BSc EE Thesis

The Sensor Patch

Group Energy

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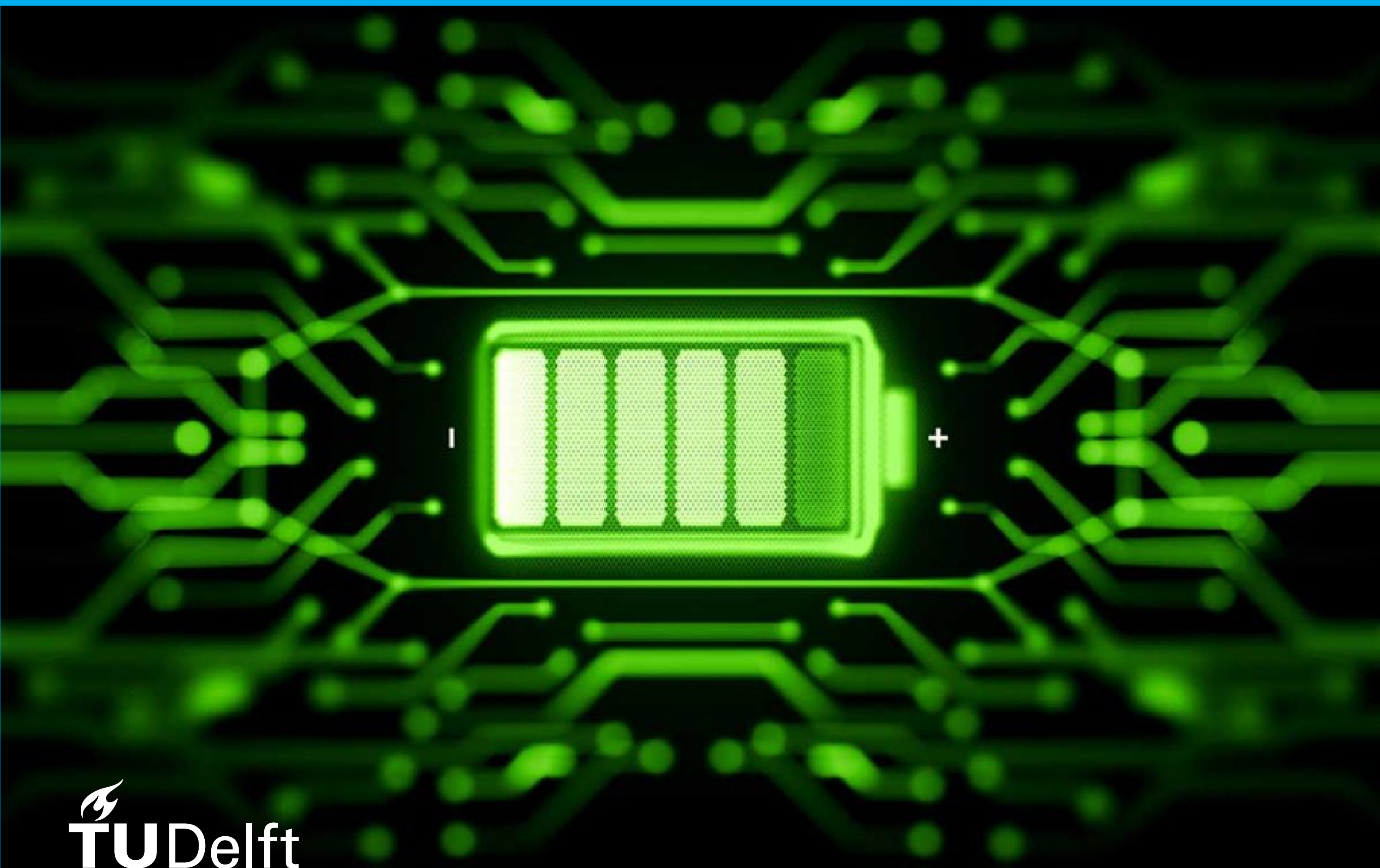

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The Sensor Patch

by

Group Energy

To obtain the degree of Bachelor of Science
at the Delft University of Technology,

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Abstract

The objective of the bachelor graduation project detailed in this thesis is to develop a wireless sensor patch that monitors the health of newborns. The sensor patch replaces the monitoring tasks of nurses during maternity care. The patch measures temperature, heart rate, oxygen saturation and bilirubin. Many babies are born with high bilirubin, causing a condition called newborn jaundice. All measurements will be done once every two hours and the data will be sent to the hospital.
This thesis focuses on everything related to energy and power within the wireless sensor patch. Energy storage, power and energy management and visualising data with the aid of a MATLAB model are topics that will be designed and implemented in this thesis.

W.M. De Laat
R.W. Roeleveld

Preface

This report was written in spring/summer of 2020. At this time, CoViD-19 has caused limitations on the research. Due to the disease many facilities at the university were not available. During the report it will sometimes be mentioned that due to circumstances certain actions were not possible. This refers to the CoViD-19 situation.

This project is part of the bachelor graduation project of 6 students at Delft University of Technology. The group of students is split up in smaller groups of 2 students which each solve a part of the design. The research was proposed by dr. ir. G. de Graaf who works at the microelectronics department of the Delft University of Technology. After the proposal was accepted by the students, they came into contact with dr. Dudink who is a specialist in neonatology and neoroscience. With his help, a better understanding about what the design should look like was found.

Acknowledgements

During this project there have been several people who contributed to our design voluntarily. We are very grateful for that and would like to thank them. A special thanks to our supervisor Dr.ir. G. de Graaf for all his time and advice in the guiding of the project and writing of the report. Also, a special thanks to Dr. J. Dudink for his advice on healthcare.

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Contents

1

Introduction

1.1. Problem definition

Maternity care has always been a big concern in hospitals. It has also developed a lot over the course of the years. It was long thought that for instance babies were unable to feel pain[28]. Recently there has also been more attention for the psychological effects on newborns on neonatal intensive care[12]. It was discovered there is a relationship between the bonding of a newborn with its mother in the first couple of days and long-term emotional well-being of the newborn.

Due to the rising awareness of this fact, hospitals are trying to improve the amount of contact a parent can have with their child [10]. One particular solution includes using a sensor patch with NFC. This way it is possible to remove all wires from the body of the the newborn. This allows the parents to pick up the newborn, thereby making it easier to bond with the newborn. This is a clever solution using NFC, but it is mainly meant for hospitals.

In order to improve the bonding between parents and newborns even further, the baby should be able to go home as soon as possible. However, newborns that are in the risk category should still be monitored. Therefore a wireless sensor patch is needed that can fulfill all the tasks that would have been done by nurses at the maternal care in the hospital. This allows for better bonding with the parents, is cheaper than keeping newborns in the hospital and could trace diseases early in newborns to prevent disease.

Scoping and bounding

The objective in this report is to provide a theoretical design of the sensor patch. The sensor patch will be designed in such a way that it can measure, process, and deliver the data to a base station. The base station, in short, will be a device that receives the data wireless from the sensor patch. What happens after the data reaches the base station is beyond the scope of this research. For real implementation of this design, a sort of IT infrastructure would be needed to handle the data but this will not be covered in this report either.

Due to current circumstances the necessary experiments could not be performed. These experiments would be needed in order to:

- alibrate the sensors of the sensor patch
- provide the actual total power consumption of the designed system
- accurately analyse and compare the power consumption of different microcontrollers and communication modules

1.2. State of the art analysis

Wireless sensors are gaining territory in the a wide range of applications. This is due to their increasingly smaller sizes, lower power consumption and increase in energy harvesting efficiencies. A wide range of wireless sensor nodes are developed such as office sensors[2], machine health monitoring [6] and medical sensors [43]. In addition, a lot of research has been done in biomedical wireless sensors field already. Wireless sensors measuring heart rate, temperature, oxygen saturation and many more are already common in patches or implants [18]. Also systems with real-time monitoring are being developed for for instance cough detection, breathing rate [9] and electrocardiogram (ECG) measurements [10].

The main concern in such products is battery life. The battery life is determined by the battery capacity and energy consumption. In consumption, the wireless communication often has the largest share. However, Battery life increased a lot recently. This is due to both increases in miniature battery capacity [31] and low-power reliable communication protocols [30].

Most designs are however not yet adapted to health care situations that give rise to very specific requirements. Most designs are made to measure vital functions and are made for adults, while much progress can also be made in more specific applications. An example of this is about research in wireless sensor nodes in neonatal intensive care in hospitals [10]. However, hardly any research has been done toward a design that can help monitor newborns at home.

1.3. Thesis synopsis

The outline of this thesis is as follows. In Chapter 2, the different requirements for the total system , the battery and the power management are discussed. In addition in Section 2.3 the decomposition of the system is explained. In Chapter 3, the design considerations of the energy model, the battery and power management topics are proposed where after in Chapter 4 the implementation of these topics is described. The overall design of the sensor patch will be proposed in Chapter 5. Finally, in Chapter 6 conclusions are drawn and our recommendations for future work are given.

2

Program of requirements

2.1. Background

Every year, a lot of babies end up in maternity care. This is a very costly environment for the baby to be in. Next to this, the environment causes a lot of stress for the babies. In addition, there are some babies every year that are not monitored enough in home care. The consequence of wrong monitoring at home results in permanent handicaps due to jaundice for 10 babies each year in just the Netherlands. Therefore, the goal of this project is to replace the maternity care with a sensor patch.

