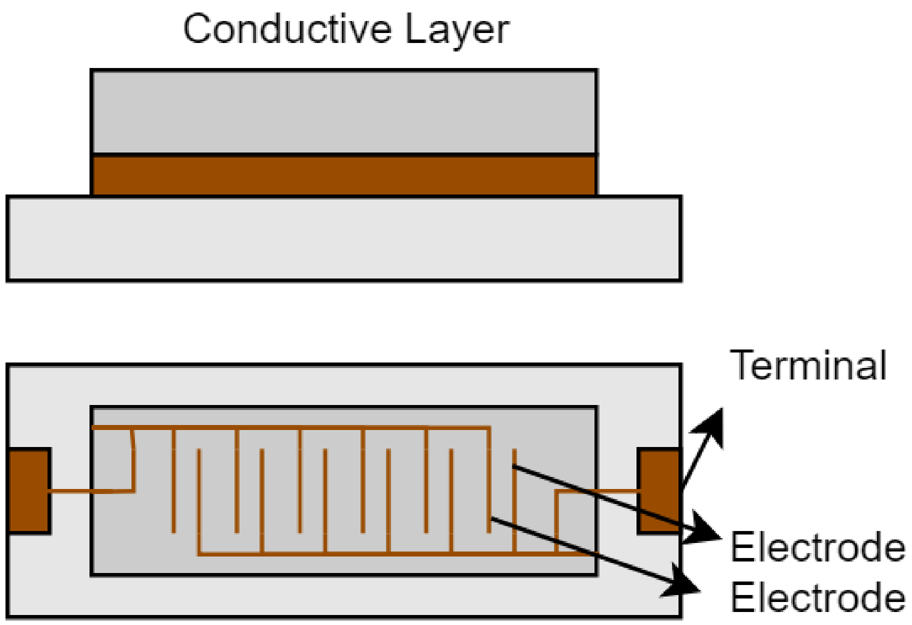


Figure 7: Schematic of the resistive relative humidity sensor

Because of its advantages in linearity, range and usage time the first capacitive type humidity sensor is used. To date, there are two common types of humidity sensors that can be interfaced with the EMB. There is the DHT11 and his successor, the DHT22. The datasheets of both sensors are compared to the required specifications below in Table 4 to determine what sensor is used.

Table 4: Humidity sensor comparison

				Meets requirement	
Parameter	**Unit**	**DHT11** [24]	**DHT22** [25]	**DHT11**	**DHT22**
Power	V	3.3-5	3.3-5	Yes	Yes
Max current	mA	2.5	2.5	N/A	N/A
Humidity Range	%RH	20-80	0-100	No	Yes
Humidity Accuracy	%RH	±5	±2-5	No	Yes
Humidity Resolution	%RH	1	0.1	No	Yes
Temperature Range	°C	0-50	-40-100	N/A	N/A
Temperature Accuracy	°C	±2	±0.5	N/A	N/A
Sampling Rate	Hz	1	0.5	N/A	N/A

As seen in the table the DHT11 excels in one category, the sampling rate. However, it fails in meeting the requirements for the range of both temperature and humidity. For temperature, this does not pose a problem since there is already a sensor installed in each LED panel capable of performing temperature measurements in the required range. However, since the sensor is included for measuring humidity it has to be able to perform measurements in the required range found in the overview of the weather in The Netherlands in 2018 [26]. For this reason and its accuracy, the DHT22 sensor is chosen.

6.2.2 Method and Setup

The sensor's accuracy and range are verified by using the 'saturated salt' method. This is a small test that uses certain salts that, when dissolved in water, produce an atmosphere containing a known relative humidity [27]. The salts are dissolved in a microenvironment, a sealed jar, and the sensor is placed inside there and continuously read and its values are recorded. The temperature is kept stable at around 25°C ±2°C because Greenspan [27] listed the relative humidity for a lot of salts at this temperature. Next to that, H. Bierma [1] found that at Hecla higher temperatures are related to more power supply failures, so an ambient temperature higher than the average found in The Netherlands in 2018, 11.3°C, is used. Moreover, the values for the sensor's performance in the datasheet are also recorded at 25°C. Finally, the mean operating temperature of the power supplies is also around 25°C, therefore, the temperature in the LED panels is kept around this value [15]. The used salts are chosen such that they produce a relative humidity in the range that is required for implementation in the LED panels. By evaluating the deviations of the sensor readings from Greenspan's known values, the accuracy is determined. Four salts are used: potassium iodide, potassium chloride, sodium chloride and sodium bromide. These were chosen with the aspects of safety, costs, availability and relative humidity in mind. They are added in the ratio salt/water specified by A. Carotenuto and M. Dell'Isola [28], those can be found in Table 10 in Appendix C. The authors use a ratio of 15:1 of air space to solution space. Although this is less than the ratio specified by ASTM standards for these tests [29] this ratio is still used for the sake of comparison with their results. The sensor's values are recorded for one hour at 0.2Hz before this method is repeated for the next chemical. This interval is chosen to eradicate the chance of unsuccessful communications as this can happen at a frequency of 0.5Hz according to the datasheet.

The test setup is shown in Figure 8. The values for the wave filtering capacitor C_1 and pull up resistor R_1 are chosen according to the datasheet [25]. As can be seen, an Arduino Nano is used to communicate the data to a laptop. With the saturated salt test completed, the found accuracy and resolution are compared to the datasheet. Furthermore, important characteristics or behaviour of the sensor are investigated in order to provide a recommendation on how to interface the sensor in the prognostics system.

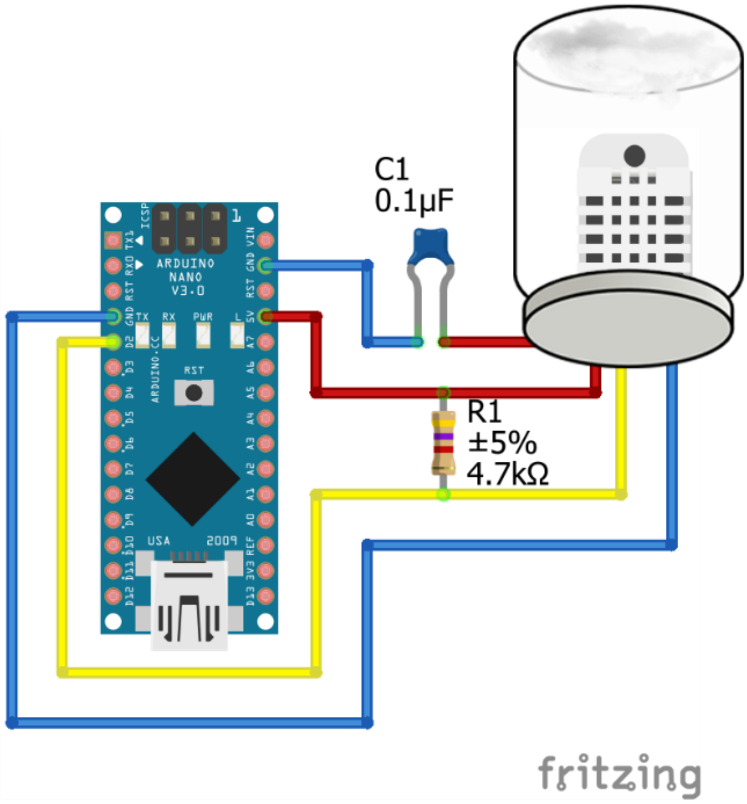


Figure 8: The test setup as it will be used in this experiment in chapter 6.2.2.

6.2.3 Results

Below the results from the test described in the previous chapter are displayed in Table 5 and Table 6. The first compares for each salt the relative humidity found by Greenspan with the measured humidity in this experiment. In the second table, the values from the datasheet are compared to the found results. Enlarged graphs of the measurements can be found in Appendix C. The graphs show for each salt the ambient temperature and the relative humidity as a result of the sensor in the microenvironment with the solution.

Table 5: Results from one hour saturated salts test on DHT22

	Greenspan Relative Humidity [%] [27]	**Greenspan Standard Error** [%RH] [27]	**Measured Mean Relative Humidity** [%]	**Measurements Standard Deviation** [% RH]
Sodium bromide	57.6	0.4	43.4	0.2
Potassium iodide	68.9	0.3	69.2	0.4
Sodium chloride	75.3	0.2	74.9	0.5
Potassium chloride	84.3	0.3	84.6	0.3

Table 6: Comparison of results to DHT22 datasheet

	Unit	DHT22 Datasheet [25]	DHT22 Saturated Salt Test Mean Over All	Deviation
Accuracy	%RH	±5 max.	±0.6 (max.: +2.7)	±4.4
Resolution	%RH	0.1	0.1	0

6.2.4 Conclusion, Discussion and Recommendation

As seen in Table 5 the results all roughly correlate with Greenspan's data. However, for sodium bromide, a humidity was measured that is incomparable to Greenspan's value. Upon further inspection of the salt, it was found that it contains only 50% sodium bromide and 50% of other chemicals. Deviations could thus be due to the fact that there was too little of the salt present in the solution or to other chemicals influencing the reaction of the salt. Also, it could be that the sensor Greenspan used was less accurate than the one used in this experiment. On the contrary, for the other 3 salts the values did correlate, so that claim is debatable. All in all, sodium bromide was eradicated from the test.

At first sight, The conducted test yielded a better accuracy then the datasheet specified. However, upon further investigation of the test data used in the datasheet, it becomes clear that this error is due to the fact that the manufacturer measured over the whole range of the sensor [30], while this experiment only investigated the relevant range. The accuracy the manufacturer found for the relevant range was 2%RH. An explanation for the difference can be that there was a different method of testing used. The datasheet does not specify via what method the data was acquired. Next to that, and more importantly, it was found that in a timespan of about 10 to 15 minutes the readings showed a slower increase in relative humidity to eventually become relatively stable. This indicates that in the beginning the air in the microenvironment was not yet saturated with the salts. It is again not known if the manufacturer took this time to stable readings in mind. When the values were stable, and the data stream was disconnected and after 2 minutes reconnected, the readings immediately started with the same value they left off with. This indicates that it was not the sensor that was slow in obtaining the values. So only during initialization, the sensor can measure faulty values, but after 10-15 minutes the signal becomes stable. The prognostics system has to take into account this behaviour at initialization. However, since humidity does not change instantaneously, this will not pose a serious problem. Overall, the sensor performs within the requirements and thus it can be used in the system for detecting the humidity.

In future research, it is advised to include a calibrated humidity sensor alongside the interfaced sensor to be able to more accurately verify its properties. In these experiments, there was no such sensor available. Next to that, it should be made sure that used salts are as pure as possible to make sure no other chemicals in the salts can influence the readings.

7. Data Transportation

Now that the sensors can be integrated the transportation and extraction of the data are investigated. As stated before in this paper, output voltages of the power supplies are already communicated to Hecla's headquarters in Hengelo. Ideally, the data acquired by the integrated sensors is communicated in the same way to the same application as to where the voltages are now found. To investigate the possibilities, first, an overview is given of the communication between the sensors, the EMB and the application. In that section also relevant properties regarding bandwidth and refresh rate are listed. Second, methods to extract and store the data into databases are researched on their working principles and ease of use. Third, as a conclusive test, the data extraction method found to be most suitable is implemented in an experimental setup consisting out of the LED panels, the software and a synthetically created failure mode and asked to gather data and store it.

7.1 Communication Overview

The way the sensors communicate their information is of interest because it influences the system's behaviour. It has an influence on the electrical characteristics of the system as the added sensors require power too. Next to the electrical characteristics, the communication of the sensors also has an impact on the refresh rate and bandwidth. The latter meaning, in this case, the transmission capacity of the sensors to the EMB and the EMB to the sensor monitoring application running at Hecla. The bandwidth measures the maximum amount of data that can be transferred in a given amount of time [31]. In this section, both transmission steps are explained and the bandwidth and refresh rates requirements are compared to the capabilities.

7.1.1 Sensors to EMB

As determined in the previous chapter, two types of sensors are introduced to the EMB to design a prognostics system. First, there are three DS18B20 one-wire temperature sensors for each of the power supplies. The challenge of which is communicating with three sensors by using one data bus while keeping the required bandwidth low. For the DHT22 humidity sensor, the challenge is to reduce the amount of current needed to transmit the data. As seen in Table 4 the maximum current is 2.5mA, which is low, but taking into account it also transmits temperature data which is not needed this maximum current could be lower if the temperature data is not measured and transmitted. These challenges are worked out below.

7.1.1.1 DS18B20 Temperature Sensor

The reason this type of temperature sensor is chosen is because of its specifications and the fact that multiple sensors can coexist in parallel and still read the temperature for each sensor separately via one wire. It is interfaced with the power supplies as shown below in Figure 9. The wires are connected to the respective input at the EMB.

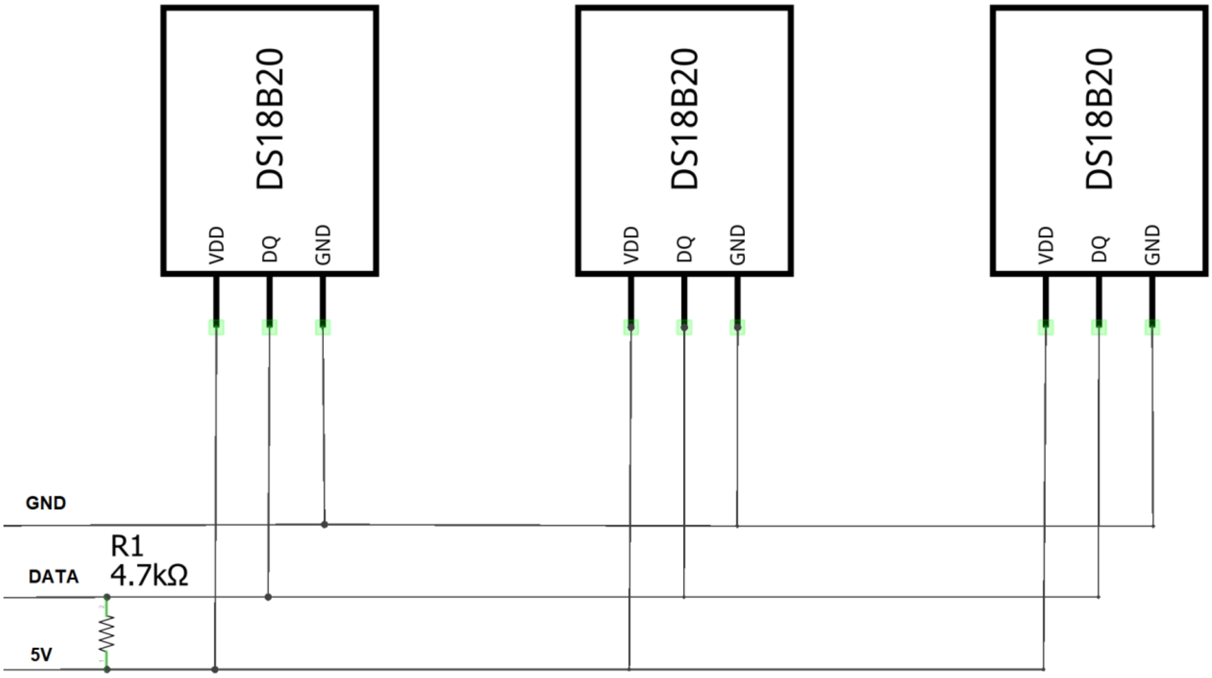


Figure 9: Temperature sensors interfaced for each power supply

The challenge of reading each temperature via one wire is solved in the code. According to the datasheet [17], this communication is called '1-Wire Bus System.' They state that the sensors are slaves to the single bus master. Meaning there is the EMB which is the master of the sensors that are connected to it. The hardware configuration is fairly straightforward. The datasheet states that the DQ pins are open-drain meaning they only use the data line when they are transmitting and disconnect from it via an internal MOSFET to allow other devices to transmit data. The external pull-up resistor R_1 is required so that the idle state is high and transmission of data can take place.

The transaction sequence consists out of three steps: initialization, ROM command and a function command. The initialization sequence starts with a reset pulse transmitted by the master and ends with multiple presence pulses from the slaves alongside their unique 64-bit ROM codes. The master device now knows that there are slave devices on the bus ready to operate. The ROM commands enable the master to speak to each sensor separately. ROM commands are for instance 'Search Rom' to identify all the slaves present on the bus and 'Match Rom' to address the sensor that matches the ROM code. In the latter case, the specific slave will respond to the function command, the other slaves wait for a reset command. The function command enables the master to read or write to the sensor's internal scratchpad. Examples are 'Convert T' which converts thermal data, stores two bytes of data to the integrated scratchpad and when finished, returns a logical one. 'Read Scratchpad' enables the master to read the temperature data from the scratchpad. Reading all of the data on the scratchpad and the CRC validation byte is equal to nine bytes of data. After this, the initialization step is issued again so that other slaves can be read. The above-described loop requires, according to the communication flowchart in the datasheet, the transportation of 32 bytes for the initialization and 25 bytes for the consecutive temperature reading of one sensor. However, to save time and bandwidth, the source code [32] has a command that when sent on the bus, all slaves start their temperature conversion. This is done by skipping the reading of the slaves' ROMs. After this, their values are read from their scratchpad. To decrease the number of bytes even more, during the 'read scratchpad' function, the master can issue a reset command. Since the first two bytes are the temperature bytes, the reset command can be called after this so the seven other bytes are not transmitted. This process takes ten bytes per sensor per reading and takes 750ms for three sensors to be read. Those values also conclude the bandwidth and refresh rate.

7.1.1.2 DHT22 Humidity Sensor

According to its datasheet [30], the Humidity sensor can also be interfaced using the one wire protocol. The communication starts when the master sends the start signal. The slave sends a response signal and, other than the communication with the DS18B20, immediately afterwards sends the 16 bits for humidity, 16 bits for temperature and eight parity bits as a check. The fact that no function command is necessary for requesting each environmental quantity separately makes it hard to reduce the five bytes needed for transmission. On the contrary, five bytes is a manageable size of data. Moreover, the refresh rate of two seconds makes its required bandwidth much lower than the DS18B20. Additionally, on the practical side of things, when investigating the source code [33] for reading data from the sensor it becomes clear that data and temperature are not read separately as the *readTemperature* and *readHumidity* functions might suggest. In fact, both values are read and transmitted but only the specified one is shown to the user. So, the bandwidth challenge cannot be tackled at its roots and thus the current remains 2.5mA. Concluding with the bandwidth and refresh rate of the humidity sensor it can be said that the required bandwidth is five bytes per two seconds.

With regards to the capabilities of the EMB, an interview was conducted with the Crestron Software Engineer R. Valk whose job is programming the LED panels and communicating relevant info back to the monitoring application. R. Valk, an authority in the AV field, pointed out the difficulties of determining the available bandwidth because as of now, there are multiple outdoor digital billboards with different internals. Some have another kind of EMB, some have extra modules inside that are not found in others and also different brands make it hard to give a uniformed answer. However, Hecla is planning on using the same system of the same brand for all components in future digital billboard projects. The EMB of which is the same that is described in the previous chapter. Thus it is wise to design with the capabilities of this EMB in mind. R. Valk argues that communicating one string of additional sensor data every five minutes is the maximum of the EMB's bandwidth performance. He showed an example of time and data being communicated. That particular example communicated 16 unseparated characters, '*dd:mm:yy:hh:mm:ss:msms'*, each character being one byte and one terminator byte at the end of the string. This results in a bandwidth of 17 bytes every second. However, this example was shown on an unused EMB, leaving all bandwidth available for communicating time. A. Valk stated that this wouldn't work on an integrated EMB because of the other services running on it. He estimated that in the real world situation, 34 bytes of prognostics data can be communicated to the EMB every five minutes and thus that is the final bandwidth for the EMB.

The bandwidth for the prognostics system is in line with the aim of this project to detect a failure before the 24-hour mark and recommendations of J. Löbker discussed in the previous chapter. Although his claim of three days until thermal shutdown at 25°C ambient temperature is not yet proven, it is assumed as the truth for now. So is T. ten Hove's claim of ten minutes per prognostics reading that is required to detect voltage or temperature trends. Communicating that information requires a bandwidth of 35 bytes every ten minutes. The refresh rates for the sensors are therefore adjusted to ten minutes and the average required bandwidths per second are calculated accordingly. Those are shown in the 'required' column alongside the total required bandwidth that is shown under the prognostics sub-column. In the capability column, A. Valk his claim regarding the available bandwidth for the EMB is shown. This, again, is multiplied to conform to the required refresh rate of ten minutes. This can then be compared to the required bandwidth of the prognostics system. This results in the capabilities and requirements for one LED panel shown below in Table 7.

Table 7: Bandwidth and refresh rate of the sensors to the EMB

		Required			**Capability**
	Unit	3x **DS18B20**	**DHT22**	**Prognostics**	**EMB**
Refresh Rate	S	600	600	600	600
Bandwidth	B/Prognostic Reading	30	5	35	68
Average Bandwidth	B/S	0.05	0.008	0.058	0.11

The prognostics reading includes three temperatures for a total of 30 bytes and one humidity value of five bytes. The prognostics column specifies the bandwidth that is needed if there is a refresh rate of 600 seconds and in that time interval the temperatures and humidity is communicated. The required bandwidth for prognostics is 35 bytes every ten minutes and the EMB can do 68 bytes every ten minutes. If the bandwidth saving method was not used, it would require 105 bytes to be communicated every ten minutes, resulting in a total average required bandwidth of 0.175B/S. All in all, the limited bandwidth challenge is addressed by cutting off the DS18B20 communication when the relevant data is known. This results in a bandwidth requirement of about 0.06B/S and an available bandwidth of 0.11B/S.

7.1.2 EMB to Hecla

The above conclusion is also the bandwidth that has to be available in the communication between the digital billboard and the monitoring application running at Hecla. Neither from the datasheet nor from the employees a value for this bandwidth is found. Therefore, this remains to be investigated in future work. For now, the required bandwidth calculated above for the sensors to the EMB is assumed to be available in the communication between the EMB and application running at Hecla. So, for the remainder of this section, a graphical overview of the communication is shown and explained.

The graphical overview can be seen in Figure 10 and for a close up on one panel, Figure 3 can be consulted. Starting at the panel level, the EMB communicates with the NPC. It sends values for like instance output voltage and in the future operating temperatures and humidity. The NPC of every panel is connected in series with the next panel. Eventually, one data bus is connected to the Lighthouse Control Master, LCM. The LCM is connected to a central network to which all digital billboards of the company are connected. Via a Virtual Private Network, VPN, the monitoring application can speak to each digital billboard's LCM which can retrieve information from a certain NPC which in turn gets it information from the EMB.

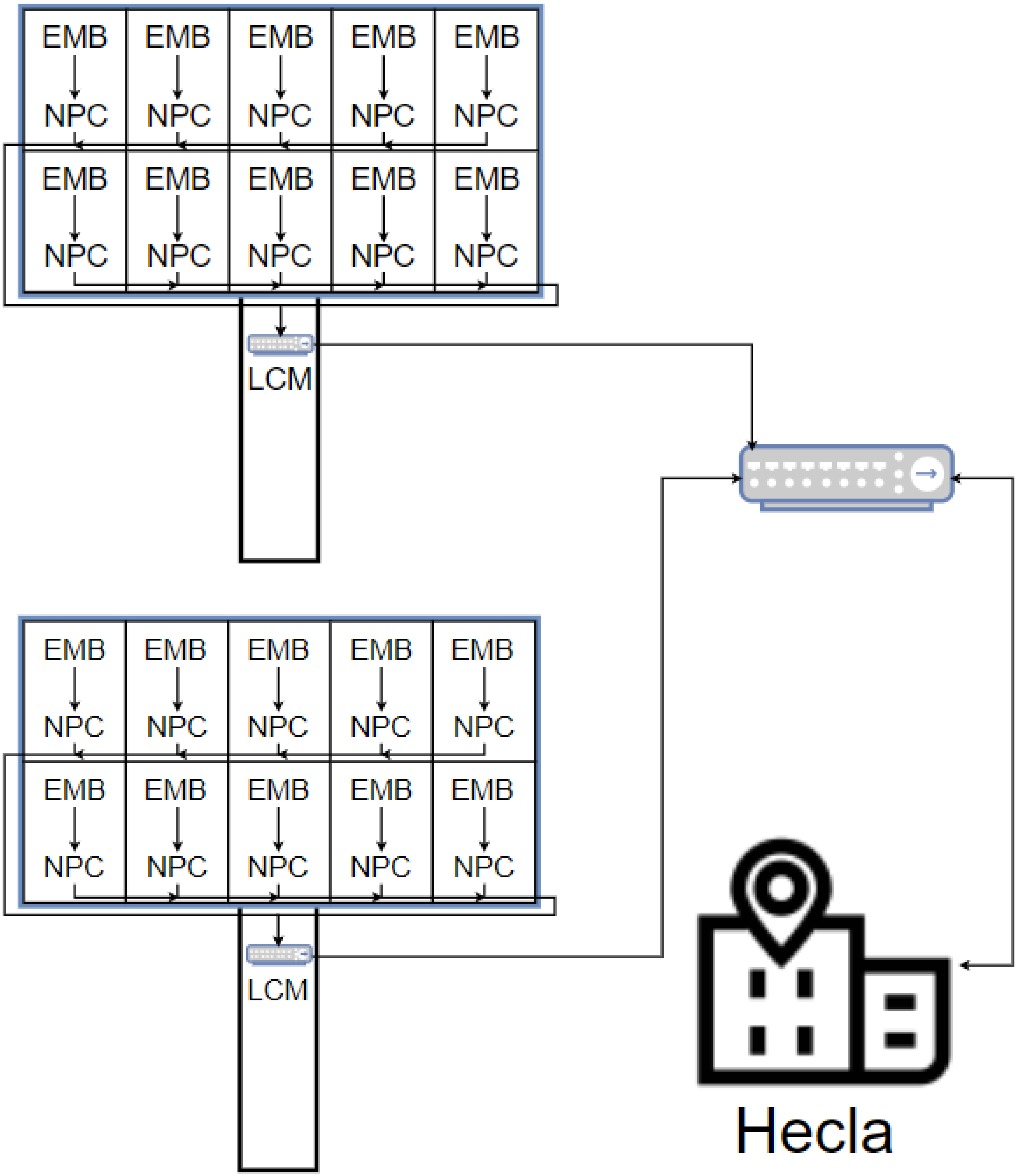


Figure 10: Graphical overview of the communication between billboards and Hecla

7.2 Data Extraction Methods

The data presented in the user interface has to be stored in a database in order to train a model on the prognostics. Ideally, the data is stored automatically in an SQL database via the software running on the monitoring application. As of this moment, a Crestron programmer adjusts the software in order to have a database integrated into the application. However, it will be integrated into the newly build digital billboard system which is different from the current systems. The author has the older systems to his disposal, so, methods to transport the data to a database for this system are researched. One could argue that this is not necessary because this method will not be used in a real-world application. However, data is needed in order to determine a model prior to the implementation in the new digital billboard system. In this section, three ways to collect the presented data and store it in a database are discussed to in the end select a suitable method for this paper. The discussed methods are implementation of an application programming interface (API), screen scraping and graphical user interface automation. They will be assessed based on working principles, ease of use and the fact if they can be used alongside the existing application. The ease of use is determined based on the level of understanding of programming needed to successfully use it. In other words, the complexity is low and the method is fairly intuitive.

7.2.1 Application Programming Interface

The first method is using an API. S. Pearlman [34] concisely argues an API to be software that acts as a messenger between two applications to be able to talk to each other and exchange data. She stresses the importance of APIs in business, however, she fails to substantiate that claim. The advantage of using this method comes in the form of reusability as also M.P. Robillard [35] notices. The latter elaborates on this by listing high-level abstractions for certain programming tasks and creating a uniform programming experience as other advantages. This means when challenges are addressed by using the same API as a building block, the structure of how the data is handled or presented is the same and thus it is easier understandable for a future user who has experience with similar APIs.

As stated above, an API acts as a messenger between two applications. An API is part of one application and returns requested information to the other application, the client. S. Pearlman [34] uses the example of someone booking a flight. The API is connected to the airline's database containing information about departure city, date, cabin class, window seats and so on. A passenger can book his flight from various websites that are all connected via the API to the same database. When the passenger has made his selection, the API delivers the airline's response to the passenger. According to a list provided by A. Zaveri et al. [36], APIs can be written in any language depending on their task. In this case, it an API for an object-oriented language such as Python or C++ would be used. In short, the API works as a mediator between a database and a client using a language suitable for the task.

The level of understanding of these languages and structure of an API are of importance for implementation and the possible adaption of the prognostics system. As S. Pearlman [34] mentions, the vast amount of libraries and frameworks, also listed by A. Zaveri et al. [36], offer building blocks for programming a personal API. However, M.P. Robillard [35] counters this claim by investigating at Microsoft what makes learning APIs so hard. He found that the learning progress is hindered by the lack of learning material available, examples not representable to the task and that the focus is on understanding a part of the design of the API. On a practical note, APIs are designed to let a client extract information from a database and they are rarely designed to store information in a database, however, forum searches show it can be done but this increases complexity.

7.2.2 Screen-scraping

When an application offers no API, screen-scraping techniques can be used to collect data. K. Newman [37] defines screen-scraping as "the process of collecting data from a web service which does not offer an API – i.e. the only access is a dynamic HTML output intended to be displayed in a web browser." In line with this, S. Flores-Ruiz et al. [38] comply and extend this definition by arguing that it is a tool for extracting content from user interfaces. They list large complex data sources, application internationalization and recording of developers' work done as contexts of use for this technique.

The technique used for scraping differs per usage domain. In screen-scraping for websites, the data is collected by emulating the server-side HTTP, meaning it requests a part of a webpage just a regular user would do [37]. The HTML text string response of the web server is filtered to get the relevant information out of it and is stored or handled further depending on the aim of the user. Another technique used is discussed by S. Flores-Ruiz et al. [38], they propose to use a screen navigator and content extractor in order to collect data from the user interface. The collection of the data on the interface is similar to how a regular user would do: click, select, ctrl+c, ctrl+v. The navigation on the screen can be done in 2 ways: define XY-coordinates of the area to click or provide a screenshot for the navigator to look for and interact with.

The first technique requires more understanding of how a web server generates the results a user asks for while the second technique requires the user to understand what steps are taken in regular interaction with a user interface. Although the latter technique seems more intuitive, the drawbacks are the fact that if the XY-coordinates method is used, the screen has to look the same at all times. For the screenshot method, the drawback is that the screen scraping program takes time to find the screenshot on the screen and from experience sometimes it cannot find it at all. Although the server-side HTTP emulation requires a more thorough understanding, it is more accurate. On the contrary, it can only provide information that can be found in the HTML and PHP files while the screen navigator technique can collect any copiable data.

7.2.3 Graphical User Interface Automation

A method comparable to the screen navigator method is found in graphical user interface automation. This method is often used in testing graphical user interfaces of desktop or smartphone applications because it is efficient in testing complex applications and thus it saves time as S. Bauersfeld and T.E.J. Vos [39] point out. It differs from an API and screen-scraping in the sense that its primary use is for (desktop) applications. The authors state it can simulate clicks and keystrokes but also drag and drop and other gestures.

The working principle behind this testing is again similar to the navigator technique, the program has an index of objects that it can interact with and performs sequences of these actions in order to test all possible actions and look for errors [39].

The difference is in difficulty and speed. A vast amount of libraries for Python exist in the field of graphical user interface automation. Since it uses the same intuitive method of simulating a user interacting with the interface, it is again understandable for the novice user who does have experience with Python. Since applications are increasingly tested using automated test methods, a lot of tutorials on how to automate these tasks can be found. A. Sweigart [40] mentions the Python library *PyAutoGui* as a powerful tool for "automating the boring stuff." The timesaving factor with using this library is the fact that a confidence level can be specified for finding the place of the screenshot that was specified. This means it will find that location faster. Although the voltage, temperature and humidity-data in the LCM software interface are unselectable, a library can be imported that can read and copy this read-only text to be used or stored in a file.

Because of these features, the *PyAutoGui* library alongside an optical character recognition program, OCR, is used to collect the unselectable data for analysis. Next to that, the author's experience with the Python language is a factor that leads to the use of this method over the API or screen scraping for which a thorough understanding of internet technology is required. No useful libraries for this are found in Python.