In order to outperform maternity care in hospitals, the sensor patch should at least measure all the parameters the nurses measure. Next to that, it should also do this at least as frequently as the nurses do. In the Netherlands, a baby in maternity care often stays there for around 2-3 days. Nurses in maternity care check on babies every 4 hours and check the following parameters:

1. Temperature
2. Heart rate
3. Respiration rate
4. Oxygen saturation
5. General appearance of the skin, including an assessment of jaundice.

This last point, general view at skin, means the nurse checks whether the baby looks healthy overall. This is done to get an impression of whether the baby might have underlying conditions that are hard to monitor with current technology. Jaundice is one of the most important examples of these conditions.

In addition, measurements performed in hospital maternity care involve multiple wired electrodes to be attached to the babies. This decreases comfort for babies and can increase their stress levels. Secondly, for the parents of the newborns this is not a pleasant sight.

2.2. Requirements of entire system

Based on the previously sketched background and consultations with J. Dudink [1] the requirements of the entire system can be described in greater detail. J. Dudink is a specialist in neonatology and neoroscience. From 2004 to 2016 he has worked as a neonatologist and researcher of neonatal neuroimaging at Erasmus Medical Center. J. Dudink is presently working at the Department of Neonatology at University Medical Center Utrecht.

During the consultations with Dr. Dudink, it was decided that the sensor patch should be located on the baby's chest. At this location, the sensor patch is not prominently visible, which is pleasant for the parents.. Moreover, there is more room for the sensor patch here than in other places. In addition, the doctor stated that the size of the sensor patch may not exceed 70mm x 30mm x 10mm (L x W x H). In order to outperform the maternity care as it is now, the sensor patch will need to perform measurements at least once every two hours to improve on the hospitals, once every four hours, in order to provide data significantly more frequent. In addition, at least the same measurements as maternity care must be carried out to guarantee at least the same level of care. This means that at least temperature, heart rate, oxygen saturation and bilirubin need to be measured. Furthermore the sensor patch needs to last for 3 days without the need to perform a recharge of the battery as this is how long babies are monitored in hospitals. In modern life, environmental awareness plays an important role. The sensor patch can eventually be used on many newborn babies, creating a lot of electronic waste if it is not reusable. It would be irresponsible not to take this into account during the design process. Moreover, one of the goals of the world health organization is to create less waste and environmental impact [21]. Therefore it was decided that the sensor patch has to be reusable and preferably usable for at least 1 year with 2 uses every week. This does mean that it must be possible to clean the sensor patch to medical standards and preferably to make it sterile.

The previous defined requirements are divided between mandatory requirements and trade-off requirements. Mandatory being the requirements which are absolutely essential for the system to be marked a success. Trade-off requirements are the requirements which are pursued as much as possible but, should they not be met, the system will still be usable to a satisfactory extent.

2.2.1. Mandatory Requirements

1. Dimensions shall not exceed 70mm x 30mm x 10mm (L x W x H) .
2. Sensor patch must be placed on the chest.
3. Must measure temperature, heart rate, oxygen saturation, bilirubin
4. The previously mentioned measurements need to be performed at least once every 2 hours.
5. Must have battery life of at least 3 days.
6. The sensor patch must be wireless.
7. It should be able to detect neonatal jaundice when the baby is at risk.
8. Be able to communicate these measurements to a hospital real-time.
9. Must be reusable.
10. Must be sterile as it will be medically used.

2.2.2. Trade-off Requirements

As the sensor patch will be worn continuously by babies for possibly three days, it is desirable to make it comfortable for the baby. This can however impact the mandatory requirements negatively like size and battery life as a smaller sensor patch would probably be more comfortable, but would limit the space for the battery and components. Making the sensor patch waterproof would make it possible for the baby to take a bath without damaging the sensor patch. It would make the design more complex and possibly negatively influence sensor accuracy. On the other hand making the device waterproof will increase life. The duration of reliable operation of the sensor is influenced by the price and availability of components and the resistance to damage. The sensor must be reliable for at least a year as this will make the sensor reusable to a high degree, however making it last longer can end up in a more expensive product. Therefor these are trade-off requirements.

1. Should be waterproof
2. The patch must provide reliable operation for one year, used on two patients per week.
3. Should not bring discomfort to the baby

2.3. Decomposition of the system

The project has been divided into three subsystems. The systems are: energy, sensors and communication and microcontroller. The system has been divided into these subsystems since they are expected to have equal weights. Besides this, each subsystem has a clear unique challenge that needs to be solved. The energy group needs to simulate the energy consumption and pick an appropriate battery. The sensor group needs to design sensors that meet a set of specific requirements. Finally, the microcontroller and communication group needs to design an efficient smart system that controls the entire system.

Energy system
The energy group focuses on everything related to energy and power within the system. Energy storage, power and energy management and visualising data with the aid of a MATLAB model are the topics and tasks of this subgroup.

Sensor system
The sensor group will design a sensor system to measure temperature, heart rate and respiration rate, oxygen saturation and bilirubin. The bilirubin sensor has to be designed since this kind of sensor is not yet available to buy off the shelf. The other measurements can be performed using already available sensors. These sensors will need to be selected based on several parameters (e.g. accuracy, energy consumption)

Microcontroller and communication system
This group will look at the implementation of a microcontroller which will act as a central processing unit for driving all actions within the system. Additionally, this group will look at different possibilities for choices of communication protocols by which the system will communicate wirelessly with the user. When a communication protocol has been chosen, this group will look at the most efficient implementation and integration with the microcontroller.

2.4. Energy Subgroup requirements

In this section the mandatory requirements relating to our domain, the energy domain, will be addressed. Our research is divided into 2 main parts: A battery selection and the power management design. For each part the mandatory requirements and trade-off requirements will be presented below.

2.4.1. Battery Requirements

The battery must provide electrical energy throughout the whole sensor patch. According to the system requirement, the battery should be able to deliver enough energy for the whole patch for at least three days. In addition, the battery should provide at least 50J electrical energy per day to power all the components including all losses. This value is based on roughly estimating the energy consumption of the MCU, BLE module, sensors and losses. The calculation of this estimation can be found in Appendix A. After consulting with BGP group members, the size of the battery should maximally be 30mm x 30mm x 7mm (L x B x H). An estimation of the peak current has been made in consultation with the sensor group. The bilirubin sensor consists of several LEDs. These LEDs can draw a current up to 40mA for at least 5 seconds at a voltage of 3.7V. The battery must be able to provide this discharge current under these circumstances. The battery does not have to be demountable since the battery is rechargeable and if the battery is defect it is permissible to throw away or recycle the total sensor patch in an external location. Safety is of utmost importance for the system. It should should meet the safety standards of hospitals, medical equipment and comply with safety legislation. It is still unknown how much external forces are applied to the sensor patch, and therefore to the battery, while using the patch. Therefore, for safety reasons, it is of great added value if the battery is as robust as possible. The price of the rechargeable battery is maximally €50,-. This value is based on an assumption that the battery lasts at least 2 years. The defined battery requirements are listed below, in addition they are divided into mandatory and trade-off requirements.

Mandatory requirements

A.1. **Rechargeability**: The battery must be rechargeable.

A.2. **Dimensions**: The size of the battery (including the mounting) may not exceed 30mm x 30mm x 7mm (L x B x H).

A.3. **Energy availability**: At least 150J of available energy that can be delivered over 3 days.

A.4. **Power delivery**: The battery must provide a peak current of 40mA for at least 5 seconds at a voltage of at least 3.7V.

A.5. **Safety**: The battery must meet the safety standards of hospitals, medical equipment and comply with safety legislation.

A.6. **Price**: The battery costs maximally €50,-.

Trade-off requirements

B.1. **Shape**: Preferably flexible if this does not reduce safety.

B.2. **Life expectancy**: The battery should last 2 years and it should be possible to fully discharge and recharge it twice a week.

B.3. **Robustness**: The battery should be as robust as possible against external mechanical forces.

2.4.2. Power Management Requirements

The power management is responsible for providing proper input voltages for all devices in the sensor patch. Also, safety is of utmost importance. The battery must be protected for fault conditions during normal operation and while charging. These fault conditions include over-charge, over-discharge, overcurrent and short circuit. After consulting with BGP group members, the size of the battery should maximally be 30mm x 20mm x 4mm (L x B x H).The circuitry must deliver at least 40mA at 3.7V for 5s, because this is necessary for the bilirubin sensor created by the sensor subgroup. The state of charge of the battery does not need to be monitored continuously, but the total system must give a signal to the hospital when the battery is below 20% of its maximum available energy. This warns the hospital that failures may occur if the battery keeps discharging. The defined power management requirements are listed below.

Mandatory requirements

C.1. **Charging** : The rechargeable battery must safely be recharged without damaging itself.

C.2. **Voltages**: The power management must provide proper input voltages for all devices in the sensor patch.

C.3. **Battery State**: The system must detect when the State of Charge (SOC) of the battery dives under 20%.

C.4. **Dimensions**: The power management circuitry, excluding the battery, may not exceed 30mm x 20mm x 4mm (L x B x H).

C.5. **Safety**: The battery must have a safety circuit to protect it from: over-charge, over-discharge, overcurrent and short circuit.

3

Design Process energy group

This chapter proposes a design to fulfill the requirements listed in Chapter 2. These requirements are based on the customer needs (2.1) to solve the problems in the problem description (1.1).
This chapter begins with a state-of-the-art analysis of other energy management modules within several energy-efficient wireless wearable applications. Next, an energy model [16] is designed with the aid of Matlab to get an insight of the energy consumption. Thereafter, a battery to power the system will be chosen. And lastly, a power management design is proposed to minimize energy consumption and to make the system reliable and safe.