7.3 Real Life Scenario

As stated above, a graphical user interface automation script is written in order to collect data from the monitoring software. In this section, a real-life scenario is presented where the goal is to obtain data to determine a first model. Another goal is to find out what property, output voltage or temperature, gives a better indication of a failing power supply. With this indication known, a recommendation is made on how severe one property weighs with respect to the other in the model. The discussed data acquisition methods consisting of sensors and the automatic recording of the values from the monitoring application are used to create a database with the relevant prognostics data. Since those are thoroughly analysed in chapter 6 and 7, this paragraph will commence with the method and setup discussing how the real-life scenario experiment is conducted and enlisting important considerations during the execution. After this, the results are discussed to conclude with a statement regarding the success of the experiment. The experiment is rendered successful if data is captured where an increase in temperature and decrease in the output voltage can be seen when a synthetically created failure mode is introduced.

7.3.1 Method and Setup

The methods used in this experiment consist of the previously discussed sensors and software. In particular, the DS18B20 temperature sensors are connected via a one-wire communication bus to an Arduino Nano with software programmed on to it that reads the temperature. Similarly, the humidity and ambient temperature sensor are connected and read. The received data is printed in the serial monitor and is later imported in an excel file. That same excel file is the location where the graphical user interface automation script alongside the optical character recognition program stores the values for the output voltages. The script and program take approximately twenty seconds to record three output voltage values. For that reason also the power supply temperatures and the ambient temperature and humidity are recorded at that same interval. During the experiment, the ambient temperature is kept constant at 23°C. This temperature is chosen because of the remarks of the project manager saying most failures occur around 25°C ambient temperature. This way the chance of the power supply going in the thermal shutdown is decreased.

Complete power supply failure is where the supply does not function anymore or goes into thermal shutdown. This renders the power supply unusable for Hecla. Since this is not desirable, another metric to power supply failure is introduced. 'Failure' in this experiment means a shift in the parameters that point in the direction of the thresholds of complete power supply failure. The thresholds are for the output voltage and temperature are mentioned in chapter 5 and correlate to the derating of the power supply at higher temperatures, e.g. 50% at 65°C.

In order to still gain data related to power supply failure, a synthetically created failure mode is introduced. In particular, the power supply cooling fan failure is used to see if the power supplies start to heat up and output voltages decrease. Since the real fan might degrade over days or even months, another approach is chosen. The fan will be stopped instantaneously and manually in order to observe the time it takes for the system to heat up. When signs of permanent damage occur or the system reaches 50°C the fan will be turned on again because according to the datasheet [15] this is the operating temperature where the supply starts to degrade. In order to replicate the real-life scenario of advertisements on the billboards, a diagonally moving rainbow gradient is shown on the screen. This is done as different colours represent different loads and thus the values of the output voltages can differ.

The power supplies are allowed a one hour warm-up period with the rainbow gradient, after this half an hour of data is recorded where no synthetic failure mode is introduced. After that, each power supply fan is stopped separately while the others are unchanged. When the critical temperatures are reached or signs of damage occur the fans are turned on again, otherwise, they are kept to hold for half an hour. Meanwhile, the ambient temperature is also recorded. The humidity is not used since it will not alter and tell nothing about the health in this situation. However, in a real-world application, it has to be implemented when data is gathered on power supply prognostics because, as researched, it is a feature in remaining useful life estimation.

The setup is shown below in Figure 11. The sensors are connected to the outside of the power supplies where on the inside of the casing the switching transistors are placed. From literature [41]–[44] and physical inspection this turned out to be the warmest part of the supply during normal operation.

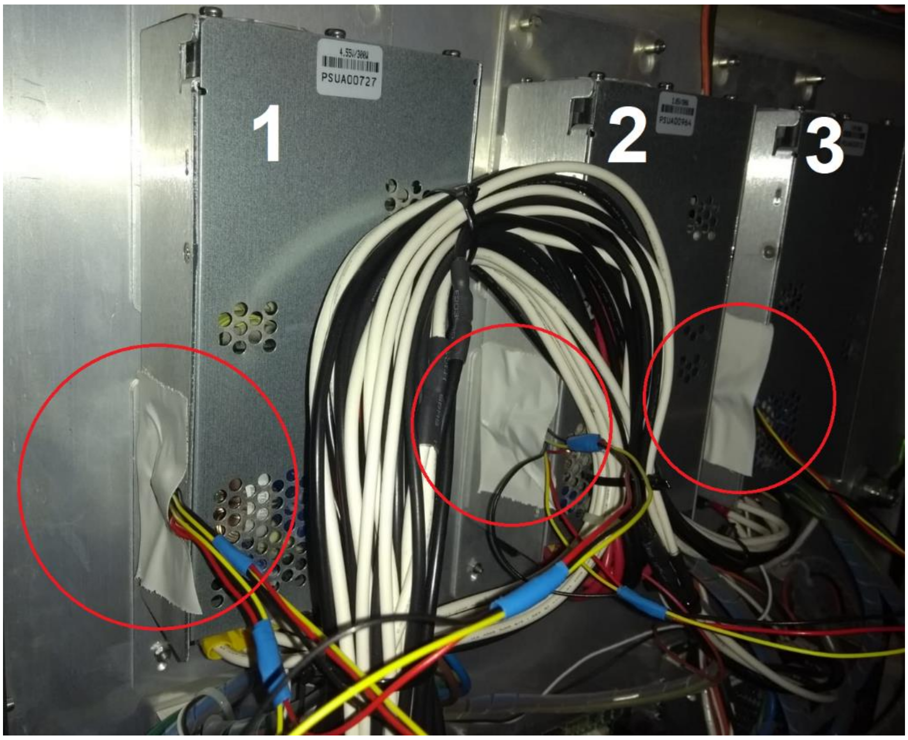


Figure 11: Setup consisting out of three power supplies (4.55, 3.05, 4.55 resp.) and three DS18B20 temperature sensors

7.3.2 Results

The results for the experiment are shown here onwards. In Figure 12 the measurements taken under normal operation are shown. The lines representing the raw readings are transparent because no useful insights could be gained from those. Instead, in the control run, a linear trend is added to see what the average behaviour under normal operation is.

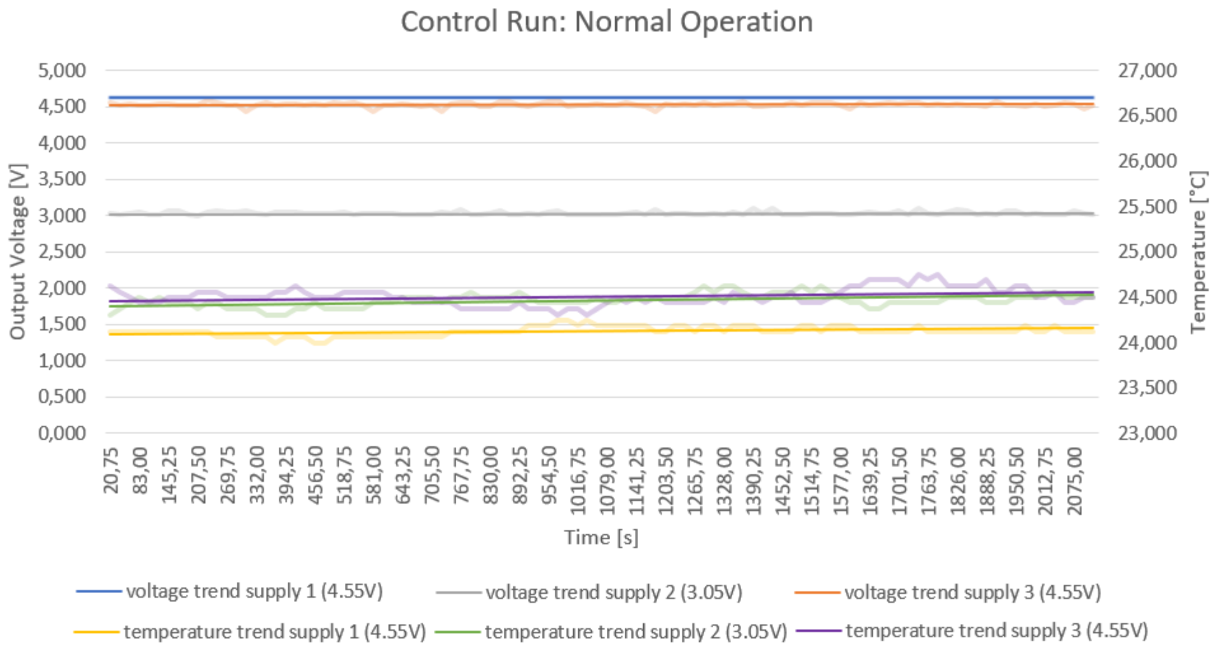


Figure 12: Results of control run

After the control run, it became apparent that the output voltage of supply 1 remained exactly 4.633 while for supply 2 and three varied slightly over time. Although this might indicate a very stable power supply, throughout the experiment the supply never showed a different output voltage, also not when the fan failure mode was introduced to it. Therefore it was concluded that the output voltage readings were not representing the real output voltage. This was verified by measuring the output voltage of supply 1 with a voltage meter. The readings of the device did vary. With this in mind, power supply 1 was discarded from the test.

The temperature and output voltage trends during fan failure are fitted with a third-degree polynomial. Y. Günham and D. Ünsal [45] propose to use this degree to compensate for sensor reading error. They argue that a fourth or fifth would yield even more accurate results, however, the trade-off is the amount of processing power needed. A first or second degree polynomial, on the other hand, is not sufficient Y. Günham and D. Ünsal argue. The differences between the bias/scale factor errors and the fitted bias/scale factor errors are too large for the polynomials to be sufficient in sensor reading error compensation. So, a third-degree polynomial fit is chosen to inspect trends and behaviour in this experiment. The results of the manually introduced fan failure for the two remaining power supplies are shown below in Figure 13 and Figure 14. A close-up comparison between the power supplies' behaviour during normal operation and when the failure mode is introduced can be found in Appendix D.

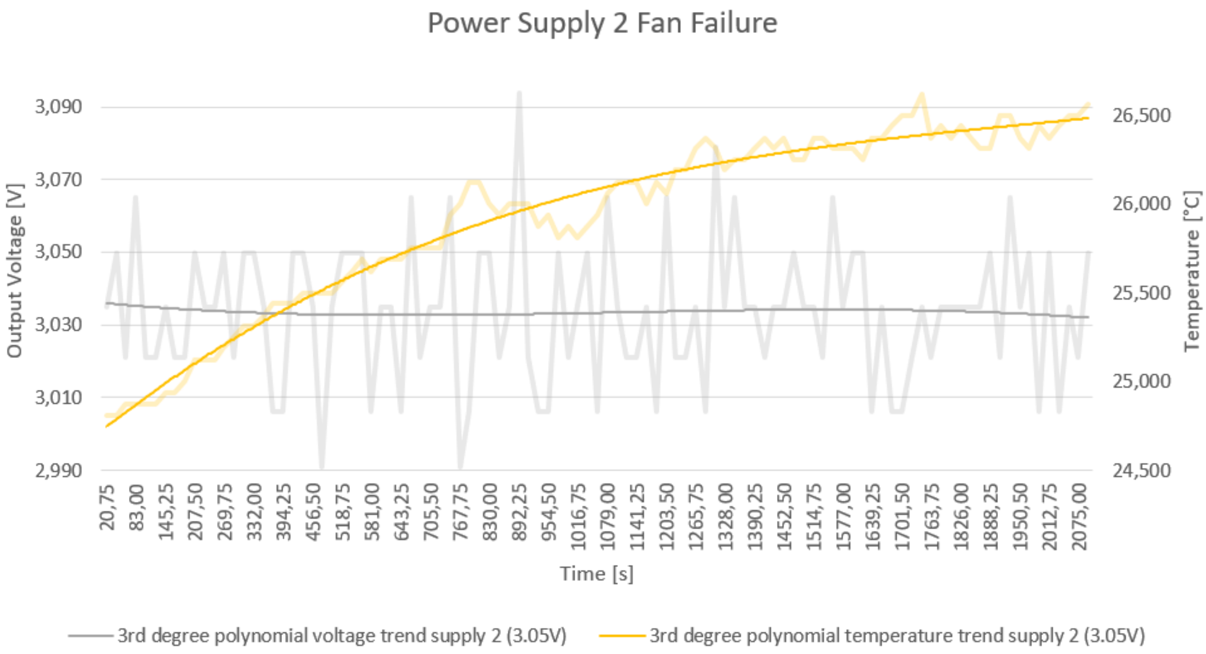


Figure 13: Temperature and output voltage measurements and trends for fan failure in a 3.05V power supply

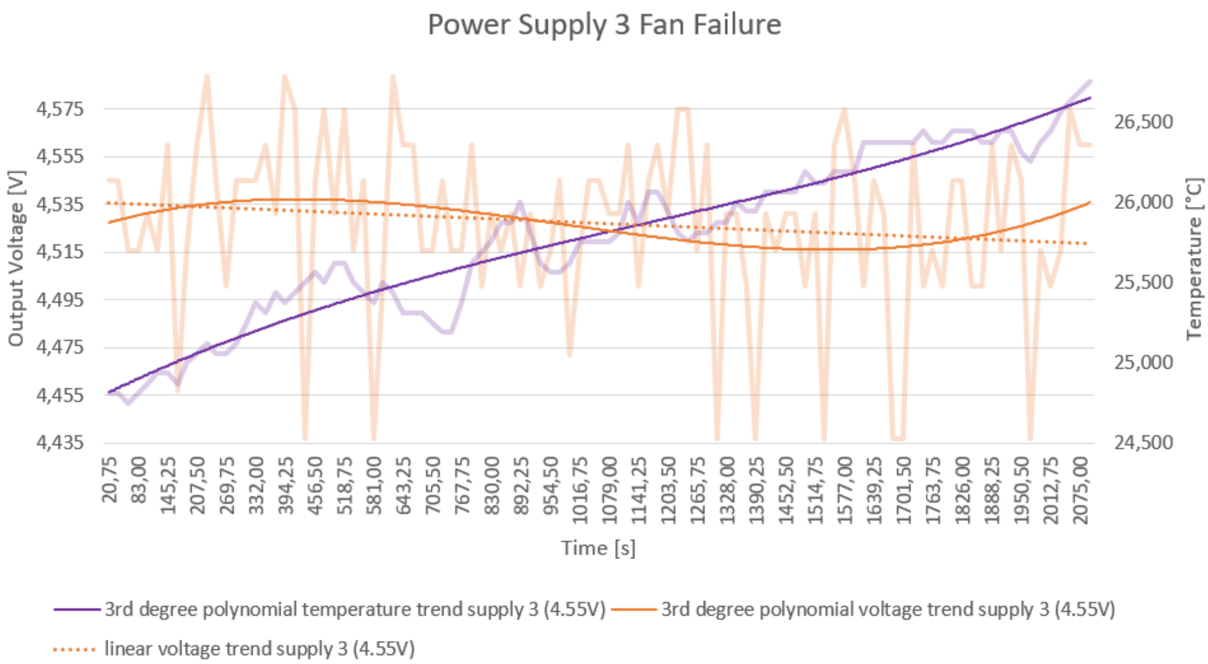


Figure 14: Temperature and output voltage measurements and trends for fan failure in a 4.55V power supply

In Table 8 a tabular overview of the results is given. In there, lowest, highest and average measurements are included for the three runs and both power supplies, PS, during those runs. Next to that, the information regarding the ambient temperature and ambient humidity are included.