3.1. State of the art analysis for the energy subgroup

The design process of the energy group will be introduced by a state-of-the-art analysis. As mentioned in the introduction of this chapter, an energy model with the aid of Matlab is designed. This concept is not new in itself, but there is very little documented about it and there is no general model for it despite the fact that it is very important to gain insight into critical factors in low power wearable devices. The only comparable model is one based on sensor nodes based on LoRa and LoRaWAN [4]. There are several battery models applied/customized to wireless sensor nodes but these are often specific to one battery type and often have parameters that depend on parameters of a real battery [27] [7].

In the last few decades many portable electronics products have been developed and sold, mainly due to an increase in energy storage in small batteries and due to increased availability of components with ultra low power consumption (μW) [15]. In the battery sector, lithium has become a major technology that has enabled the development of many new devices. A new "revolution" can take place when (flexible) thin film batteries are fully developed because the energy density of these size batteries can even be higher [33] [11].

As mentioned earlier a lot of improvements have been made in low power electronics. Companies such as Texas Instruments, Maxim Integrated and Analog Devices have special product lines for this type of electronics. Important low power components for our system are DC-DC converters, protection circuits and battery chargers.

3.2. Energy Model Design

In this section, the goals and the realization of an energy model are presented. The idea behind the energy model will first be explained together with its goals. Next, general techniques used in the model will be explained. The section ends with an explanation of simulations specific to components and an explanation of the total system simulation. In section 4.1 the results of the models will be discussed. The Matlab codes can be found in Appendix B.

The idea behind an energy model is to get an understanding in the energy consumption of the entire system and of all components separately. It helps the designers of the sensor patch to choose their components carefully as energy is scarce. Simulations of the energy consumption will lead to many interesting trade-offs that can help the engineer in designing an energy-efficient system. These trade-offs will impact many domains of the components. For example, the dimensions of components influence the energy consumption as well as different voltage levels. This model must help the group to meet every requirement listed in Section 2.4.

To help the group members, it is important that different components (or subsystems) can be simulated. The consumption in deep sleep, active mode and per measurement must be calculated and visualised so that the components can be compared. In addition, there must be a total simulation of the entire sensor patch. This should not take too long to run so that it is easy to simulate other components, preferably it takes less than a minute to do the calculations and visualizations. For the total system simulations it is important that the duration of the simulation can be specified, but it is also useful if there is the possibility that the simulation continues until a certain amount of energy is consumed. A summary of these desired functionalities is listed below.

1. **Modules**: The following parts of the system are considered as separate modules; the sensors, the microcontroller and the communication module. For each module the model must give insights and enable comparison of the following topics;
   1.1. Energy usage in deep sleep.
   1.2. Increase in energy usage if measurements increase.
   1.3. (Maximum) current drawn in active and sleep mode.
2. **Full system**
   2.1. The full system simulation must provide insight into the course of energy consumption. It also has to show how much energy each component consumes, and how much energy is consumed at each stage.
   2.2. For the full system simulation their must be the ability to set minimum simulation time and minimum energy until the simulation is allowed to stop.
3. All calculations and visualisations shall be performed within 1 minute of run time.
4. There must be the ability to save different system and sub module simulations.

The simulations can be divided into two groups: component simulations and full system simulation. The component simulations include simulations specific to sensors, microcontrollers and communication modules. This makes it easier to compare different sensors with each other without the simulation taking longer than necessary and allows characteristics that are more important at component level to be better displayed. The total simulation is a simulation in which a complete sensor patch is simulated. In this simulation, it is important to gain insight in the consumption of the sensor patch at any time and what the difference is in consumption between the components used. This allows a better assessment of whether it is possible to read out a certain sensor more often than strictly necessary. Performing more measurements provides more certainty about the health of the newborns but also ensures that the sensor patch is empty sooner. A full system model of the sensor patch will be made to gain more insight into these kinds of considerations.

The model will be built with the aid of Matlab [16], since this is a very powerful application in both calculations and visualisations. For example, Object-oriented programming techniques can be used in Matlab and it has a special app designer in order to easily create User Interfaces (UI) which can make simulations easier to perform.

3.2.1. General Features

A number of general choices and working methods applied to the design of the model will be explained below. First, the structure of the distribution of code across multiple files is explained. After that it will be explained why classes have been used in the code, hereafter it will be explained how it is ensured that the code is executed at optimal speed. Finally, it will be described why a user interface can speed up simulations.

Code Structure

The total energy model will consist of many lines of code. To make the code easier to read and easier to use, it is important to use a clear structure. The code of our Matlab model has been divided into multiple files, these files can be categorized into 4 categories (the names between the parentheses refers to the filename structure): Initialization (init_), calculation (calc_), visualization (disp_) and the main group (main).

The initialization functions load the parameters of the components that can be used for the simulations. All calculations take place in the calculation functions. All figures and tables are created In the visualisation functions. Each component type (sensors, MCU, etc.) has its own Matlab function in each category. This makes it possible that during design and testing not all codes and functionalities are called every time, which makes debugging easier and makes it possible to work with several persons at the same time on separate pieces of code. There is only one Matlab script that is not implemented as a Matlab function and that is the main script. This script calls all other functions, and does no calculations or visualisations. The only task of the main function is to call other functions and to select specific components for certain simulations.

Classes

With Matlab it is possible to program object-oriented, so you can use objects and thus create classes. By using classes there is a central place where the properties of this class are described. This makes the code easier to understand, also specific functions (called methods) can be added to classes so that codes need to be copied less often. Classes are also widely used in other programming languages such as C# and phyton, making it a general term for programmers. Classes also make the script easy to expand and increase modularity. A counterpart of classes are structures in Matlab, structures are very similar to a class but to use them you don't need to define them in a central place. Another disadvantage of structures is that you can always add extra properties to the structure which makes it easier to make errors in the code. Also, you can't protect certain properties of structures from the rest of the code, but this can be done with classes by making a property private or protected. For the above reasons, care has been taken to apply classes where possible so that the code is more readable and usable.

User Interface

Modern techniques and tools (such as Matlab) enable engineers to easily develop simple applications (apps). In Matlab this is also possible by using the App Designer. With this tool you can easily build an app by simply dragging and dropping blocks. Moreover, it has been designed in such a way that little extra code needs to be written to use existing scripts in the application. As described earlier, our model should provide insight into the energy consumption of the sensor patch. In the development and use of this product the "simple" question often arises, what if? What if we take measure more frequently, what if the power increases in deep sleep, what if we send data from several that have taken place in the past hours at once? These kinds of questions cause a lot of simulations to be done to get more insight in how the sensor patch "behaves".
For example, to run a full system simulation and get a good visualization, the variables have to be filled in as shown in Code 3.1. If other sensors need to be used or if, for example, parameters of sensors need to be adjusted just once to see their effect, this code will need to be adjusted or extended. Because the code is abstract, it is more difficult to modify simulations and mistakes are also made faster.

Code 3.1: Variables that need to be adjusted for each full system simulation

```
S_Sensors = [Sensors.Data(:,2) Sensors.Data(:,21) Sensors.Data(:,27)];
S_MCU = MCU.Data(:,2);
S_Com = Transmission.Data(:,2);
S_names = [Sensors.Name(1,2) Sensors.Name(1,21) Sensors.Name(1,27) MCU.Name(1,2)
    Transmission.Name(1,2) "Total"];
I_Array = [ (3600*2) 1 1 1 1 1];
T_Max = 3*24*3600;
E_Max = 0;
```

Figure 3.1 shows how sensors can be selected in the application, in addition, all parameters (except Name and Type) are customizable and immediately available for use in the simulations. This makes it easier to simulate the influence of specific parameters, and it also provides direct insight into the values of the other components, in this case sensors.
To conclude, it was decided to make a simple yet powerful application because making an app in Matlab with the App Designer is very easy, but most importantly because it helps to execute simulations easier and faster.

3.2.2. Component Simulations

Many different products are available for each component used in the sensor patch. Component specific simulations have been made, to help in making component choices but also to gain insight into the energy consumption properties of different components. Below the different simulations on component level will be explained.

Sensors | MCU | Transmission

Selected	Name	Type	Default interval ...	V_in [V]	I_m [mA]	T_m [s]	T_pr [s]	I_ds [mA]
☐	TP117	Temperature	3600	3.3	0.135	0.0155	0.001	0.00015
☐	Si7051	Temperature	3600	2.8	0.09	0.007	0.001	6e-05
☐	AS6212	Temperature	3600	3	0.04	0.036	0.001	0.0001
☐	MCP9808	Temperature	3600	3.3	0.2	0.25	0.001	0.0001
☐	MAX30208	Temperature	3600	1.8	0.067	0.015	0.001	0.0005
☐	MAX44006	Temperature	3600	1.8	0.01	0.4	0.001	1e-05
☐	TMP102	Temperature	3600	3.3	0.007	0.026	0.001	0.01
☐	STTS751	Temperature	3600	3	0.05	0.084	0.001	0.003
☐	SMT172	Temperature	3600	3.3	0.06	0.0018	0.001	0.00022
☐	MAX30205	Temperature	3600	3	0.6	0.044	0.001	0.00165
☐	LIS3DH	Respiratory	3600	2.5	0.02	60	0.001	0.0005
☐	MMA8491Q	Respiratory	3600	1.8	0.04	60	0.001	2e-06
☐	ADXL363	Respiratory	3600	3.5	0.013	60	0.001	1e-05
☐	ADXL362	Respiratory	3600	3.5	0.013	60	0.001	1e-05
☐	ADXL357	Respiratory	3600	3.3	0.2	60	0.001	0.021

Figure 3.1: Sensor selection and adjustment in the energy model app.