Table 8: Overview of power supply fan failure results

		Power Supply 2 (3.05V)			Power supply 3 (4.55V)		
	Unit	**Min.**	**Mean**	**Max.**	**Min.**	**Mean**	**Max.**
Control Run							
Temperature	[°C]	24.31	24.47	24.62	24.31	24.51	24.75
Voltage	[V]	2.991	3.036	3.094	4.437	4.532	4.589
Ambient Temp.	[°C]	23.40	23.49	23.80	-	-	-
Ambient Hum	[%RH]	46.70	47.30	47.60	-	-	-
PS 2 Failure							
Temperature	[°C]	24.81	25.92	26.62	24.69	24.84	25.00
Voltage	[V]	2.991	3.034	3.094	4.437	4.534	4.604
Ambient Temp.	[°C]	23.40	23.50	23.60	-	-	-
Ambient Hum	[%RH]	46.00	46.36	46.70	-	-	-
PS 3 Failure							
Temperature	[°C]	24.37	24.52	24.69	24.75	25.78	26.75
Voltage	[V]	2.991	3.036	3.094	4.437	4.527	4.589
Temperature	[°C]	23.40	23.54	23.70	-	-	-
Humidity	[%RH]	45.20	45.88	46.20	-	-	-

7.3.3 Conclusion

From the results, it can be seen that the researched measurements on the system indeed are correlated to a failing power supply. In Figure 13 it can be seen that the temperature rises and the output voltage drops as expected. Also in Table 8, the calculated mean output voltage during a failure is lower than during the control run. Still, the voltage measurements show no difference in extreme values between the control run and the failure run. When the experiment was conducted for a longer period of time, the absolute minimum value would have been lower while the maximum stayed the same. This is what the trendline shows. One could argue to then only use output voltage as an indicator for failure, however, the operating temperature shows a much stronger reaction to power supply failure. As seen in the figures, the trendline for the temperature shows a clear sign of the power supply heating up. Both the extreme maximum as well as the average are higher during the failure run than during the control run. This is in line with what was researched. Although the increase in temperature could be due to a higher ambient temperature, the ambient temperature measurements show no sign that that was the case. During the control run the average temperature was 23.49°C and during the failure run it was 23.50°C, this difference is too small to have a significant influence on the results of the test. The same conclusions can be drawn for power supply 3, 4.55V. The mean output voltage is lower during failure and the temperature rises while the ambient temperature remains about the same. From Figure

14 however, it is observed that the third-degree polynomial trend line does not show clear behaviour. The added linear trend, on the other hand, does show that the output voltage drops. Therefore it can be concluded that the experiment successfully shows the correlation between fan failure, output voltage and operating temperature. These parameters, therefore, can be rightfully used in power supply prognostics. It can also be concluded that operating temperature should weigh heavier than output voltage in a prognostics model.

In a future analysis of prognostics data, six behavioural trends should be researched. First, as can be seen in Figure 14 the output voltage shows an alternating behaviour with a negative trend. No clear factors can be pointed for this behaviour based on the collected data. Therefore in future research, it should be investigated as to why the output voltage alternates when the fan fails. This is important because it can influence the prognostics system resulting in false positives. Those can occur when during the descending part of the wave the prognostics system gives an alarm for a failure or a certain time till failure while this is not the case or correct yet. Second, the future experiment should be conducted over a longer period of time with a gradual degradation of the fan. This way a more accurate representation of the scenario can be seen in the data. Thirdly, in line with the previous recommendation, the influence of the ambient temperature has to be researched. Because as the employees at Hecla and the literature state, this has an influence on when the power supplies fail. An additional behavioural trend that could be investigated is the influence of a broken tile on the output voltage. If this correlates with an instantaneous change in output voltage, the prognostics system could be expanded with a broken tile detection system. What also has to be investigated, is the question as to why the temperature of the 4.55V power supply rises about linearly while the 3.05V power supply seems to go to a horizontal asymptote. If this is the case, it could be that the 3.05V power supplies fail less often than the 4.05V power supplies. Finally, during night time the digital billboards output a dimmer image which can have an influence on the output voltage of the power supply. Ideally, the data is acquired from currently operating digital billboards and an accelerated life test on both power supplies. This way most artefacts can be accurately pointed out and an accurate model could be trained to determine the remaining useful life.

8. Analysis Framework

As stated above, when real-time data is recorded and also the degrading and eventually failure of a power supply is captured a model is trained to predict the time until failure. As stated in chapter 4, the actual training and evaluation of the model is not possible since the chances of getting real-time data of a degrading power supply are low. Therefore in this section, a recommendation is made to Hecla on how to set up a framework for power supply prognostics. This recommendation starts with an investigation on what the framework should look like. Meaning what are important limitations and stakeholders' interests to take into account. Next, prognostics models are explored to conclude with a recommendation for the company on what type of prognostics framework or software to use and what the materials for doing so cost.

8.1 Prognostics Framework Considerations

When choosing to implement a prognostics system, research has to be conducted as to what the framework should achieve and what limits the framework in doing so. The first entails the requirements set by the stakeholders of the system and the second an analysis of the possibilities. In this section, both subjects are researched. The first by interviews with the employees, the second by careful review of what has been found in this paper and the digital billboard system so far.

8.1.1 Requirements

The requirements for the system are discussed with the project manager J. Löbker, AV technician and ICT support T. ten Hove and the Crestron programmer R. de Valk. According to Löbker, the system is required to send both the operating and ambient temperature to the monitoring software at Hecla. He argues that based on this, the decision can be made whether or not the fans are operating or the power supplies are failing.

Ten Hove agrees and adds that output voltage is still an important parameter. He provides an example that when the output voltage drops to around 88% of the rated output voltage, the image on the billboard has colour deficiencies. This is not tested but for now, assumed to be true. However, this remains a question for future research in the field. Because on a critical note, the output voltage has the ability to rise during night time because less light has to be emitted.

De Valk rightfully adds that for that fact, the time and date have to be taken into account when prognostics are made. He points out that in the digital billboard system that is to be used this is possible. He argues that the integrated light dependent resistor, LDR, can also be used for this. The LDR is currently used to adapt the brightness of the screen to go less bright during the night and brighter during the daytime. One could argue that sending just one value for the LDR would omit the need for the system to take into account the current time and date which requires more processing power. However, the LDR is more sensitive to random errors. For instance, when cars drive by at night, the headlights cause the LDR to put out a lower resistance, tricking the system into assuming a day like situation. The opposite can be true when it is for instance a cloudy day. On the other hand, by just using time and date, dangerous situations on the road can occur when a bright image is displayed during a solar eclipse for instance. Discussing these with R. de Valk he pleas for using both the LDR and the system that takes into account time and date. These technologies can then verify each other. They should verify each other because otherwise faulty prognostics could be made and dangerous situations can occur on the road.

None of the interviewees mentions humidity as a requirement. This can be explained by the fact that for them it never seemed to be the cause of failure. Still, the author suggests this is a requirement in the prognostics system as it is highly likely that humidity and the corroding fan are related. However, other than the operating temperature, the humidity has to be observed over a longer period of time in order to say something about the remaining useful life. For example, if for the past half an hour high operating temperatures are observed it indicates a failure in the near future while half an hour of high relative humidity does not tell anything about the power supplies health in the near future.

From all three interviewees, it was clear that the main interest was in the remaining useful life. Meaning a time until failure is a property that has to be calculated with the above-mentioned requirements taken into account. In conclusion, both operating and ambient temperature, output voltage, the LDR, the time and date and relative humidity are required in order to predict the remaining useful life.

8.1.2 Limitations

The single most important limitation that follows from this paper is that the data currently available is only partially representative for the real-life situation. In this paper, the behaviour of the variables of operating temperature and output voltage as a result of a not working fan have been researched. In the experiments, the ambient temperature, brightness as a result of the time of the day, humidity, broken tiles and other failure modes were left unchanged due to constraints in time and resources. Because of this, the model that can be trained with the information gathered in this paper is not accurate. Instead, in the prognostics system, a loop needs to be included that continuously adjusts the weight of the parameters of the model and so becomes more accurate over time.

8.2 Models

Now that the requirements and limitations of the model are known, the available models are researched. According to The MathWorks, Inc. [46] and X. Si et al. [47] three ways to estimate remaining useful life can be chosen depending on the available data. The models they enlist are a similarity model, relying on lifetime data from similar machines from the healthy state till failure. A survival model, or proportional hazard model, that can already be used when only the time till failure is known. And, when data is available about something between healthy state and failure state but a failure threshold is known, a degradation model can be used. A graphic representation is shown in Figure 15. In this section, all three are investigated for their advantages and disadvantages to conclude with the recommendation for the company on what model to use and a flowchart of the prognostics system.

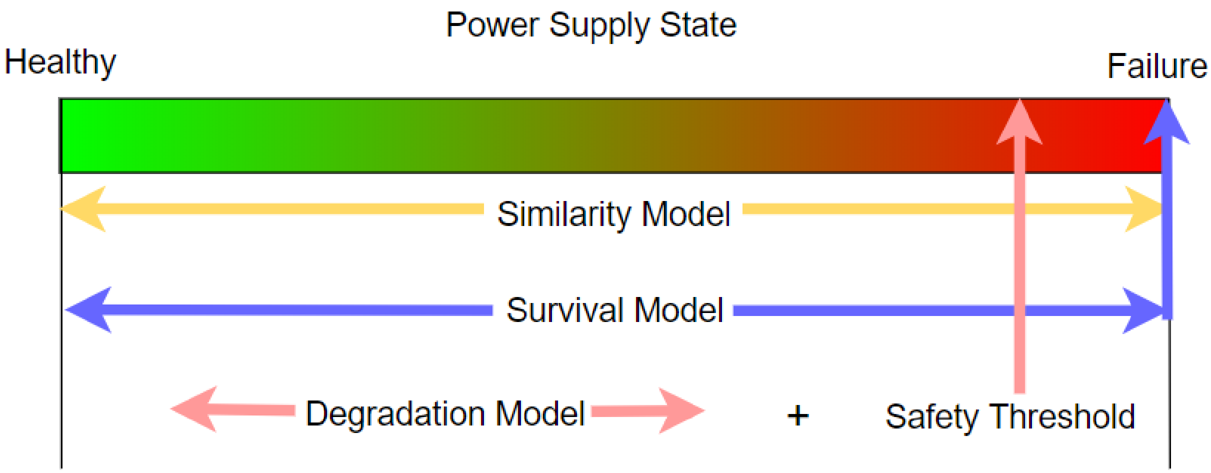


Figure 15: RUL prediction models and their respective required information

8.2.1 Similarity Model

As stated above and as can be seen in the above figure, a similarity model relies on a database of run-to-failure data. The methods used in the model compare the current path the monitored device has to historic failure paths and bases the remaining useful life on the path that most closely resembles the current path [46].

Many papers have investigated the advantages of adopting this model in prognostics systems. Two clear advantages can be distinguished from them. First, Z. Xin et al. [48] point out the accuracy of the model due to an adaptive filtering method for the error. This means that the weights of how the predicted time is calculated are changed to reduce the error until an optimal set of weights is found to minimize the error. Z. Lui et al. [49] elaborate on this by stating that the predicted remaining useful life is not the weighted average of all historic remaining useful lifetimes, but rather the weighted average of the remaining useful lifetimes of the run-to-failure data that most closely resembles the current path. Second, M. Samie et al. [50] look at future scenarios by noting the usefulness of such a model when a new subsystem is introduced. For this paper, it would mean that when a different kind of power supply is to be implemented. The model can still be used with only minor changes. These changes will again be made in the weights that the failure predicting properties have according to M.

Samie. In short, the advantages of the similarity model are in the fact that it is accurate and sustainable for future applications.

However, the accuracy of the model comes at a cost. To start, Z. Lui et al. [49] point out the effect a random part of the degradation model can have on the prediction of the remaining useful life prediction. When the random part exhibits a relatively large change, the current path of the monitored device deviates from the known paths and the resulting prediction can deviate significantly from the actual value. Furthermore, the dataset should be large. Training data from NASA's Predictive Health Management challenge, PHM2008 [51], consisted out of 218 run-to-failure simulations and 21 sensors monitoring various properties every second. From this dataset, 70% of the data was needed to get the error in the prediction down to 3% with a standard deviation of 20%. In line with this is the disadvantage that the dataset has to contain run-to-failure data. Which is not the case in the digital billboard power supply situation. All in all, the core to the disadvantages of this model is the lack of and random errors in the data needed in order to do accurate predictions.

8.2.2 Survival Model

When data regarding the time till failure is known the survival model can be used. It uses multiple run-to-failure times of the device that is being monitored to calculate the probability of a certain remaining useful life [46]. To make it more accurate, many papers [46], [47], [52], [53] suggest to use covariates. They enlist covariates as for instance environmental variables such as operating temperature or loads.

The combination of known run-to-failure times and environmental factors offer three advantages for this model over the similarity-model. First, X. Si et al. [47] mention the fact that new covariate information can easily be integrated into the baseline proportional hazard model function. They argue that the effect of the added property can then be easily evaluated on its usefulness for remaining useful life prediction. This would not be possible in the similarity-model because currently monitored data entries have to be the same as the historical data entries. Another advantage, mentioned by Z. Ma [53], is the fact that this model is capable of dealing with incomplete observations of failure events or random errors. Where random errors in the similarity-model throw the model off guard, in the survival-model it does not. This is because the survival-model does not have a path to follow. For example, on iteration one a random error in temperature is measured, for this iteration the probability of a shorter time till failure will be high. On iteration two, the temperature measurement contains no error, so the probability of a later time until failure will be high. X. Si et al. [47] finalise the advantages with the notion that the model does not need event data such as failure or thresholds in order to predict the remaining useful life. This is because it is strictly based on time variables. In sum, the advantages of the survival-model lay in its flexibility and how it operates when there are random errors.

This flexibility can however also be a disadvantage for the remaining useful life prediction. Firstly, X. Si et al. [47] point out the situation that exists when the newly chosen covariates do not include the covariates included in the current baseline proportional hazard functions. The model is now unable to compare the covariates and so, no accurate estimation regarding the time till failure can be made. In a model where the variables are fixed, like the similarity model, a prediction can always be made. Another limitation, mentioned by the same authors, is the fact that this model calculates a probability of a certain time until failure. They note that a point prediction cannot be accurately made due to the large variability. Instead, they argue for calculating the probability of a certain interval where the failure will take place. Thirdly, they also mention the critical review that is needed on how covariates are modelled since some are a result rather than a cause. For instance temperature, the temperature of the power supply is a result of degradation while the ambient temperature is a cause of degradation. When modelled wrong, the model is unable to give an accurate estimation of the interval in which the failure will take place. Finally, similar to the disadvantages of the similarity-model, a large amount of data is needed in order to be accurate. No clear examples are found regarding the volume of data, however. Concluding, the limitations of this model are the fact that it bases its remaining useful life on probability, covariates have to be carefully chosen and evaluated and data is needed on the time it took until the device failed.

8.2.3 Degradation Model

When the time it took until failure is not known, nor the values for healthy operation but instead data is available about a degradation process and the failure threshold, the degradation model can be used. The models predict the remaining useful life based on the estimation of the time it takes for a sensor value to cross the threshold value [46].

This method offers three advantages over the other two suggested models. For a start, this model does not require any information about the failure event other than a threshold. This means that this model can already be implemented based on theoretical values. The second advantage is mentioned by X. Si et al. [47] and is the fact that, similar to the survival model, random errors do not cause significant errors in remaining useful lifetime predictions. Finally, the reviewed literature [47], [54], [55] point out the mathematical advantage and physical interpretations that make this one of the most effective methods for prognostics. X. Si et al., for instance, show that the first passage time, the time the lower part of the confidence interval passes the threshold can be formulated analytically. All in all, the advantages of the degradation model are in its simplicity and the fact that it can be implemented without any run-to-failure data.

There is also a downside to some advantages. The fact that random errors do not cause significant errors in the prediction is because no integration method is used. X. Si et al. [47] note this has as a downside that the information contained in the sequence of observations is ignored. A second limitation they point out is the fact that the remaining useful life is predicted with a linear degradation path in mind. As could be seen in the conducted power supply failure runs, the failure indicating variables showed no clear linear behaviour. Therefore, Z. Wang et al. [55] developed a method that counters these problems by taking the historic data sequence into account and adjusts its calculated remaining useful life for systems with nonlinear degradation. They found that their model is applicable and effective and moreover gains significant improvements compared to models of for instance X. Si et al. [47]. In short, the disadvantages of ignored historic data sequences and nonlinearity are countered in degradation models.

8.2.4 Prognostics Model Flowchart

With regards to what model is most appropriate, the conclusion is that the degradation model is the best model to start with. This is because of the limitation of available data regarding failure. What is only known are the thresholds set by the datasheets and service mechanics. For instance, as discussed in chapter 5, the datasheet [15] specifies a 100% healthy power supply at 50°C operating temperature deteriorating to 50% healthy at 65°C. Another such threshold was pointed out by T ten Hove claiming colour deficiencies are outputted when the output voltage drops to 88% of its rated value. Furthermore, the previously conducted experiment captured the part of the lifecycle of the power supply on which the model could base an estimation. When enough data is gathered, the company could choose to switch to a similarity-based model for its advantages in accuracy. The disadvantage of random errors causing the model to be inaccurate can be countered by introducing a variable threshold for every next value read. For example, the next temperature reading cannot differ from the current reading with more than 2°C. For additional smoothing ten temperature values can be read and averaged to one value and then used in the model. However, these possible solutions have to be researched in future work. For now, the concluding prognostics flowchart is shown below in Figure 16. A critical note has to be placed here because as was seen in the experiment results, the 3.05V power supply reacts differently (with regards to operating temperature and output voltage) to fan failure than the 4.55V supply. Therefore two different degradation models have to be trained for the respective ratings.

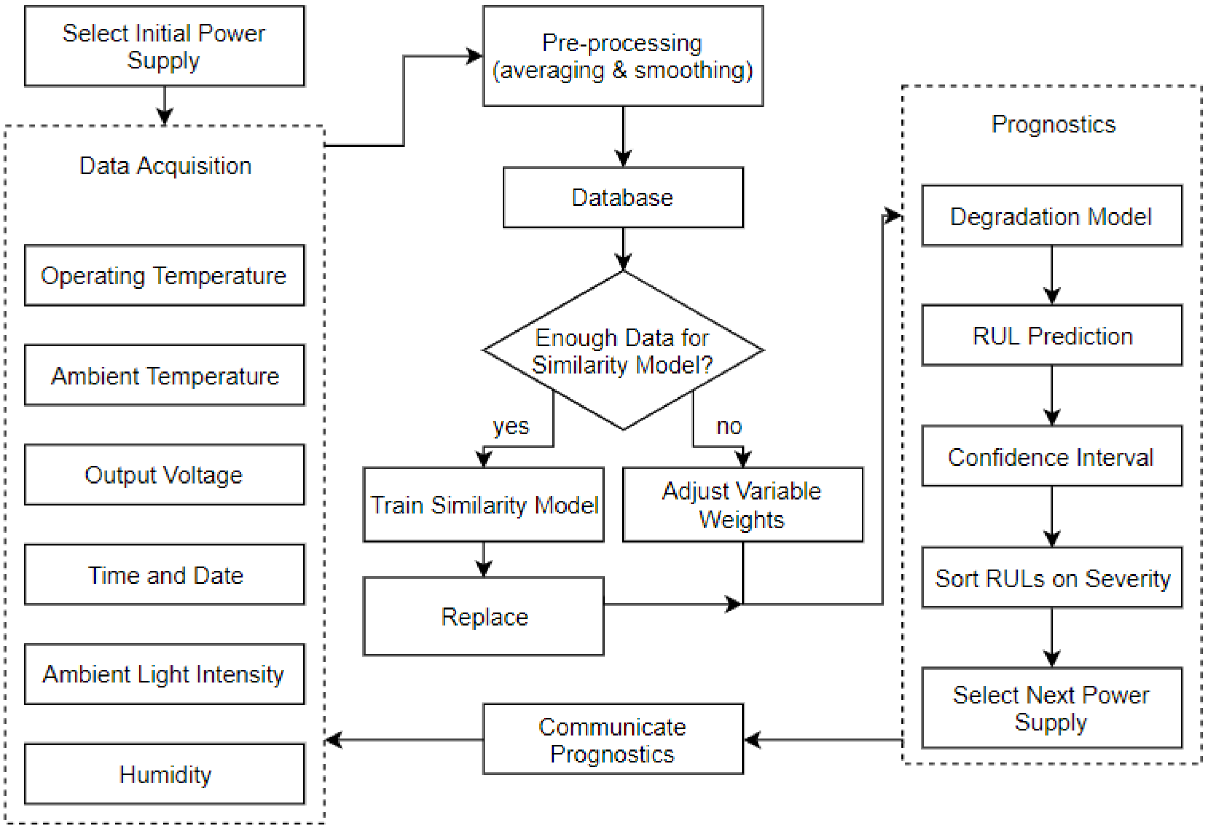


Figure 16: Power supply prognostics flowchart

However, a critical look needs to be taken at how the full prognostics system is brought into practicality. Therefore, an ethical review on the project is shown in chapter 11. Since the ethical considerations do not contribute to how the system should look like but rather to how stakeholders might perceive it, it is presented after the concluding chapter and recommendations for future work.

Regarding the costs of this system a quick calculation is made to assess the financial advantages and disadvantages of this system. The material costs of this are shown below in Table 9. The prices are gathered from a popular Chinese online shopping website and only give a rough indication as prices might change over time.

Table 9: Material costs for implementation of the system

		Amount per panel	**Price per component**	**Price per panel**
Component	**Type**	#	€	€
DS18B20	Temperature sensor	3	0.51	1.53
DHT22	Humidity sensor	1	2.48	2.48
Total				4.01

As can be seen in Table 9, the costs regarding installing the sensors and adapting the code are not known so they could not be taken into account in this calculation. Similarly, the amount of money that the companies who rent the digital billboard charge Hecla for not showing their advertisements is not known. Therefore, this remains a subject for investigation in future work. In short, no conclusion can be drawn to whether the system is financially feasible to implement.

9. Summary and Conclusions

Finalizing this paper, a conclusion is drawn regarding the feasibility of this project. The main research question was how remotely monitoring digital billboards predict the time until failure of the digital billboard system. This paper investigated and tested the relevant electrical and physical properties that correlate to digital billboard power supply failure. Furthermore it researched what components to use and how to accurate they are. After that, it presented the communication methods that are used and that can be used and ways to deal with the limitations of the components and modules in the current system. Finally, based on the data available it recommended what prognostics model to use as a start and when enough data is gathered. A concluding prognostics system flowchart finalizes this feasibility study. Overall, it presents a feasible method of obtaining and communicating the relevant data and provides a recommendation on how to set up the analysis framework. Based on the literature and results the proposed system can predict power supply fan failure, the most frequently occurring failure mode, within 24 hours. The success of this project can be underlined by the fact that as of now, Hecla is reprogramming the EMBs in order to be able to send the suggested sensor information to their monitoring application.

10. Future Work

This paper can benefit from future work in several fields. On a financial note, Hecla has to determine whether or not the extra costs of four euro per panel weigh out the charges they get from the companies who claim their advertisement is compromised. On the other hand there are practical aspects in this paper that benefit from more extensive research. As mentioned in the discussion section of the experiments on the humidity sensor a calibrated relative humidity measuring should be used to be certain about the accuracy of the test and the sensor. If such a device is available then also pure salts have to be used so no other chemicals are influencing the readings. Furthermore, there are various investigations that are beneficial to this paper regarding the bandwidth. For a start, the minimum bandwidth was obtained by a conversation with employees however an accurate test needs to be conducted as to what time interval is desirable for prognostics in this field. In line with this is the research as to what is the exact available bandwidth between billboard and Hecla. Both these bandwidths can be researched by stressing the data communication rate between the EMB and LCM and LCM and Hecla. If it turns out more bandwidth is available than required for the proposed prognostics system to be accurate, the possibilities for other sensors to predict other failure modes can be researched. To do this, an accelerated life test can be conducted on the power supply while monitoring varying properties like load, temperature and relative humidity. Doing this can also reveal the time it takes for a power supply to go into thermal shutdown at a certain temperature. Integrating a gradual degrading power supply fan should then also be incorporated in the test. Which is useful information for the prognostics model. Even if it turns out no extra sensors need to be added for other failure modes, an investigation can be done to research if the mentioned Pareto Principle is applicable to this prognostics model project. Regarding the model, a method for smoothing or thresholding random errors from the sensor readings have to be researched. Another threshold to be researched is the threshold as to when colour deficiencies are visible on the output image on the screen. For now, this is only known by conversations with employees. An experiment with a variable power supply can be conducted. From this, follows the limitations found in the discussion of the real-life scenario experiment. As discussed the dimmer image during night time, can result in a higher output voltage at that time. The monitoring application running at Hecla has the capability to change the light intensity so the change in output voltage can then be investigated. Another factor that might influence the output voltage is whether or not all the tiles are operating. This can easily be tested by disconnected one or multiple tiles. In the tests, however, the output voltage showed an alternating behaviour. It should be researched what is the cause for this. For all of these mentioned future research opportunities they have to be conducted for both the 3.05V and the 4.55V supply. Which concludes the final remark that is that the overarching goal of future research in this field is “Above all else, show the data.” – Edward R. Tufte [56].

11. Ethical Considerations

Introduction

Using remote monitoring technologies in digital billboards used for commercial purposes leads to some ethical and philosophical issues. It is important to be aware of these issues as they can lead to product failure. In the design process, an iterative protocol for detecting ethical and philosophical questions needs to be implemented in order to address the questions before they turn into problems. In this paragraph, the ethical issues concerning the use of a prognostics system in digital billboards are researched. These issues are addressed using tools to implement ethical reflection, deliberation and judgement into the design flow. With these tools, the ethical design flow will be well integrated, made explicit, regularized and operationalized. The toolkit consists out of 7 tools: ethical risk sweeping, ethical pre- and post-mortems, expansion of the ethical circle, case-based analysis, ethical benefits of creative work, thinking about the terrible people and ethical feedback and iteration.

Each of these tools will be discussed and applied into detail in the case to make sure all ethics involved with the development of this system are considered. The tools are iteratively applied because a solution can bring up other ethical problems that need to be addressed in another iteration of the toolkit's tools. In the end, a conclusion will be drawn that specifies the final design solution.

The prognostics system design consists out of 3 steps: data acquisition, data transportation and decision making. The acquisition step is done by using sensors monitoring critical parts of the digital billboard system that allow for proper failure prediction. The critical part for this design is the power supply of which the temperature and the humidity surrounding it is monitored alongside the outside temperature. Data transportation is done via a VPN connection with the company Hecla who owns the billboards. Decision making is done based upon a model that was trained with data acquired from failing digital billboards. For these steps, the ethical concerns will be presented here by using the above mentioned iterative process.

Ethical risk sweeping

The first tool is ethical risk sweeping. Before using this tool, a clear definition of ethical risks should be given. Vallor, Shannon, Brian Green, and Irina Raicu define this as follows: "Ethical risks are choices that may cause significant harm to persons, or other entities/systems carrying a morally significant status or are likely to spark acute moral controversy for other reasons" (p. 4) [57]. In order to sweep such risks, they first need to be found. This paragraph will focus on finding ethical risks per step of the designed system and get rid of them.

Starting off with the data acquisition step, there is a concern regarding the confidentiality of the sensor's specification. The temperature and humidity sensors all have a datasheet that specifies their accuracy, precision and resolution. However, these specifications can deviate from device to device, which can, in turn, have consequences for the prognostics system. When a temperature sensor is not accurate, the prognostics system can assign a remaining useful life to a certain component that is significantly off with the actual remaining useful life. Therefore, each sensor should be tested in a laboratory setting where the temperature and humidity can be regulated to verify its specifications regarding accuracy, precision and resolution. Next to this, the sampled values by the sensors should not contain random errors. These errors can occur when a sensor has a misreading for instance. In that case, the software should eradicate this value. Finally, to make the readings more accurate, the values for temperature and humidity have to be sampled 10 times and the average is to be transported to the server running at Hecla.

Next, the data transportation step requires a review of its data protection. By using a VPN connection the IP-addresses will be masked so hackers are unable to direct the attack on a specific pc. Although this is true for now, in the future ways to hack a VPN will be found. The environmental data acquired by the sensors is now a part of the company's strategy and unique selling point, predictive maintenance on the critical components. It will cause harm to the company when information regarding the digital billboard's current health is accessible for competitor companies. Because of this, data transportation and storage need to be well secured. This can be done by encrypting sensitive data and storage in a protected and offline database.

Finally, for decision making, a similar concern as the one with the sensors is found. The decision making is done based upon a model trained with data of failing digital billboards. When this data is not accurate in the training process, the model becomes faulty. It looks for different properties and values then it should. This is a serious concern as the remaining useful life can be determined to be much shorter, resulting in premature maintenance. Or too late, resulting in digital billboards showing faulty colours or no image at all. The company will be held responsible for this and has to compensate the people renting the billboard for not being able to convey the advertisement as it was intended. So, until data from real-life scenarios is available, the prognostic system should not make decisions about the remaining useful life. The system should first focus on data acquisition and transportation until enough data is available to train an appropriate model.

Ethical pre-mortems and post-mortems

Now that the ethical risks on individual steps are known. The view can be broadened to other important ethical risks. In pre- and post-mortems the question of what is the worst that could happen is at the centre stage. For pre-mortems, when a worst-case scenario is found, the team sits together to find the combined causes of the failure, find the blind spots lead them into it, find out why the product failed to act on it, figure out why or how the wrong action was chosen and what can be done to reduce the risk of failure. In this paragraph, each of these questions will be investigated. So first, an ethical worst case scenario is determined.

The worst case scenario for this system is when it harms people. In this case, the remaining useful life prediction provided by the prognostics system can induce stress and a feeling of an increased workload for the service mechanic.

The combined factors that cause the service mechanic to be stressed and have a feeling of an increased workload is the time component and possible sensory overload that is introduced. If multiple billboards provide their remaining useful life, the service mechanics are urged to hurry from one billboard to another in order to fix them before they break down. This overload of information and the time component together create unpleasant working conditions and could lead to mental and physical health issues.

These issues were not spotted because the effects on the mental state of service mechanics of the system were not considered. The focus was on the design of the system on the back-end which does not take into account how the data is presented. However, still, a recommendation has to be made on the presentation of data to the end user, the service mechanics.

These recommendations can be implemented in the front-end as well as the back-end of the system. For the front end, the application that shows the remaining useful lives has to only show the prognostics of the billboards that are first in line in the time until failure. Furthermore, this has to be limited to only show the prognostics of billboards that fail within three days. These three days are chosen because that is when, according to the project manager, failing components show their degradation on the output image on the billboard. Before the three day mark, no signs of degradation can be seen on the screen. One could argue that these solutions should be implemented in the back-end directly. However, constant data collection is necessary to train the system. Therefore the back-end of the system has to be strictly for developers only. No one except the system designers can enter this part of the system and review or change parts of the system. If service mechanics were able to do this themselves, they could change parameters as such that there is no longer any digital billboard that communicates its actual remaining useful life. A service mechanic would want to do this so he doesn't have the time pressure and workload that he experiences with the system.

For post-mortem, on the other hand, the team should think of ways how to solve the worst case scenario after it already happened. For this, a scenario where a component was replaced because the prognostics system communicated its reaming useful life as less than three days is assumed. But in fact, it turned out the component was healthy and could last another three months. This lead to the service mechanics getting frustrated with the system. If this happens, questions that the design team should ask themselves are figuring out why the project failed, what combined causes led to the ethical failure, what was learned from this failure, what protocol could have prevented this failure and what needs to change to do a better job next time.

The ethics that collide here are utilitarianism and duty ethics. The first one is more focused on outcomes and less at rules while the latter focusses on the actions taken more than the results that action has [58]. When applied to the scenario it means for Bentham's utilitarianism that the service mechanics did well because the result is that the digital billboard was serviced before it failed, resulting in maximum benefit for the greatest number of people (Hecla, renters, targeted people, etc.). For Kant's duty ethics it means that they did well because they followed the rules that the prognostics system implied by showing the remaining useful lifetime and so they repaired the screen. However, both theories do not take into account how the service mechanic feels about his actions and if he is satisfied with following rules implied by a system or servicing a billboard that didn't need any service. Rather than living up by rules or having the feeling of doing this work solely for others, the mechanics should feel satisfied.

Causes that lead to this issue of service mechanics getting frustrated is because of mixed interests in the system. Hecla aims to have everything serviced before digital billboards fail. This will enhance their image in the digital advertising industry and possibly lead to financial benefits. In order to do this the remaining useful life is used as rule and measure for the mechanics. However, they are proud people, proud of their jobs and now they have to service things that do not look like they need service. They cannot physically see the impact they have on doing their jobs. This affects their feeling of dignity and necessity of their work.

From this, the team can learn that there is a need for dynamics in the system that keeps all stakeholders satisfied with the workings of it. It should be noted that service mechanics have a different kind of ethical theory that they value which is virtue ethics. This highlights the virtues the mechanics have in their ethical behaviour. For them, pride is of great value. The impact such values have can also be seen in Maslow's Hierarchy of Needs shown below in Figure 17 in the second highest need of esteem.