Battery insights

There are many different rechargeable batteries available but not all of them will be suitable for the sensor patch. In order to help with the final battery choices, it is important to understand the characteristics of the possible batteries. The data of the batteries can be entered in an excel sheet. If the Matlab model is stopped, the excel file will be imported and some calculations will be performed with the data after which it will be visualized.

Sensor simulation

It is important to understand what the energy consumption is when the sensor is on and when it is off. In addition, a measurement can take place twice a day or every hour, so it is useful to know how much energy a sensor consumes depending on how many times a day the sensor is activated. Of course, the peak current or duration of a measurement can also influence the choice of a sensor. To be able to do this, calculations and visualizations will be made specifically for sensors.

Microcontroller and transmission simulation

It turned out that different microcontrollers and transmission modules/methods are not easy to compare. Different microcontrollers have different sleep modes and active modes, in addition different, different parts of the micro controller can be used in different modes. On top of that, it is difficult to get the right numbers from datasheets because for example a microcontroller can work on many voltages, but also has a different consumption on each voltage. In a way, the same problems apply to the transmission module, but for this module there is also a choice of different transmission techniques (e.g. WiFi, LoRa and BLE) which makes it very difficult to compare. In the end it turned out that both the micro controller and communication module were chosen fairly quickly by the microcontroller and communication subgroup because of which it was given a low priority and eventually not implemented after all.

3.2.3. Full System Simulation

In this section important parts of the complete system simulation model will be explained. The results and visualizations of this model will be discussed in Section 4.1 and the Matlab files can be downloaded from GitHub, the link to the GitHub can be found in Appendix B. In Appendix D.2 tables show which parameters are needed per sensor, microcontroller and transmission module so that the model can use these components.

Stages

In the simulation a distinction is made between different stages in which the Sensor Patch can be situated. An overview of the stages can be found in Table 3.1. By making a distinction, and saving them per unit of time, the contribution of different components to the total energy consumption can be better evaluated. This makes it possible, for example, to calculate how much energy is consumed in deep sleep. It also makes it possible, for example, to compare energy consumption in deep sleep with energy consumed by the sensors during measurements, which would otherwise not be possible.

Interval Array

In order to save electrical energy consumption, it must be possible not to read out all the sensors at all measurements. Or it may be that a certain sensor measurement (e.g. bilirubin) is much more important for a

Table 3.1: An overview of the possible stages in which the module can be situated.

Name	Description of the stage
Stage 1	All components are in deep sleep
Stage 2	The system wakes Up
Stage 3.x	System performs measurements x= # of sensor that is active.
Stage 4	System performs additional calculations
Stage 5.x	Data transmission to base station x=1: Normal operation. x=2: Transmitting data. x=3: Receiving data.

certain child than other measurements (e.g. temperature and heart rate) making it desirable to perform the important measurement more often. But what is the impact of this? Or how much longer can the sensor patch be powered if the bilirubin is only measured once every 5 hours while all the other sensors are read every hour? It is useful to be able to simulate this because it can lead to large differences in energy consumption. To simulate this, a matrix has been designed which is called I_Array. This matrix is constructed as follows; the first column represents the interval time, the other columns indicate which components of the system (sensors, microcontroller and transmission module) are on or off by being 1 or 0 respectively. Each row of the matrix is a new interval in which, for example, other sensors can be activated. The code takes into account that it can happen that 2 intervals are activated simultaneously (for example every hour and every 5 hours). As a result, components will not be activated too often or too little. An example of the Interval array is shown in Figure 3.2.

Interval [h]	TP117 Temperature	BMA280 Respiratory	OB1203 HeartRate	MSP430FR5994	nRF52810
3600	☑	☐	☐	☑	☐
7200	☑	☑	☑	☑	☑
0	☐	☐	☐	☐	☐

Figure 3.2: Example of an interval array for the full system simulation

Dynamic step sizes

A simulation should be as accurate as possible so that as much insight as possible can be gained from the computed values. A problem is that the simulation should preferably be able to simulate for at least 3 days, while the consumption during a measurement should also be able to be calculated in detail. The duration of a measurement is in the order of a few tens of seconds while simulating 3 days means that 259,200 seconds must be simulated. In addition, some sensors are only on for a few milli seconds and the transmission and reception time of the communication module is also of this order. This accuracy goal causes two problems. The first problem is the enormous amount of data that is generated when multiple multi-dimensional matrices contain millions of rows because for example a measurement is made every 10ms. The second problem is the speed of the simulation, the simulation time will be very long if millions of points have to be calculated. The solution to these problems is an automatic step size implementation. When the Sensor Patch is not active and therefore in deep sleep, it consumes the same amount of power as long as it stays in deep sleep. Moreover, there is a very long time between 2 consecutive moments when the Sensor Patch is active. By making larger time jumps at the moments that the sensor patch is in deep sleep, a lot of unnecessary measurements are avoided. In the end, the simulation is designed in such a way that even in active mode it is determined for each stage whether the step size can be reduced or increased. The step size is then determined by the most significant time specification. By applying this, a high quality of accuracy is guaranteed at all times without collecting unnecessary data points.

3.2.4. Conclusion

The energy model has been successfully designed. With the aid of MATLAB[16] many different plots can be made. These plots include the energy usage of every component and of the total system. Many different parameters can be adjusted for different operation purposes. The Matlab codes can be found in Appendix B. In the next chapter, Chapter 4, these plots will be shown.

3.3. Battery Design

In this section the battery design will be explained. First, there will be some general remarks that affect the battery choice and the way in which the choices are made. After that, different chemical battery compositions will be compared and different formats will be explained in respectively Sections 3.3.1 and 3.3.2. Finally, in Section 3.4 the battery will be chosen for the sensor patch prototype.

In Chapter 2 the mandatory requirements for the battery were discussed. these are listed briefly in Table 3.2. It is important that all requirements are met, yet there are certain requirements that will speed up the reduction of the pool of suitable batteries. It has been decided not to go into all the characteristics of a battery if it does not meet an important condition in a fundamental way, because the purpose of this report is to choose the right battery and not to explain all the available batteries. Therefore, some battery types or properties may appear to be treated insufficiently.

Table 3.2: Short list of the mandatory battery requirements from the program of requirements.

Rechargeability	Must be rechargeable
Dimensions	Not exceed 30mm x 30mm x 7mm (L x B x H, incl mounting)
Energy availability	At least 150J divided over 3 days
Power delivery	40mA for at least 5 seconds at 3.7V
Safety	Meet safety standards of hospitals and comply with safety legislation.
Price	Costs maximally €50,-

The following remark is about the safety of the battery, this is very important because the sensor patch is placed on the body of a newborn. The safety of a battery is affected by two elements: the physical properties (chemistry and enclosure) of the battery and the battery management system (BMS). The latter will be designed and implemented in respectively Section 3.5 and Section 4.3, which discusses the power management structure of the sensor patch. In the current section the physical properties of the battery are discussed. It is important to note that the operation of new battery types can be considered unsafe in the medical sector, despite the standard comprehensive safety tests. This is due to the very high safety standards in the medical sector, moreover, the sensor is placed on the skin and therefore the consequences of an incorrectly functioning battery can be even greater. So it is wise to choose a technique that is very reliable and has a low risk of malfunction. For this reason it is not judicious to use a new or experimental battery type for the sensor patch, because those batteries generally have an increased risk of malfunctioning. [5]

There is also a note to be made about the battery costs. Our analysis of available batteries indicated that all the batteries we compared never cost more than 30 euros. On the other hand, an hour of research by one person costs at least 30 euros. During prototyping, it can save a lot of time if a battery can take more measurements than will eventually be needed or if the battery is much more robust against peak currents so that a researcher can obtain results faster or has fewer problems to solve. For these reasons, the study only compared batteries costing a maximum of 50 euros, but the batteries were not compared on price.

Lastly, the decrease in available energy due to peak currents can influence the battery choice. It is common knowledge that discharging a battery with higher current values results in less energy being extracted from the battery. There are two problems that make it difficult to include this issue in the comparison between rechargeable batteries. Firstly, the impact of this phenomenon not only differs per chemical composition but also the shape of the battery plays a role. [44] Secondly, only the impact on the available energy is known for a large part of the battery types when the battery is continuously discharged at different current speeds. The sensor patch only has a peak current dozens of times a day due to the bilirubin sensor. the effect of this can be very different than drawing a high current continuously. [32] Therefore, including the impact of peak currents on the available energy is very difficult and will not be taken into account in the battery choice that will be made.

3.3.1. Battery chemistries

Table 3.3 shows the rechargeable batteries that have been examined [23] [37]. In addition a Silver zinc battery was considered, however only one recheargable version has been found of this type. This is the ZPower XR7734, which uses a relatively new technique and this type is not yet often implemented in other devices.

That is why the decision was made in advance not to include them in further comparisons and choices. Battery types such as silver oxide and zinc carbon are not considered since those are not rechargeable battery types.
You may have already noticed that there is no column in Table 3.3 about the power the battery types can deliver. This has not been included because research has shown that with small batteries the maximum power depends mainly on the size of the battery and that there is no strong difference between chemical compositions.

Table 3.3: Comparison of multiple battery chemistry's.