Figure 17: Maslow's Hierarchy of Needs [59]

To prevent Hecla from coping with frustrated service mechanics several protocols have to be introduced. Firstly, the mechanics have to be able to see what they do, they have to see the impact they have when a screen is serviced. Second, they have to more or less 'determine themselves' if service is necessary. This can be done by using the cameras that are already aimed at the digital billboards. As stated before, when components are about to fail they can show faulty colours on the output image. By using the cameras, the mechanics can inspect if there are already colour deficiencies on the billboard from which they received a prognostics message. If not they can choose not to go there yet. This decision making will still their esteem needs. Furthermore, by doing this, they can choose to service the screens when there are faulty colours and so they can see the impact of their work. The project managers at Hecla state that the faulty colours will be minimal and that cars passing the billboards alongside the road where they are placed, will not notice this colour difference. But the trained eyes of the mechanics will see it.

Finally, there needs to be a protocol in the design process that thinks of these kinds of scenarios in order to take everything into account and not be surprised by this kind of events. These pre-and post-mortem scenarios have to be implemented after every design iteration.

Expanding the ethical circle

Ethical risks can occur when not every stakeholder is taken into account. To do this, the team has to consider expanding the ethical circle, meaning look at people that are (in)directly affected by the product and the potentially the just identified pre- and post-mortems. In the following paragraph, some critical questions that invite explicit reflection of the product and recommendations are asked. One very powerful tool that has to be used in this expansion is the ACTWith model. An overview of this model is shown below in Figure 18.

o/o	o/c
c/o	c/c

Figure 18: ACTWith model

The iteration starts at the lower left corner and moves clockwise through the model and after enough iterations, it leaves the model on the lower right corner. The 'o' and 'c' stand for open and close respectively. Their place, either upper or lower, represents the mind and the position respectively. With the position is meant 'to stand in someone's shoes' so get yourself familiar with the situation, with the mind is meant 'what do you now think of this.' By making enough iterations through this model it is possible to understand peoples thoughts from their point of view. And so, in this case, the team can try to find the values for the stakeholders affected by the product.

The first question regards to interests, desires, skills, experiences and values of indirectly affected stakeholders that were simply assumed rather than consulted. One aspect of this case is the fact that it was assumed that people driving on the highway and see the digital billboards are not too much distracted by people working on the boards that it distracts them. This was a result of the 'bubble' mentality. Since the designer team only consisted out of people familiar with the audio and video branch nobody gets distracted by a digital billboard that has service going on to it. Furthermore, nobody looked at it from the perspective of the target audience of the billboards. For this, it should be researched whether drivers are distracted by service on digital billboards and consider nightly repairs as an alternative. This could be done in the form of an online questionnaire with people driving on roads alongside which the boards are placed. Because of the bias employees and the design team at Hecla have, no tests can be conducted by putting ourselves in the situation of the drivers. Instead, a control and test group can be asked to drive a certain route and afterwards take a questionnaire and interview them about their experiences and distractions. This way the design team can get a view of what is going on inside the head of the drivers and when back at the drawing table, work those findings out in the design. When finished another test similar to the first one has to be conducted in order to verify or restart the design.

Case-based analysis

Not only by expanding the ethical circle but also by looking at other cases, some ethical issues might be spotted right away. The procedure is as follows. First, find a similar case, then identify relevant parallels or differences between the cases, then evaluate the choices made and their outcomes and finally reason with the help of that case parallel risks, opportunities, solutions and risk mitigation strategies [60].

A similar case to the one presented here is a case where prognostics on a Neonatal Intensive Care Unit. It argues that individual knowledge and experience of those involved must be taken into account when dealing with prognostics. Those involved were in this case experts as well as parents who by capitalizing on prognostics markers and using similar reasoning, reached different conclusions regarding a child in a neonatal intensive care unit. The child in question was Tom, who was put in an incubator because he weighed less than one and a half-pound. He was hooked up to a respirator for mechanical ventilation and supplemental oxygen and other medication. His reaction to medication was not good and on request of the parents, the doctors saved him every time. This is because the parents visit Tom daily and based on their observations and interactions have a different view on his health than the doctors or nurses.

The similarity thus is clear: there are different stakeholders that have different reasoning regarding prognostics. There are the doctors who compare the situation with other situations, ‘theoretical children.’ They are similar to the prognostics system who is trained with many fault scenarios and bases the prognostics for a screen on their training and currently observed parameters. On the other hand, there are the parents who look at their child from a different perspective, they see a child getting better, getting worse or fighting for his life. One could argue that this perspective is more subjective and superficial. The parents show similarity to the service mechanics: we see this, so we do this. Also, Tom’s father refers to the health of Tom in comparison to the health of other children in intensive care. He sees Robert getting better after a heart operation so why wouldn’t Tom make it.

However, other than the doctors, he doesn't know what is the case-specific for Tom. Their prognostics are based upon other situations they see around them

As stated before, the doctors listened to the requests of the parents. This would be different in the prognostics system where the mechanics act in response to the prognostics system. However, in the same paper, a case is presented where there are the parents of Maureen who never visit their child and rely on what the doctors tell them on the phone. The question here is what is better with regards to the child, the digital billboard.

The choices the doctors make is to educate the parents when their child is put in intensive care. They teach them to recognize the signals that indicate improvement or worsening of the situation. They teach them technological reference points such as respirators, kind of incubator and the way the child receives nutrition. However, a critical note is placed here because these technological markers for prognostics tend to vary for every case. This again affects how the parents respond to what the doctors say. Tom's father at some point no longer takes for granted what the doctors say, because he has been seeing the devices Tom is attached to for days now, he to some extent knows what is going on. At first admission, he did listen to the doctors for he didn't have a clue however now he doesn't accept everything unquestioningly and wants to speak to experts rather than nurses that happen to take care of Tom at that given day. There is a constant dynamic between the doctors and parents on how the child is doing and what should be the next step. Similarly, the mechanics become/are familiar with failure modes in the digital billboards and should consult someone overviewing the prognostics system to verify their considerations.

As stated above, as stated above, upon the first introduction of the system, the service mechanics have to be guided and educated on how to interpret the relevant parameters. Next to that, there should be someone available for them to consult when they are not sure about a prognostic warning. In time the mechanics will get a feeling of what the prognostics mean and that that is an opportunity to act independently on this. This is eventually what would make the system most efficient. However, a parallel risk is that the service mechanics, similar to the parents, feel like they know just as much as the prognostics system and question decisions the system makes. For this, there needs to be some sort of hierarchy introduced. It would not respect the mechanics if they were subordinate to a computer program. Therefore, the man behind the prognostics system should always be there as a higher entity to consult when there is confusion about a decision.

Remembering the ethical benefits of creative work

After all these ethical risks and worst case scenarios, it is time to remember why the team does all this. This paragraph aims to implement a workflow that makes the ethical benefits explicit and deepens sincere motivation to create them. The ethical benefits are the goals that are tried to be achieved. To keep this goal at the centre of the design and keep the team motivated there is an investigation needed as to why is the team doing this and with what goal in mind. Furthermore, will society be better off with the designed product or is it just a new thing to sell. Has the ethical benefit of this technology remained at the centre of the work and what can be sacrificed to achieve this? Routinely asking the team this question will result in a motivated team if the ethical benefit is right though.

To start, the team goes back to when they got the case assigned. The goal was to design a predictive maintenance system for digital billboards to enrich the service of Hecla and save money by eradicating the chance of downtime. The aim was to benefit all the parties, Hecla for enriched service and advertisement companies for having no downtime. This is a good end in itself and the life of the greatest number of people is made better. The team can be motivated for this goal as there are no ethical drawbacks that are not addressed in the above paragraphs. For society, it can not clearly be stated whether or not this system has a positive or negative influence on it. Although questions can be raised as to what extent advertisements alongside road cause dangerous situations for users due to them being distracted, this is not due to the system that is implemented by the design team and thus is subject for another team to investigate. On the contrary, one could argue that a fully functioning billboard distracts less than a partially working billboard. Yet again, this remains subject for another study.

The aim for Hecla to save or even make money can be up for debate. As N.D. van Egmond and H.J.M. de Vries state in their Major Value Orientations in the Population shown in Figure 19.

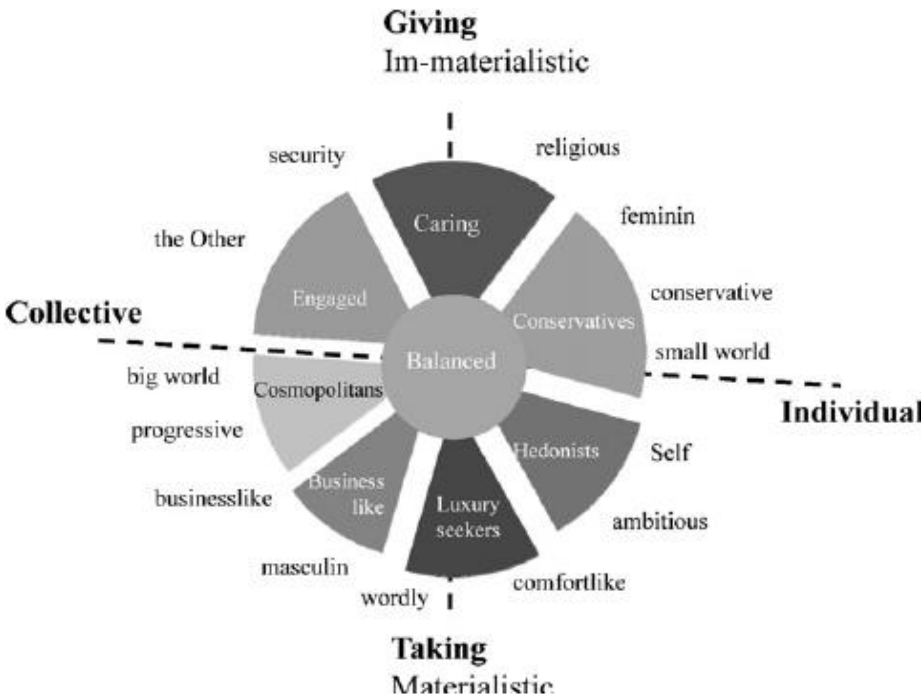


Figure 19: Major Value Orientations in the Population [61]

The aim to benefit as many parties as possible is a collective goal in the business-like sense. As of now, society is focussed on oneself and looks for luxury, this product will try to balance the society in a more collective sense by trying to benefit everyone. However, make it even more balanced, an im-materialistic element could be added to the product. One could argue that there is enhanced security and safety because road users are not distracted by faulty billboards. However, as stated before this cannot rightfully be claimed until this is explicitly researched.

The benefit of making a more collective society can be a motivation for the team to continue the design. Next to that, the team can generate motivation if it turns out that this product actually does enhance security for society.

Think about the terrible people

What happens when the product falls into the hands of a terrible person. A scenario of what can then happen was already given in the paragraph about ethical risk sweeping. A rival company gaining access to the data might extract valuable information to increase its position in the market in relation to Hecla. The solution for that scenario was already presented in that same paragraph.

Closing the loop: ethical feedback and iteration

The last part of the toolkit is finishing the research and implement ethical feedback loops and make sure more iterations of this ethical protocol are used. Not only in the design phase but also when a product is on the market, a constant review of ethical concepts to the society at that point in time needs to be done. In this paragraph, it is tried to get this understanding into the company culture. If this is embedded the company will most likely not fail two products in a row again.

The first step needed is for the company to understand that ethical design is a never-ending task. This can be done not only by reviewing ethical concepts at certain moments in the design stage, but also look back to previous projects and look on what ethics were involved there and if everything was addressed the right way. Also in meetings about the future the company or future project they have to make ethics a subject of the conversation. In short, ethics need to be present in an organization's past, present and future.

The second step is gathering information on how your products are currently doing in an ethical sense. This data can be of subjective nature in the form of a questionnaire distributed under stakeholders, where they review the product of interest. But better is objective feedback. In the digital billboard case, the team chooses for the metric of measuring how many times the system predicts failure in time. From this data, specifically chosen questions can be asked to gather information about the confidentiality of the service mechanics in this product.

The third step is to design and implement a standard process of quality management and support. In this case, this was already integrated by letting the service mechanics have the ability to connect to someone overviewing the prognostics system. Remarks and suggestions can be made to the same person. Also in future product designs, the ability to connect to a real human being while using a product has to be present.

Finally, there is a protocol that has to be developed that takes care of responsibilities in ethical iterations. In other words, a strategy plan for analysis, communication and usage of ethical data is made. The choice to continue with a product of which the ethical group already knows it is going to fail should never occur. Therefore the responsibility of closing the loop and making the decision is with this group. However, it has to be taken into account that this ethical group is not owned by the company but is independent.

12. Appendices

Appendix A

Possibilities for remote monitoring the health of digital billboards: A literature review

Time is money. Downtime is a loss of money. In the advertising industry, the losses caused by digital billboards unable to show the commercial advertisements of its clients, are directly recoverable on the company renting out the advertising equipment. In this case, the company Hecla, a top-5 Dutch total solution provider in audiovisuals, is renting out the advertising equipment consisting of large format indoor and outdoor LED screens. Not working LED-panels or LEDs that display faulty colours result in a commercial that does not convey the message as it was intended. Next to that, it will have a negative influence on the image Hecla has in the digital advertising industry. Only when someone notices and reports a fault, Hecla knows they have to go to the screen and repair it. Of course, Hecla wants to prevent this downtime by servicing the screens just before they fail. This graduation project aims to, in order to reduce the costs and benefit all the parties, design a system that predicts and communicates the time until service of the outdoor digital billboards along the road is necessary. This aim can be divided into three subjects: the measurements of the electrical quantities in the LED arrays, the transportation of this data and the analysis of the data. A substantial part of the research will be about the second subject, the transportation of data.

This data transportation entails the electrical quantities measured in the LED system that need to be sent from the remote location of the billboard to a server where the data can be retrieved for analysis. Knowledge about the possibilities of this remote monitoring technology is required to adequately choose the right method for Hecla's equipment and thus helping them to offer more extensive service to their customers. Therefore, the goal of this literature review is to investigate which remote monitoring system is most suitable for remotely monitoring digital billboard equipment.

To acquire this knowledge, first, a clear definition of remote monitoring will be established for this paper. Second, examples of goals in use contexts of remote monitoring are presented. From thereon, the different types of communication of remotely monitored data to a server is investigated. In there, also the capabilities of those communication types are given and finally, a conclusion about the suitable way of performing remote monitoring on Hecla's digital billboards will be drawn.

Remote Monitoring

The description of remote monitoring varies for the particular field where it is applied in and where the focus in that field lays. A vast number of remote monitoring solutions and applications of the technology thereof are present on the market., so the found descriptions are compared to distil a general definition.

Firstly, an important focus is the acquisition of data by using sensors. There are J. Yick et al. who point out that the technology of remote monitoring “consists of a number of sensor nodes (few tens to thousands) working together to monitor a region to obtain data about the environment” (p. 2292) [62]. Although this paper focusses on remote monitoring, the wireless sensor network described by J. Yick et al. forms the key feature of this craft. They state that this definition is common for all wireless sensor network applications and list, among others, applications in the military, health, public/industrial, environmental and business. So, remote monitoring makes use of sensors to gather information.

Adding to this, these sensors cost money and obviously costs and benefits are an important focus when adopting a technology. So, this focus should be taken into account for the definition of remote monitoring as it will be used in this paper. H. Ghayvat et al. elaborate on this by demonstrating the benefits of harnessing wireless technology over the wired network. They note the improvements regarding complexity, installation, costs and scalability of such a network [63]. However, it is not just the system side of things that cause the financial benefit. Costs can also be caused by the fact that it is costly to visit the site of interest. A.F.Z. Abidin et al. support this by argueing that in some cases the site can not be visited regularly due to environmental or safety-related factors [64]. So, although safety and environmental factors do not pose a problem for Hecla’s equipment, the focus on costs for getting to the site are indeed a motif to adopt the technology or not.

Finally, this technology is a hot topic and thus is widely under development. The further development of the system offers ways to improve the capabilities and efficiency of it. Additionally, Y. Zhang et al. show the future perspective of remote monitoring by observing the many institutes and researchers researching this system [65]. The foreseen future of an investment is something companies focus on when debating on whether or not to adopt a technology. Therefore this is a factor that will be present in the definition of remote monitoring as it will be used in this paper.

All in all, the presented papers focussed on different factors that could be taken into account when defining remote monitoring. This, as stated before, shows the variety of applications and focusses of the technology in those applications. A common ground found in all papers was that the technology is more cost effective then the current system used. Additionally, as the name suggests, everyone agrees that the system is placed in a remote location and is wireless. Also, some papers suggest that it should be scalable and offer perspective for the future. These different factors lead to the definition of remote monitoring to be distilled as: The process of wirelessly obtaining scalable sensor information of a remote system or device to cost-effectively monitor the health of it.

Goals in use contexts of remote monitoring

As seen in the previous paragraph, remote monitoring is applied with a variable focus in mind depending on the context. As will be discussed in this subsection, remote monitoring is used in different contexts to serve as a way to get insights into the bigger picture of the context it is monitoring. These are examples of contexts, but do not specify a concrete goal. The most widely known remote monitoring context is from space. Data from these dadicated satelites are used daily to bring the weather forecast. Y. Lei et al. add unmanned aerial vehicles to this list, for their usage for agricultural goals for example [66]. Although A. Refice et al. challenge this argument by suggesting that that is considered remote sensing [67], the devices certainly do offer ways to monitor the earth, as J. Yick et al. points out [62]. They lists, among other things, natural disaster relief, hazardous environment exploration and military target tracking and surveillance as scenarios in which this technology is applied. Nevertheless, the use contexts of remote monitoring are not limited to monitoring from the air. J. Yick et al. observe, next to aerial, five types of areas where remote monitoring can be applied: the terrestrial, underground, underwater, multi-media and the mobile area. Remote monitoring using multi-media platforms is obviously the area in which goals in use contexts are of interest seen the approach of this paper. In short, also within the area of use, there are various use contexts, the goals in the multi-media platform will be discussed in further detail.

To start, remote monitoring is a common feature used in home automation to supervise the system for safety concerns. Y. Zhang et al. outline the importance of a remote supervision system as it can warn when devices are about to fail [65]. Failure of home automation systems that are able to control heaters, washing machines and alarm systems obviously pose risks [68]. Therefore, a user of a home automation system should be able to see the health of the system and be notified of failures and imminent risks if the system cannot solve the failure itself. Otherwise, the user might be confronted with unexpected safety risks. Thus, remote monitoring is used in home automation applications to guarantee safe usage.

Next to home automation, there are commercial use contexts, which mainly focus on the cost-benefit analysis. In commercial contexts, such as smart meters, the smart grid and smart vehicle safety monitoring, the main goal is to be cost-efficient [69]–[71]. As Y. Cheng points out, smart metering has its challenges: there is a risk on cyber attacks that can compromise the business but also remote locations that “account for a big portion of the smart metering operation costs” [71]. This, of course, are costs that a business wants to address immediately. Another commercial use context is used by insurance companies. Y. Wang and X. Jiang argue for a system that monitors vehicle data [69]. When an accident occurs, the data obtained can be taken into consideration by the insurance company to determine the right amount of financial compensation. Hence, remote monitoring is used in commercially available devices, services and applications to take adequate actions based on the data found and provide integre systems in order to save money.

Finally, there is the goal to prevent these events from happening by analysing remotely monitored contexts. Q. Werian et al. describes a system for online monitoring and forecasting of electrical equipment to ensure stable and safe operation [72]. This way, he argues, adequate measures can be taken to prevent eminent failure of power supplies. A.F.Z. Abidin et al. support this statement by listing parameters “such as temperature, humidity, voltage, current and wind condition.” (p. 1) as conditions that are of influence of the systems operation and health [64]. Another context where remote monitoring is used for forecasting is in geological changes and climate behaviour. R. Alberto et al., for instance, use remotely sensed data to monitor the evolution of floods [67]. This way, they argue, future floods can be predicted and measures can be taken beforehand. In sum, remote monitoring is used to be able to make predictions about behaviour and prevent events from happening or take appropriate actions. With regards to the goals in use contexts of remote monitoring, it can be concluded that the technology serves three goals: provide system safety, act on device failures and prevent events from happening.

Methods of communication used in remote monitoring

The different application areas of remote monitoring ask for different ways of communicating data. In the home automation contexts, the internet is the prefered communication method. Both W. Qi et al. and H. Ghayvat et al. demonstrate the usefulness of the internet for communication in this context [72], [63]. In their papers, they use the ZigBee protocol because of its real-time monitoring abilities, "tremendous specifications to short range and urban environment" and operation on the license-free frequency band. Because in most homes, wireless internet access points are already present, there are no efforts needed to set up the communication infrastructure. J. Yick et al. add to the benefits the fact that ZigBee, similar to Ieee 802.15.4, is relatively cheap and uses low power [62]. However, they also state that range is low, 10-100 meter. Hence, ZigBee's internet communication is used in short range remote monitoring applications for its ability to work in urban environments, low costs, low power consumption, high speed and easy connectivity.

However, in some contexts, wireless internet connection is not an option or has no coverage, for this situation the existing mobile phone network GSM can be used. Mobile phones, when making calls or sending texts, make use of the GSM protocol to connect to base stations which will connect them eventually to the intended receiver. Advantages of GSM, as N. Misal list them, consist of the ability to be connected to the remote monitoring device at all times [68]. They, together with A.F.Z. Abidin, add to this the benefits of its long range and coverage all over the world [64]. Just like ZigBee, GSM operates on an infrastructure that is already present and that can be easily joined. LPWAN is a device offering this service and is consuming low power and is low on maintenance. LPWAN makes use of narrowband internet of things technology inherited from GSM networks [70]. The last advantage is the fact that more and more SIM-card providers offer unlimited use of SMS and phone calls of which the data transmission rate is just as fast as you are able to send messages. In short, the GSM communication protocol of LPWAN used in contexts where internet connectivity is not an option, it is low in power consumption and maintenance, easy connectivity and low on operation costs.

Additionally to narrowband internet of things, there is the Long Range (LoRa) system. LoRa is an LPWAN technology able to build up an own private remote monitoring network comparable to wifi routers. Y. Song et al. note its energy efficiency, security, scalability and, together with Y. Cheng et al., its coverage up to 22 kilometres as advantages of this technology [70], [71]. They add to this the fact that The Netherlands has “deployed a LoRa network that covers the entire country” (Y. Song et al. p. 461) so that it, in fact, works similar to narrowband IoT but in a private network. Y. Cheng points out that LoRa uses the free ISM (industrial, scientific and medical) band for communication. However, both authors mention its low data transmission rate as a drawback. All in all, in The Netherlands LoRa is used in similar contexts as narrowband IoT and adds to its features the fact that it offers private networks, however, the communication is slower. With regards to the communication methods used in remote monitoring, a distinction can be made between using the internet and using existing communication methods and use public or private networks, again it depends on the use context.

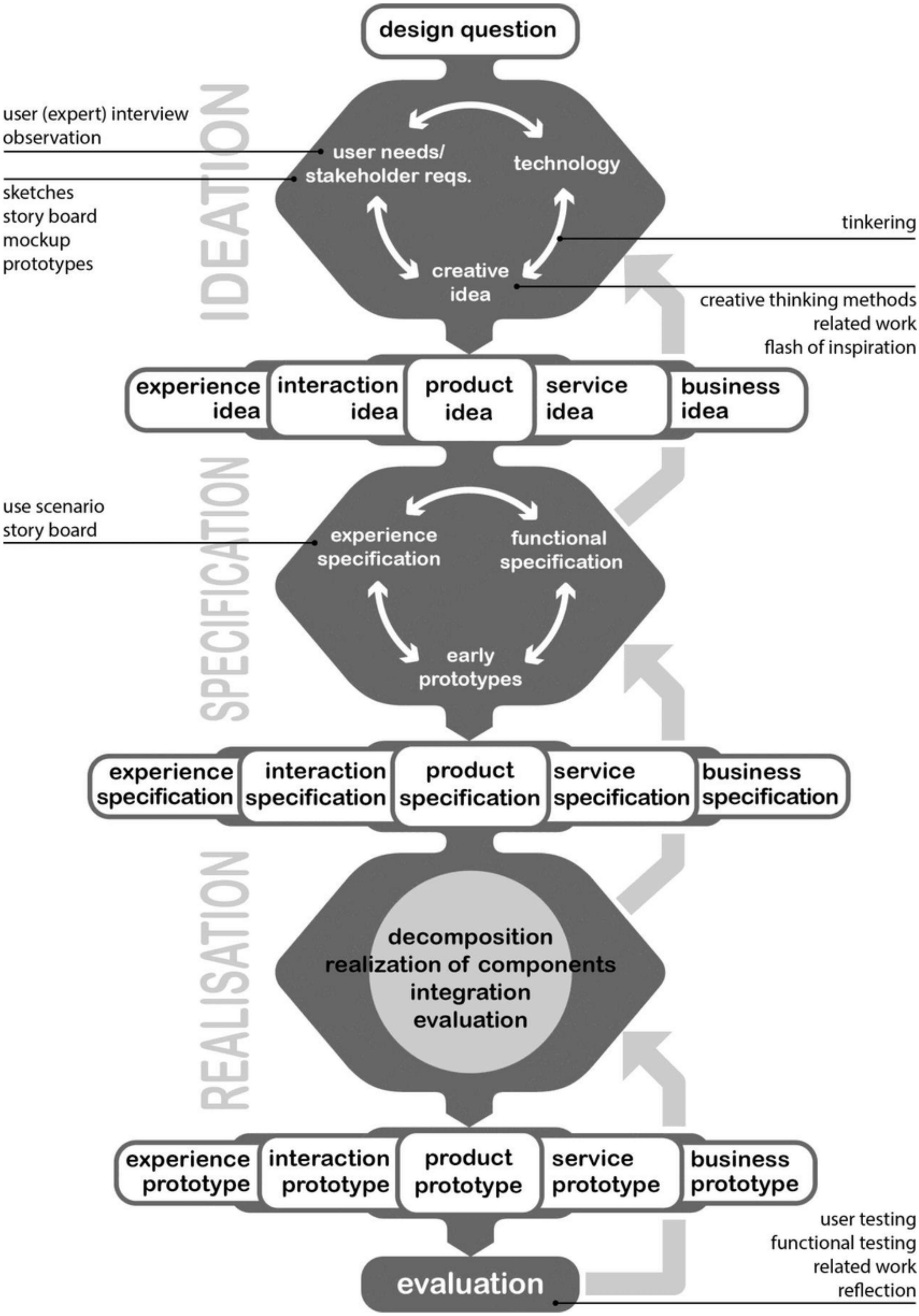
Conclusion

To conclude, this paper depicts the possibilities for remote monitoring in digital billboards. To do this, three main areas were investigated: remote monitoring as to what it is and why it is used, goals in use contexts and methods of communication. The investigation demonstrated that remote monitoring is used to wirelessly obtain data from multiple sensors of a remote system or device. This is done to cost-effectively monitor the health of those systems. The three goals in different use contexts explain this costs concern. Those goals include, but are not limited to the safety in home automation and the risk of system failure, the integrity of systems and the ability to take adequate measures and prevention and prediction of harmful events. For these goals, different methods of communication can be utilised depending on the use context. Existing infrastructures offer easy connectivity but, other than internet connectivity, can be limited in data transmission rates.

With this information the main research question asking what is the most suitable remote monitoring system for Hecla’s digital billboard equiment can now be answered. For Hecla, a system using narrowband IoT or LoRa to communicate sensor data would be prefered since their digital billboards are placed in remote areas where no internet connection is available. This way, also the costs for information communication will remain lower. Next to that the low power and low maintenance features of these technologies make this a suitable solution but that is the same for all discussed communication methods.

This paper gave insights into the current remote monitoring applications and possibilities. The existing literature shows a growing interest in the field. However, to be able to correctly prescribe the remote monitoring solution for the intended field of use an investigation should be done as to why digital billboards fail, what properties should be remotely monitored. When this is known, the solution can be more specifically adapted to those requirements. Furthermore, no clear answer is found to the question of what influences the communication range. This is however a critical property, because the found ranges are for ideal situations and thus are not representable for the real situation. Finally, other methods of remotely checking on digital billboards (such as artificial intelligence, regular physical checks, statistically plan visits etc.) have to be investigated in order to be certain that the right way is chosen.

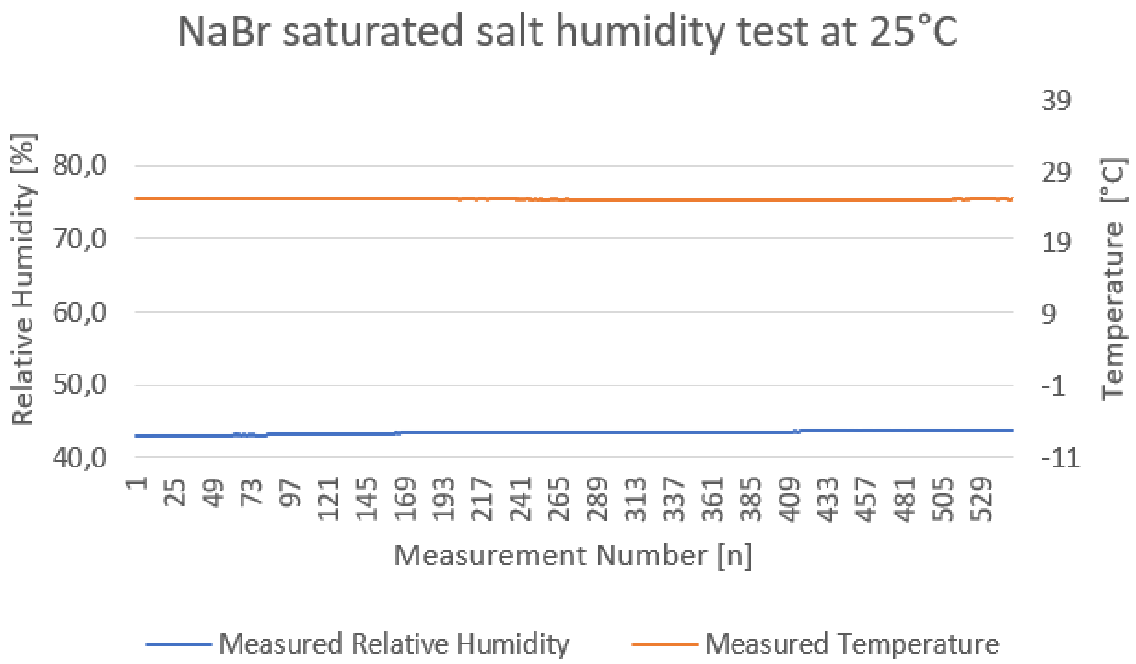
Appendix B

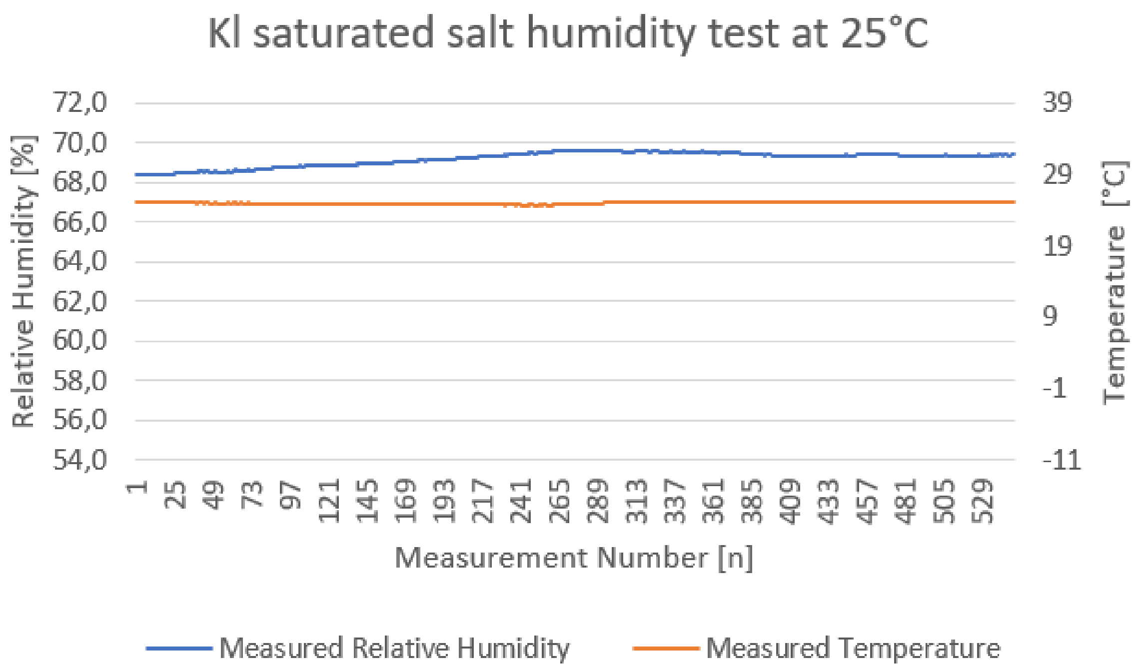

design question
IDEATION
user (expert) interview
observation
sketches
story board
mockup
prototypes
user needs/
stakeholder reqs.
technology
tinkering
creative
idea
creative thinking methods
related work
flash of inspiration
experience idea
interaction idea
product idea
service idea
business idea
SPECIFICATION
use scenario
story board
experience specification
functional specification
early prototypes
experience specification
interaction specification
product specification
service specification
business specification
REALISATION
decomposition
realization of components
integration
evaluation
experience prototype
interaction prototype
product prototype
service prototype
business prototype
user testing
functional testing
related work
reflection
evaluation