Battery chemistry	Available in small sizes	Self discharge	Specific energy	Safety	Memory effect	Life cycles
Lead- acid	No	-	-	-	-	-
Nickel-cadmium	Scarce	Fast	Low	-	-	
Rechargeable Alkaline	Moderate	Very slow	Low	Moderate	No	Very low
Nickel-metal hydride (NiMH)	Yes	Slow-medium	High	Proper	-	Moderate
Low self-discharge NiMH	Yes	Very slow	Moderate	Proper	Very small	Moderate
Lithium-ion	Yes	Very slow	Highest	Depends on specific type	No	High

Figure 3.3 shows performance characteristics of mutiple battery chemistries. If the colored box is further on the outside then this is positively for that property. In addition, Figure 3.4 shows the energy densities between different battery chemistry's. It should be noted that both figures give a general picture of the technologies and are not specifically about small batteries.
From these figures and from Table 3.3 it can be concluded that the only two interesting battery chemistry's for our application are the NiMH and Li-ion. Therefore these battery techniques will be further investigated.

NiMH Battery Characteristics

The small NiMH battery versions often have a rated voltage of 1.2V, so a DC-DC boost converter must be used to supply the system with more than 2V. In addition, a NiMH battery must contain many more electrons to achieve the same energy density as lithium batteries because lithium batteries often have a rated voltage of 3.7V. NiMH batteries used to suffer a lot more from the memory effect, this has been reduced considerably in recent years, but is still noticeable in most of them. This type of battery still has a significant self-discharge of 10% in the first month to sometimes as much as 20%. The materials from which this battery is made are less harmful to the environment than Lithium. On the other hand, lithium-ion batteries are a lot less harmful to the environment to produce. Despite the fact that the total production has an impact on the environment, the way the product is handled and how it is disposed of has a greater impact on the environment. So making sure the battery is used less intensively and lasts longer so you use half as many batteries can have a much more positive impact than the difference in environmental impact during the production of both chemical batteries. That is why this argument is difficult to include in the considerations.

Lithium Battery Characteristics

Li-ion cells have high specific energy and power since lithium is a light metal. Unlike NiMH, there are many different chemical lithium battery compositions. An overview and comparison of a number of rechargeable lithium-ion chemistries can be found in Appendix C. Each chemistry has its own advantages and disadvantages, often it is a trade-off between energy density, power density and cycle life. With larger lithium batteries thermal stability becomes more important. In our application the battery is not heavily loaded, or only briefly loaded, therefore the thermal instability has negligible influence. Some other key differences with NiMH is that Lithium batteries are more sensitive to the charging algorithm and generally they are more costly than NiMH. However the costs of small batteries of both types don't differ much. An advantage of lithium is that it is available in more small sizes than NiMH.

In the next phase of the process of finding the right battery, different battery shapes will be compared. This is done because for our project the shape is very important. The battery has to be small, resistant to

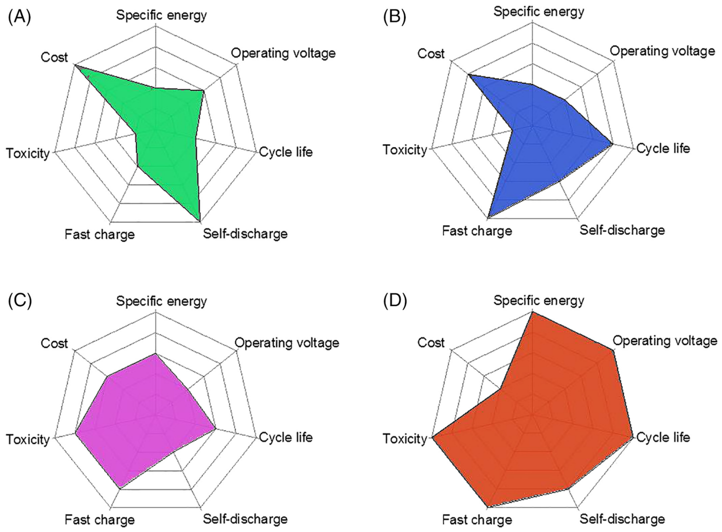

Figure 3.3: Performance comparison of A, lead-acid, B, Ni-Cd, C, Ni-MH, and D, Li-ion batteries. [15]

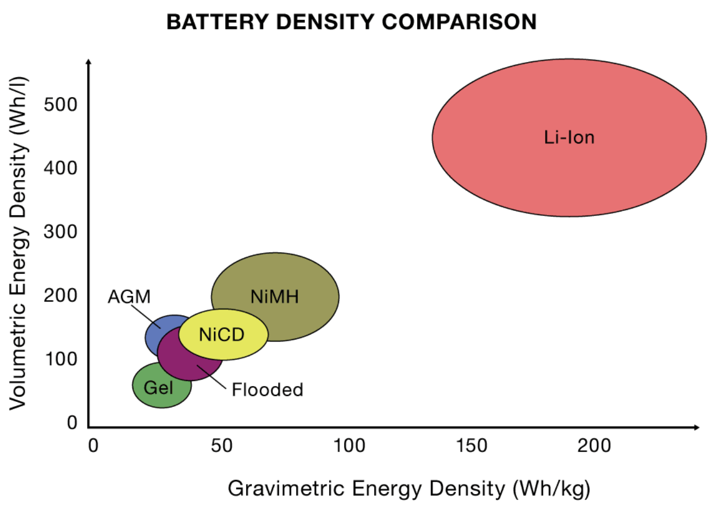

Figure 3.4: This is an battery density comparison from the book Off Grid Solar. [20]

mechanical loads and preferably as safe as possible as mentioned in Section 1. In addition, the shape has a greater influence on the mechanical properties of the battery than its chemical composition.

3.3.2. Battery shapes

The battery to be selected will be placed in a prototype to be used in a medical application. In this application, the sensor patch, it is important that the patch fits well on the skin. On top of that, the battery should not be too big because this has a negative influence on the comfort of the sensor patch. Lastly, a sensor patch that is too large can also cause the patch to detach sooner or make less effective contact with the skin, making measurement results less accurate or incorrect. Therefore the battery must not be larger than $30x30x7mm$ (L x W x H) as stated in the program of requirements of the battery, moreover, a smaller is highly preferred.
As mentioned in the previous section, there are many different lithium batteries with different properties. However, in practice not all of them are available for commercial applications. Another remarkable phenomenon is that not all chemical compositions are available in all formats, this is because some formats are only possible if the chemical composition is not liquid or the casing must be strong because the composition is liquid.
The first choice that has been made, for safety reasons, is to go for an existing battery size instead of having a custom battery made. This is because an existing battery size is cheaper in mass production, faster to deliver

and also (proven) safer because they are already used in many (different) applications.[5]

The most important shapes for us are Pouch, Cylindrical, Prismatic and the Button cell. Figure 3.5 shows the approximate appearance of these batteries. In addition there are also thin film batteries, this falls under the pouch battery shape and is characterized by being very thin, there are even batteries that are thinner than 1 mm. The disadvantage is that these batteries cover a large area to contain the same amount of energy. Because the battery does not cover other components, this type of battery cannot be used for the sensor patch. This can be reconsidered after practical tests show how flexible the patch, and therefore the battery that covers the entire patch, must be. Of course there are other battery formats, but the smallest ones of these are too big for our application anyway, so these formats will not be discussed.

(a) LiPouch battery

(b) LiPrismatic battery

(c) LiCylindrical battery

(d) LiButton battery

Figure 3.5: Different battery shapes

Pouch size

The Pouch is a widely used format and is available in many shapes, in addition, some variations are a bit flexible. Of all formats, this variant generally has the highest energy density per liter because of its high spatial efficiency. The disadvantage of this type of batteries is that they can swell up after many discharges and if the battery is dysfunctional it can also start to swell extremely. In addition, it should normally be placed in a sturdy housing because the battery is vulnerable to mechanical forces. Regarding safety, some versions are equipped with a built-in temperature sensor (NTC) to better control the battery operation but the battery has no other built-in safety functions.

Prismatic size

The Prismatic model is very similar to the Pouch model, the main difference with the Pouch model is that the outside is made of aluminium. Because of the aluminium housing the battery will hardly ever swell. This casing causes the battery to be is a bit heavier and contain less energy compared to the Pouch for the same size. This size also contains (sometimes) a temperature sensor.

Cylincrical & Button size

The Button version is actually a cylindrical size but is characterized by being wider than the battery is high while the other way around is the case with cylindrical batteries. Both batteries are known for their standard sizes (AA, AAA, CR2045 etc). An advantage is that this type of battery is more resistant to mechanical forces than the other types. This can be a big advantage in the first versions of our Sensor Patch because it is still unknown how much force is exerted on Sensor Patch when it is attached or used. This is also reflected in the robustness trade off requirement in Section 2.4.1. One of the disadvantages of these types is that they have a lower energy density than the pouch and prismatic. Another drawback is that these battery types have less heat dissipation because they have a smaller surface area, for the sensor patch application this will not be a problem because the power consumption is very low. The biggest advantage over the pouch and prismatic size is that cylindrical and Button batteries often have 2 built-in safety functions. The first is a current interruption device (CID) that ensures that current can no longer flow when the battery is overcharged. This ensures that the battery does not overheat during overcharging and, in very extreme cases, does not explode. A second safety mechanism is a positive thermal coefficient resistor, the resistance is low when the temperature is low and at high temperatures the resistance is high which reduces the current and therefore the temperature will stagnate.