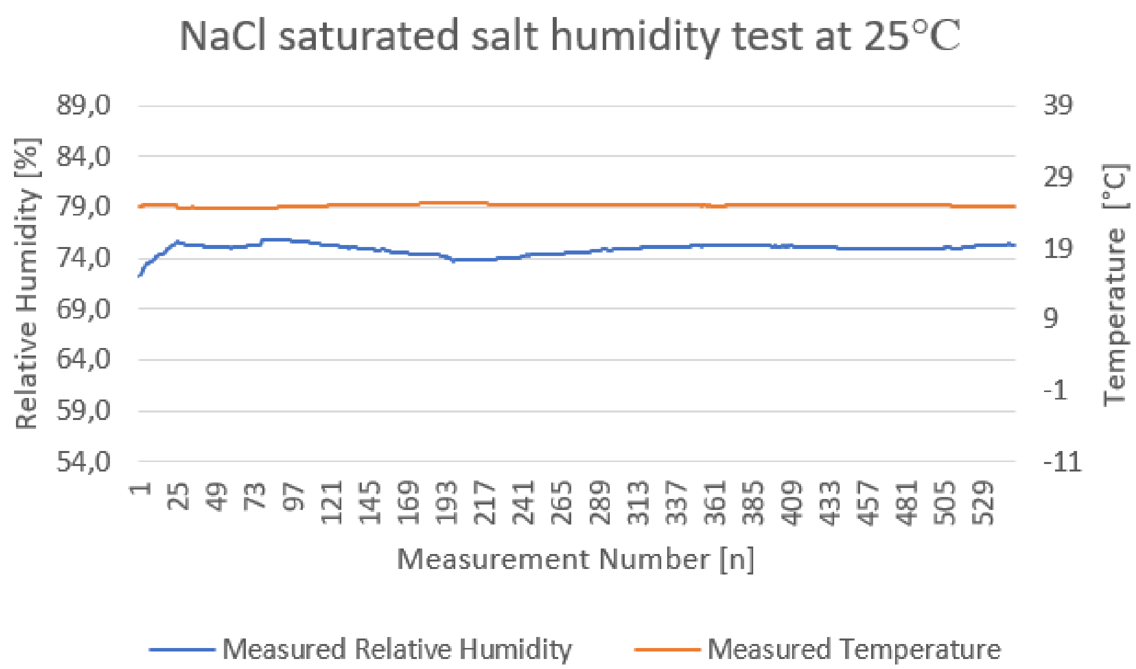
Appendix C

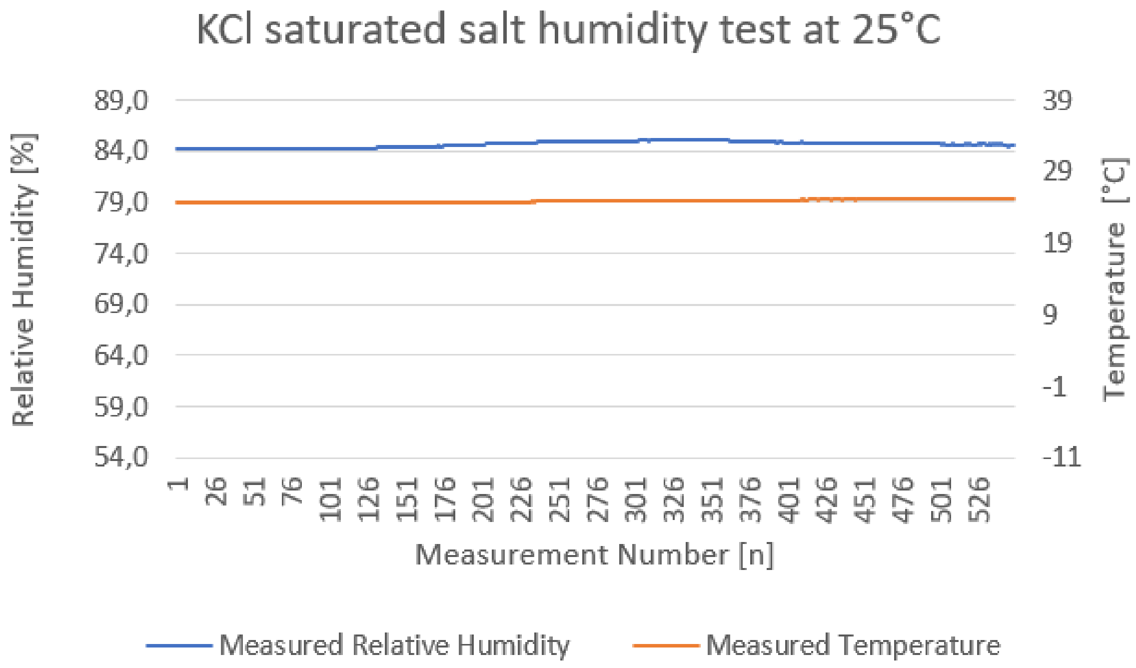
Table 10: Ratio of salt to water for the saturated salt method

Salt	**Chemical formula**	**Ratio** (g of water – g of salt)
Sodium bromide	NaBr	1:3
Potassium iodide	KI	1:3
Sodium chloride	NaCl	1:2.2
Potassium chloride	KCl	1:4.1

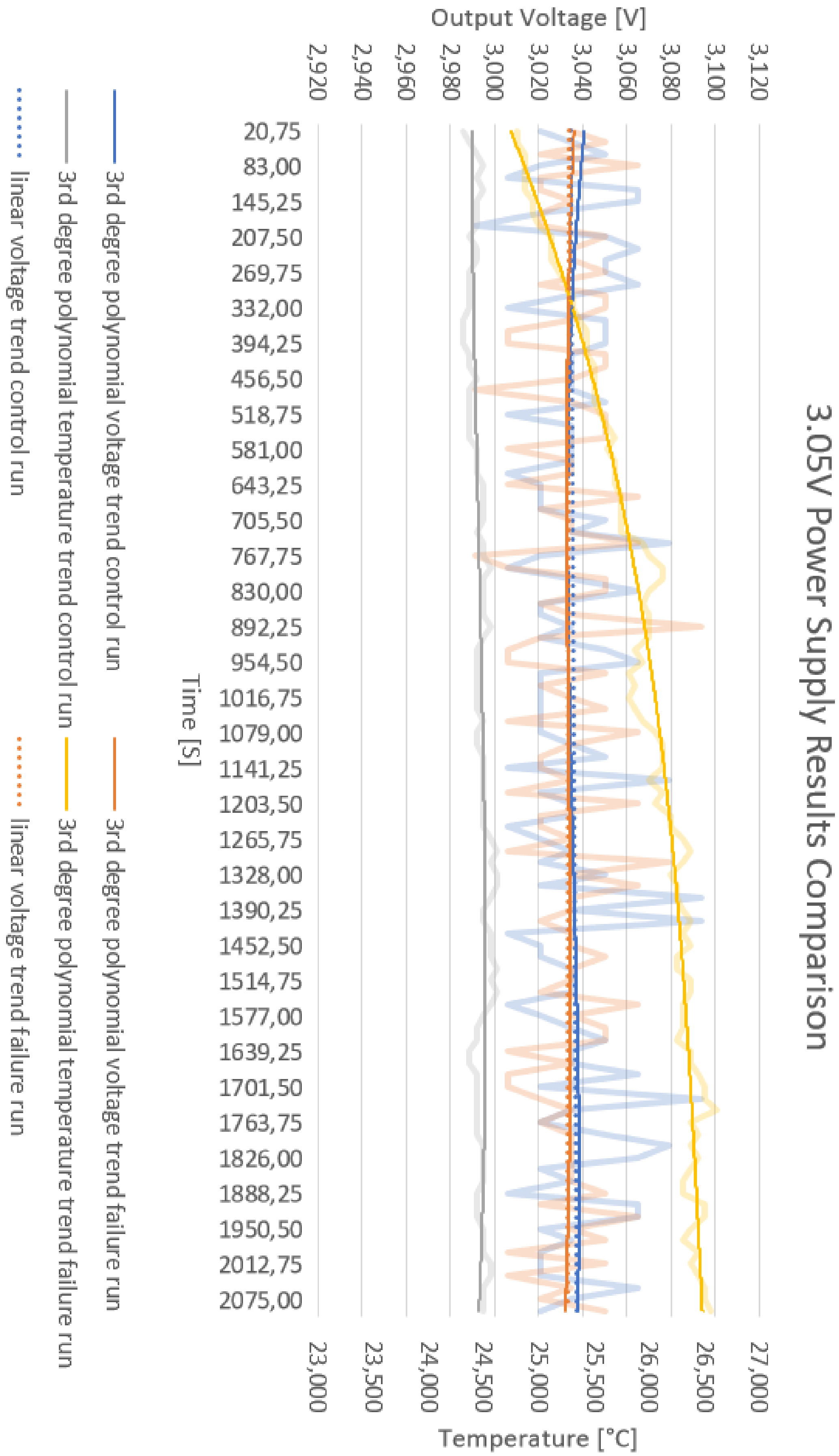



KI saturated salt humidity test at 25°C
72,0
70,0
68,0
66,0
64,0
62,0
60,0
58,0
56,0
54,0
Relative Humidity [%]
39
29
19
9
-1
-11
Temperature [°C]
1 25 49 73 97 121 145 169 193 217 241 265 289 313 337 361 385 409 433 457 481 505 529
Measurement Number [n]
Measured Relative Humidity
Measured Temperature

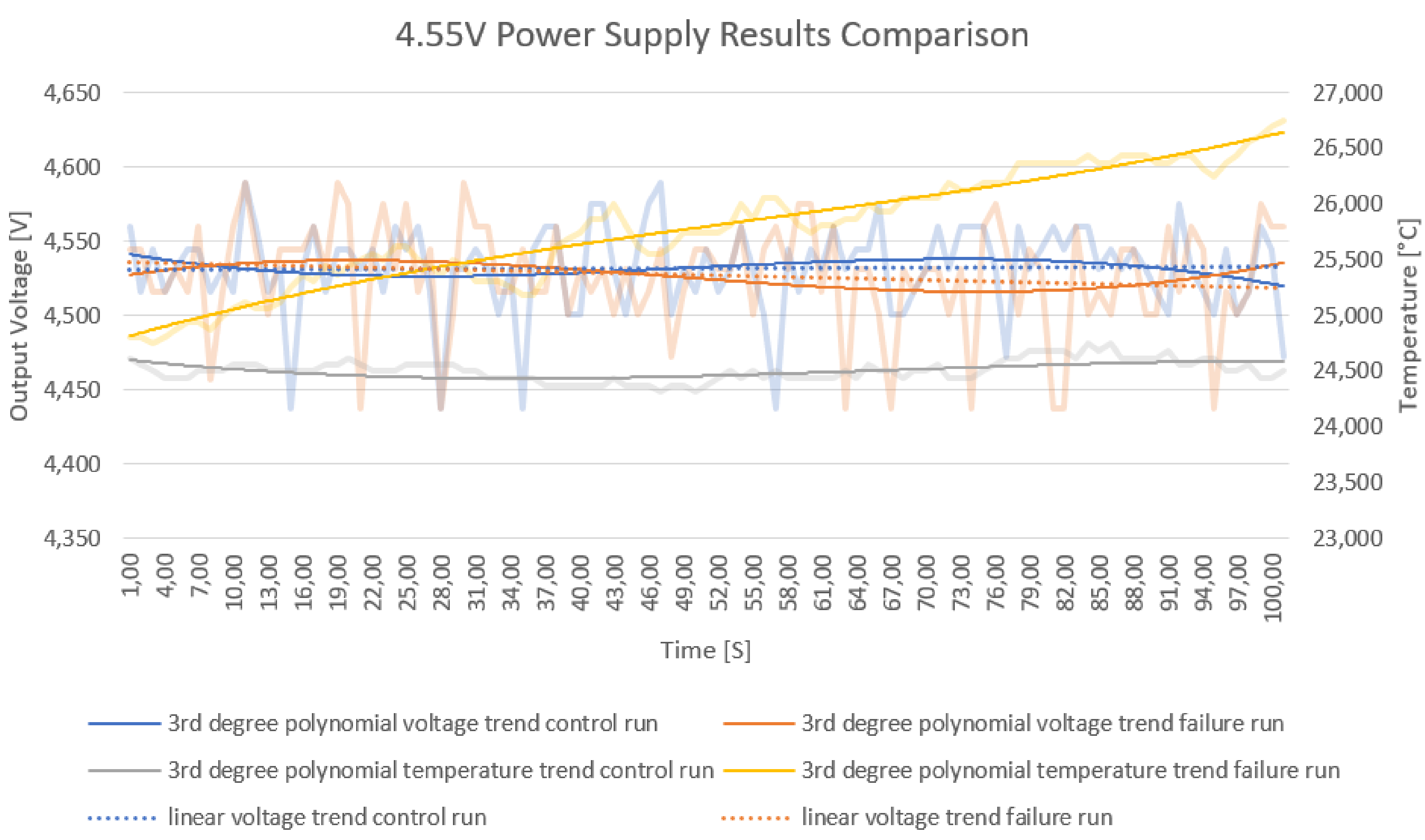

NaCl saturated salt humidity test at 25°C
89,0
84,0
79,0
74,0
69,0
64,0
59,0
54,0
Relative Humidity [%]
39
29
19
9
-1
-11
Temperature [°C]
1 25 49 73 97 121 145 169 193 217 241 265 289 313 337 361 385 409 433 457 481 505 529
Measurement Number [n]
Measured Relative Humidity
Measured Temperature


KCl saturated salt humidity test at 25°C
Relative Humidity [%]
89,0
84,0
79,0
74,0
69,0
64,0
59,0
54,0
Temperature [°C]
39
29
19
9
-1
-11
1
26
51
76
101
126
151
176
201
226
251
276
301
326
351
376
401
426
451
476
501
526
Measurement Number [n]
Measured Relative Humidity
Measured Temperature

Appendix D



3.05V Power Supply Results Comparison
Output Voltage [V]
Time [S]
Temperature [°C]
3rd degree polynomial voltage trend control run
3rd degree polynomial temperature trend control run
linear voltage trend control run
3rd degree polynomial voltage trend failure run
3rd degree polynomial temperature trend failure run
linear voltage trend failure run



4.55V Power Supply Results Comparison
Output Voltage [V]
4,650
4,600
4,550
4,500
4,450
4,400
4,350
27,000
26,500
26,000
25,500
25,000
24,500
24,000
23,500
23,000
Temperature [°C]
1,00 4,00 7,00 10,00 13,00 16,00 19,00 22,00 25,00 28,00 31,00 34,00 37,00 40,00 43,00 46,00 49,00 52,00 55,00 58,00 61,00 64,00 67,00 70,00 73,00 76,00 79,00 82,00 85,00 88,00 91,00 94,00 97,00 100,00
Time [S]
3rd degree polynomial voltage trend control run
3rd degree polynomial voltage trend failure run
3rd degree polynomial temperature trend control run
3rd degree polynomial temperature trend failure run
linear voltage trend control run
linear voltage trend failure run

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