3.4. Choice of the battery

Multiple chemical compositions of batteries have been proposed in Section 3.3 from which it can be concluded that lithium batteries have the best properties for our applications, provided that safety can be sufficiently guaranteed by the shape and battery management system. The main advantages of lithium compared to other chemical compositions are the many choices of small sizes, high energy density, relatively low environmental impact and low self-discharge.
Next, different formats were considered because this has a major impact on the physical properties of the battery. Important aspects that lead to a choice here are of course the requirements as described in 2.4.1. But in addition, we find it extra important to emphasize that a battery must be chosen for a prototype / proof of concept device. That is why it is now preferable to have a battery with more energy than should be needed so that more data and information can be collected in the early phase of development. A higher degree of data and information collection can improve the speed of designs. At a later stage in the development it becomes more important to improve comfort and therefore reduce the battery size (and stored energy) so that it only lasts for example 5 days. With this reasoning the choice was made to go for a rechargeable Lithium button cell battery. The higher safety (both mechanical and electrical) and high energy density on a small size are the main advantages compared to other shapes. As a result, it can now be concluded that the trade-off requirement, concerning a flexible battery as mentioned in section 2.4.1, has unfortunately not been met. Since the safety of a flexible battery, as explained above, is a lot less than that of a button cell battery.

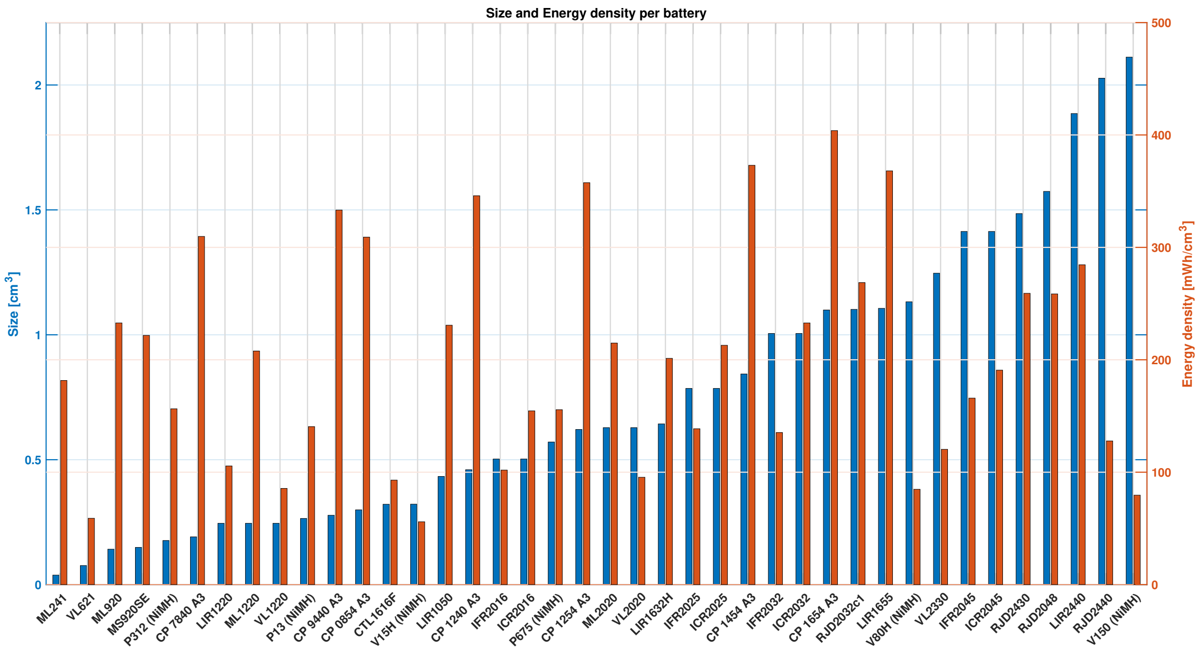

Figure 3.6: Bargraph of the size and energy density of all the batteries.

Due to previous research and choices it is easier to compare real batteries. As mentioned in 3.2.2 a Matlab script has been made in order to easily compare different characteristics. Two very important characteristics are the size and energy of the battery. A small battery with much energy is preferred. In addition, the battery must be able to deliver at least 40mA for 5 seconds. Only batteries that meet the requirement regarding the size are considered and for extra insight NiMH batteries that fulfill this requirement are in the comparison too. Figure 3.6 is one of the graphs made by the model. It shows the energy density in $[mWh/cm^3]$ and the size in $[cm^3]$ of each battery. The other figures which show the energy capacity, power and power density of the batteries are not shown here due to their sizes, but they can be found in Appendix C. Both the energy and power numbers are all based on the nominal voltages of the batteries. When the peak current is drawn from the battery, the voltage would drop due to the internal resistance of the battery resulting in a lower peak power. The precise voltage the battery would drop differs per battery type and its current capacity which makes it hard to take it into account. Regarding the energy, since not all the batteries have the same voltage-SoC plot, the total energy would differ too, despite the fact that for example both batteries are rated 50mAh. Despite the possible deviations of the values from reality, it does reflect the differences in broad lines.

From Figure 3.6, it can be seen that the batteries of type CP-XXXX-A3 have higher densities compared to others of the same size. Another point to note is that the energy density does improve when the size increases. Although it was to be expected that the largest battery would have the highest energy density, this is not the case. The CP1654A3 has the highest energy density, while it is not one of the biggest batteries in the comparison. It can also be noted that some NiMH outperform lithium batteries in the smaller size range ($< 0.7cm^3$) but the NiMH batteries underperform as soon as the size increases. The P13, which is a NiMH battery, does have a higher energy density compared to other lithium batteries in the same size range. Surprisingly, it does also outperform some lithium batteries when it comes to the power it can deliver. This can be seen from Figure C.3. It is important to note that the power values from the VL and ML series might deviate, because this is not (properly) mentioned in the available datasheets. From the same figure it can be seen that again the CP1654A3 has excellent specifications while its dimensions are only 16mm in diameter and 5.4mm high.
The CP1654A3 is produced by Varta which is an based in Germany and is known for its high quality battery products. The cycle life of this battery is well above 500 cycles even at a 1C discharge rate. Other specifications of this battery are listed in Table 3.4, from this is can be concluded that the battery meets all the requirements.

Table 3.4: Specifications of the CP1654A3 produced by Varta. [40]

Brand	Varta
Type	CP 1654 A3
Chemistry	LiNixMnyCozO2 (MNC)
Diameter / Height	16.1mm / 5.4mm
Weight	3.0 gram
Nominal / Peak Current	240mAh / 360 mAh
Min / Nominal / Max Voltage	3.0V / 3.7V / 4.2V
Impedance Initial	$< 0.4\Omega$@ 1kHz
Fast / Standard Charge Time	3h / 5h
Cycle Life	>500 at 1C discharge rate
Safety feature	Build in CID

3.4.1. Conclusion

In this section, the battery was chosen. The battery is the **CP1654A3** by Varta. It meets all given requirements listed in Section 2.4.1.

3.5. Power Management

This section will introduce the design considerations for power management. Selecting energy-efficient components within the system does not necessarily mean that the total system will be energy-efficient. Therefore, a smart power management design consisting of different voltage regulators are designed to create an energy-efficient system. Also, protection circuitry is of utmost importance because the sensor patch will operate on a newborn's skin. This section introduces battery protection for normal operation and for charging the battery. The design of the power management will be analyzed together with design requirements. In the next chapter, an implementation method will be given.

3.5.1. Voltage regulation

Every component has a voltage range in which the component is designated and to which its characteristics are related. This voltage is needed as input of such a component. Since the sensor patch consists of multiple devices, different voltage levels are needed to feed every device. These operational voltage ranges of every device in the sensor patch are listed in Table 3.5.

Table 3.5: Voltage supply range

Device	V_min	V_typ	V_max	Unit
MCU (MSP430FR5994)	1.8		3.6	V
BLE Module (nRF52810)	1.7		3.6	V
Temperature Sensor (SI7051)	1.9	2.1	3.6	V
Respiration Rate Sensor (IIS2DLPC)	1.6	1.8	3.6	V
Bilirubin Sensor & LEDs	3.7		5.0	V

Is it possible to feed every device straight from the battery, such that the battery output voltage equals Vdd for every device? Unfortunately, the answer is no. The voltage curve of the battery can be seen in Figure 3.7.

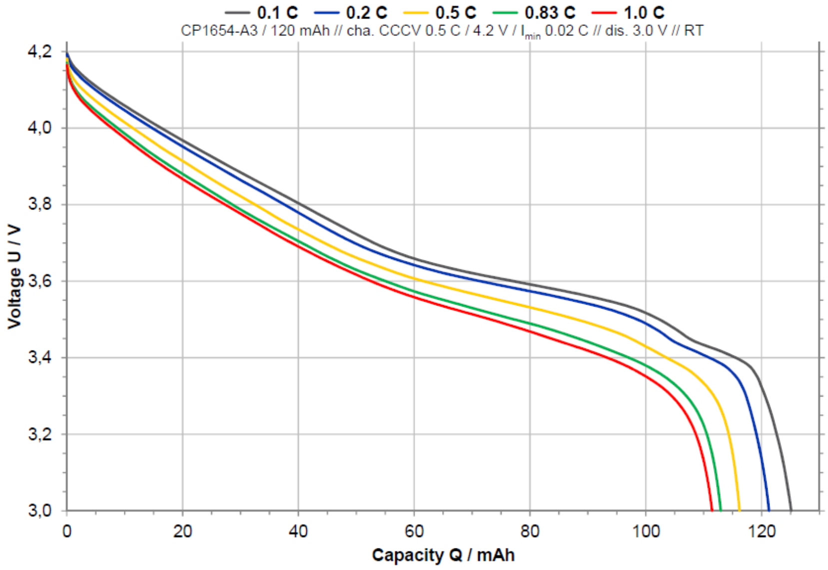

Figure 3.7: CP1654A3 - Discharge characteristics at various C-rates

The different DC voltage ranges needed to feed the different components are listed in Table 3.5. As can be seen in the Table, the maximum allowable voltage of the MCU, BLE module, temperature sensor and respiration sensor is 3.6V. The output voltage of the fully charged battery is higher than 3.6V. Therefore, a circuit is needed in order to reduce the battery voltage to maximally 3.6V. Such a circuit could be a linear regulator: an LDO, or a switching regulator: a buck converter or a buck-boost converter. The advantages and disadvantages of every circuit will be briefly listed in the *buck conversion* paragraph. The bilirubin sensor needs minimally 3.7V together with 40mA for at least 5s, according to Requirement A.4, to emit enough light for its sensing purpose. As the battery voltage could drop below 3.7V, a buck-boost converter or boost converter is needed in order to correctly feed the sensor. The design choices will be explained in the *Buck-boost conversion* paragraph.

Buck conversion

Advantages of a linear regulator include the absence of switching noise and it is a relatively small and simple device which makes it also cheap. The disadvantage of a linear regulator is the 'loss of energy'. A linear regulator dissipates energy, or heat, across the regulation device to regulate the output voltage.

Advantages of a switching regulator is that a switching regulator is highly energy efficient. The disadvantage of a switching regulator is size. In its simplest form, it needs at least an inductor, capacitor, diode and fully controller switch. A switching regulator has switching noise. Lastly, a switching regulator is more expensive than a linear regulator. All these points are listed in Table 3.6.

Table 3.6: Linear regulator vs. Switching regulator

	Linear Regulator	**Switching Regulator**
Design Flexibility	Buck	Buck, Buck-boost
Efficiency	Low (depending on Vin-Vout)	High
Complexity	Low	Medium
Size	Small	Medium
Total cost	Low	Medium
(Switching) Noise	Low	Medium
V_out	1.9V - 3.0V	1.9V - 3.0V (buck) 1.9V - 3.6V (buck-boost)

A linear regulator must have an output voltage lower than 3.0V since a linear regulator can only lower the voltage of the battery's voltage and the lowest voltage of the battery is 3.0V. With this reasoning, the voltage difference between the input and output of a linear regulator is relatively large for most of the battery's SOC. For example, if V_{out} is set to 2.5V, the voltage difference between the battery output voltage and 2.5V is almost 1.0V on average. This will make the system inefficient. Also, a DC-DC buck converter needs an output voltage lower than 3.0V, for the same reason above. However, the efficiency can be higher than that of a linear regulator. A buck-boost converter can convert the voltage to every level in-between 1.9V and 3.6V.

How does the input voltage of a device influence its power consumption, performance and measurement accuracy? The datasheets of every device have been analysed with $V_{in} = 2V$ and $V_{in} = 3V$.

For the MCU, the gate capacitances are fixed, thus a higher rail voltage results in more current flow and a faster rate of charge. This will improve the performance of the MCU. On the other side, more rail voltage means more power consumption, since the input current remains the same according to the Datasheet [36]. Processing speed is less important than power consumption for the sensor patch, therefore a lower voltage is preferred.

The BLE module has internal voltage regulation. This voltage regulation can be an LDO or a DC-DC buck converter if an LC-filter is manually connected. The operating voltage of the BLE system is 1.3V [19]. This means that an LDO will lose a lot of energy, or heat, converting the Vdd voltage. Therefore, the internal DC-DC buck converter must be used for low energy mode. Once the DC-DC buck configuration is chosen, it does not matter what voltage is being supplied to the BLE module, since the power consumption will is approximately the same for $V_{in} = 2V$ and $V_{in} = 3V$. The processing speed is independent of Vdd.

The temperature sensor has an internal voltage regulation. It is assumed that an LDO with an output voltage lower than 1.9V regulates the voltage. The power consumption is so small, that it does not matter what value Vdd is. More important is the measurement accuracy: the measurement accuracy is a function of temperature. If the LDO dissipates a lot of energy, the measurements can be less accurate. Luckily, the power consumption of the LDO is so small that its heat dissipation is almost independent of the measurement accuracy. For these reasons, it will not matter what value for Vdd is chosen.

The respiration rate sensor will consume more energy at higher Vdd voltages. It must be said that the energy consumption is extremely low. The accuracy of the respiration rate sensor is mostly dependent on temperature instead of the input voltage.

A small summary of the ideal Vdd is given in Table 3.7.

Table 3.7 concludes that a lower voltage is preferred from the devices' side. This filters the choice between an LDO, Buck-converter and a Buck-boost converter. Namely, an LDO is extremely power inefficient for this voltage down-conversion, and there is no need for an integrated boost conversion. For this reasoning, a DC-DC buck converter will be used. An implementation method will be explained in section 4.3.1.

Buck-boost conversion

The buck-boost converter is a power converter that converts the input voltage to a another DC voltage at the output. In section 3.4, the choice of the battery was made. The discharge characteristics of the CP1654A3 can

Table 3.7: Ideal Vdd for each device

Device	**Ideal Vdd: 2V or 3V**
MCU (MSP430FR5994)	2V
BLE Module (nRF52810)	2V (LDO) N/A (DC-DC)
Temperature Sensor (SI7051)	N/A
Respiration Rate Sensor (IIS2DLPC)	N/A

be seen in Figure 3.7. This voltage is not high enough to feed the bilirubin sensors and its LEDs. Therefore, a boost converter is needed to boost the voltage to minimally *3.7V*. An important requirement for this boost converter is that it must be able to supply 40mA when the LEDs are turned ON, which is Requirement A.4. A stabilized voltage of *3.7V* consumes 12% less energy than, for example, a stabilized *4.2V* , according to the simulations of the sensor group [38]. Note that a boost converter can be used instead of a buck-boost converter above the *4.2V* output. The higher the input voltage of the bilirubin sensor, the more energy it consumes. Therefore, a DC-DC buck-boost converter with an output voltage of *3.7V* will be designed. An implementation method will be explained in section 4.3.1.

3.5.2. Battery management

The battery management circuitry manages the rechargeable Lithium-ion cell by protecting the battery from operating outside its safe operating requirements. A battery charger, which must be implemented since the battery is rechargeable, falls under battery management together with a state of charge monitoring design. Because safety is of utmost importance, a battery protection design will be given in this section together with the battery charger and a state of charge monitor. The section begins with a trade-off on how battery cycle life could be improved.

State of charge bounds

State of Charge (SOC) is the level of charge of an electric battery relative to its maximum capacity. A battery with a SOC of 0% means that the battery is 'empty'. This means in practice that the battery could exceed its safety bounds. Even when the battery has no load attached, it leaks charge. This phenomenon is called 'self-discharge'. For safety reasons, Requirement C.3. is proposed to make sure the battery will never reach 0% due to self-discharge. Of course, it is unlikely that self-discharge causes the last 20% to discharge. But a warning signal to the hospital does not immediately mean that the sensor patch stops measuring. The extra time before the sensor patch is not performing any measurements can discharge the battery even more. And if the battery is not recharged immediately, then self-discharge can play a role in safety. Note that a drawing a high current for LEDs will also lower the voltage for a short period of time, this could result in surpassing the safety margins of the battery. Therefore, a 20% SOC safety margin is reasonable.

Battery cycle life improvement

The book "Lithium-ion Battery chemistries' by John T. Warner states: *"For every 10% DOD that is reduced, the cycle life increase is roughly 50% over the 100% DOD cycle life"* [42]. The battery has approximately more than 500 charge-recharge cycles before 80% of its charge capacity is left, according to its datasheet [40]. If it takes 3 days to measure a newborn, and 1 day to recharge the battery, then a single cycle takes up 4 days. This means that the battery lasts at least 2000 days. This is long enough to make the sensor patch economically viable and it is plausible that another component wears out before the battery wears out. For this reasoning, it is not needed to set bounds on the SOC levels to improve battery cycle life.

Battery protection

The battery protection module could also be known as the protection circuit module (PCM). The battery protection must detect a variety of fault conditions, such as overvoltage, under-voltage, discharge overcurrent and short circuits. Any of these fault conditions will damage the whole electric system and it could destroy the battery in a highly unpleasant way. For all these reasons, it is concluded that a battery protection circuit must be implemented. See Requirement C.5.

Battery charger

A battery charger will make sure that charging the battery will be done safely by protecting it from,for example, overvoltages/overcharging. One could argue that a battery charger circuit is needed inside the sensor patch. However all sensor patches will be collected and sent to an external location where the charging is done. Therefore, the charging circuit could also be integrated into the external charger. Eliminating the battery charger circuitry from inside the sensor patch will benefit the total available area and energy. On the other hand, the safety is top priority for the system. It can not be stressed enough. If a person, at home or the hospital, decides to charge the battery, disastrous outcomes could take place. This chance is very slim, but the consequences are huge. Solely for this reason, the safety preference, a battery charger will be implemented inside the sensor patch.
The battery manufacturers‘ specified constant current charging rate is the maximum charging rate that the battery can tolerate without damaging the battery. The datasheet of the CP1654A3 battery [40] recommends some low current consuming battery chargers. Notice that the time it takes to charge the battery is not important for the sensor patch as it will be charged in huge batches in an external location.

State of charge monitoring

A requirement for the power management module is that it must warn the hospital when the state of charge (SOC) dives under 20% (See Requirement C.3). The goal of this requirement is to let the hospital know that the battery is almost empty and that safety and functionality are not ensured. The state of charge monitor must send a signal to the microcontroller that the battery is below 20% of its capacity. The MCU & Communication group wants a *'Low power flag'*, which means a HIGH bit ('1'), at an input of the MCU. Luckily, such a monitoring system does not have to be complex, since it does not have to continuously monitor the state of charge. A design method for monitoring the state of charge is by looking at the voltage of the battery. The voltage and state of charge are related to each other, as can be seen in Figure 3.7. Two methods have been considered:
The first method is to compare the output voltage of the battery with another voltage using a physical voltage comparator. The comparator can give a 'low power flag' or digital '1' as an output signal when the voltage dives under the safety threshold. This method requires additional circuitry.
The second method is that the microcontroller constantly checks the voltage level of the battery using the ADC and saving these digital values in its memory. The MCU can then process the digital voltages and decide when the battery is too low on charge. A signal will be sent to the hospital, when the charge is too low. This method does not require additional circuitry.
A comparison between the two methods is listed in Table 3.8.

Table 3.8: Comparison of monitoring designs

	Design 1: Comparator	**Design 2: Microcontroller**
Dimensions	Medium	Minimal
Power usage	Small	Minimal
Costs	Small	Minimal

After comparing the two monitoring designs it can be concluded that the monitoring will be done by the microcontroller.

3.6. Conclusion

In this chapter, a design for the energy system is proposed to fulfil every requirement listed in Section 2.4 with the aid of a Matlab energy model (3.2). The battery is a lithium-ion rechargeable button-cell, CP1654 A3. The discharge characteristics are of importance for the power management design and can be seen in Figure 3.7. The power management circuitry consists of a DC-DC buck converter 3.5.1, a DC-DC buck-boost converter 3.5.1, a battery protection circuit, a battery charger circuit and state of charge monitoring, all listed in Section 3.5.2. The next chapter will explain the implementation methods of the energy model, the battery, and the power management circuitry.

4
Implementation

This chapter discusses the implementation of the system. Several electrical circuits will be worked out from which its design originates from Chapter 3. These designs were based on the program of requirements in Chapter 2. This chapter begins with an implementation of the energy model. Next, the implementation of the battery will be discussed. Thereafter, the implementation of the power management will be given. Finally, a small conclusion is presented in which the implementation is revised.

4.1. Implementation of Energy Model

In this section the results of the energy model will be visualized and discussed. The visualization that has been implemented to assist in making battery choices has been used in Section 3.4 and will therefore not be discussed here. First, a simulation and comparison of different, in this case temperature, sensors will be discussed. After that, the results of a total system simulation will be explained. And finally a conclusion will be given about the energy model.

4.1.1. Sensor simulation

For this simulation, a number of temperature sensors have been selected whose characteristics are already defined in the Matlab model, for clarification, the parameters of these sensors are listed in a table in Appendix D.1.

Figure 4.1 shows the power of the sensors during one measurement and the total energy consumption to perform one measurement. It also shows whether a sensor needs to be turned on for a long time; If the power is low while consuming a relatively large amount of energy, it means that the sensor will be on for a longer time compared to the rest. This can for example be clearly seen with the MAX44006 sensor.

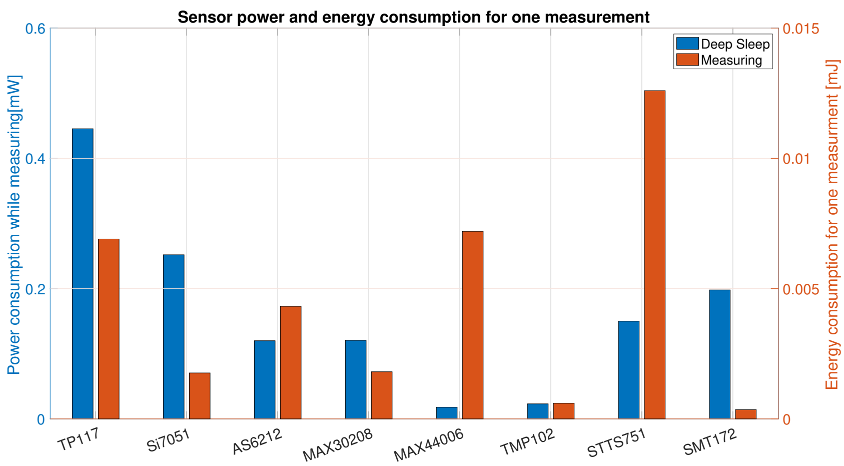

Figure 4.1: Bargraph of the power drawn and energy usage for each sensor during one measurement.

Another result of the sensor simulation is Figure 4.2. The left graph shows how much energy is consumed per sensor, depending on the number of measurements performed per day. This graph does not include energy consumption during deep sleep. This makes it more clear that the influence of the difference in energy consumption for one measurement has a bigger influence when measuring many times a day. In the right graph of Figure 4.2 the total energy consumption per day is calculated including the consumption in sleep mode. This shows that the TMP102 has a very high energy consumption in sleep mode and therefore might not be a suitable sensor.

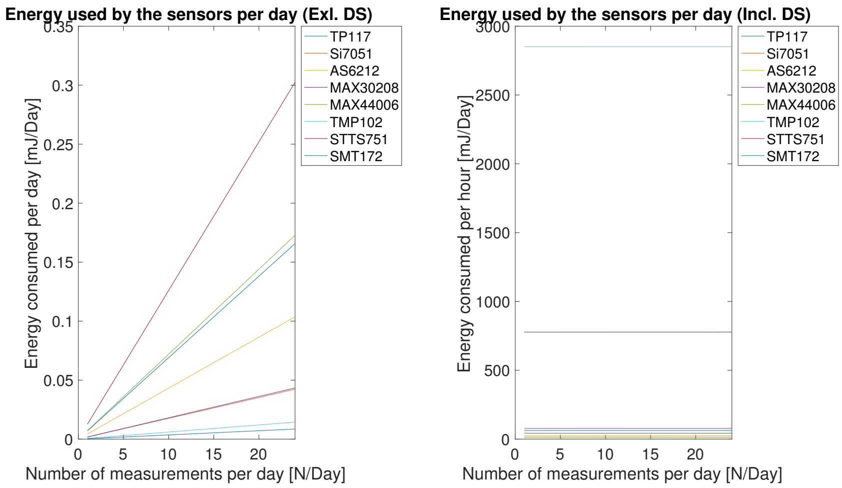

Figure 4.2: Plot of the energy consumed per sensor per day, depending on number of measurements.

4.1.2. Full system simulation

The full system simulation is an important simulation to get an idea of the total energy consumption of the sensor patch. The results of this simulation that will be discussed here are performed with the components which will also be used in the final sensor patch. The used parameters of these components can be read in Appendix D.2. The sensor patch is simulated for 3 days and all measurements are taken and sent every hour. Unfortunately it is not possible to include the losses of components such as converters, safety circuits and the battery in detail in this simulation, because this is not yet implemented in the Matlab model. To compensate, a variable can be used that represents the total system losses, in this simulation it is assumed that 20% energy loss takes place in the whole system. The model is built in such a way that sensors are not activated at the same time. This can be simulated in the future if the microcontroller and sensors allow it. As sensors are read one after the other, the microcontroller may be turned on longer than necessary, this will be discussed further in this section.

As mentioned in Section 3.2.3, a variable step size has been implemented to make the simulation fast and not take up too much memory. The result of this method meets the expectations and the variation of the variable step size can be seen in Figure D.3 in Appendix D.3. Another graph created by the simulation is the development of the total energy consumption over time, which can also be seen in Appendix D.3. Figure D.4 is made to get extra insight in the course of the stages, power and energy during a specified measurement.

Figure 4.3 shows how much energy each component consumes per stage. This also makes it clear how much a stage contributes to the total consumption. From this figure, it can be seen that the bilirubin sensor consumes a lot of energy (!) and that the consumption during the measurement stage is the largest part of the total energy consumed. It is also surprising how much the micro controller consumes during the measurement stage. This is because the microcontroller is in active mode simultaneously when the respiration sensor is measuring for 30 seconds and the bilirubin sensor is measuring for 5 seconds additionally. The total active state of the microcontroller is now 35.4 seconds, by doing the bilirubin measurement at the same time as the breath measurement it is possible to save 10% of the energy consumed by the micro controller, which is not the case in the simulations.

The maximum power drawn by each component is shown in Figure 4.4, as well as the energy consumption per component. It is important to know that losses are not taken into account in this figure. Since the calculated values are shown above each bar, it is easier to compare the lower bars with each other. In this way,

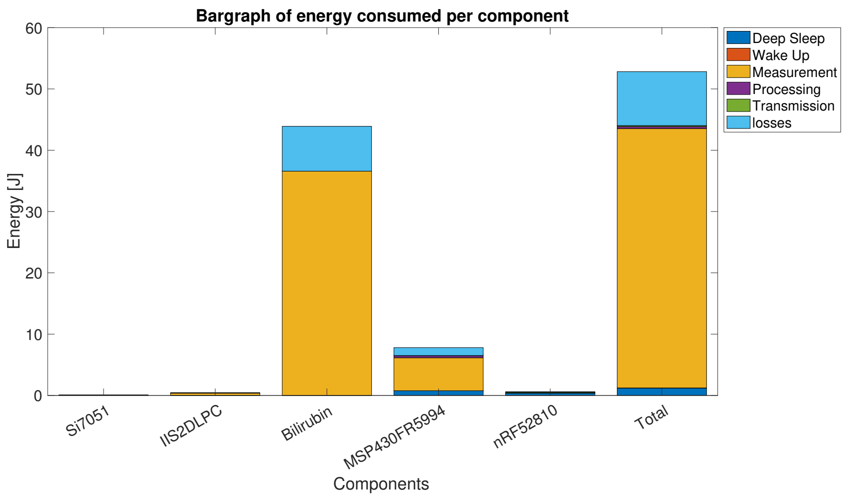

Figure 4.3: Energy usage per component divided per stage in the full system simulation.

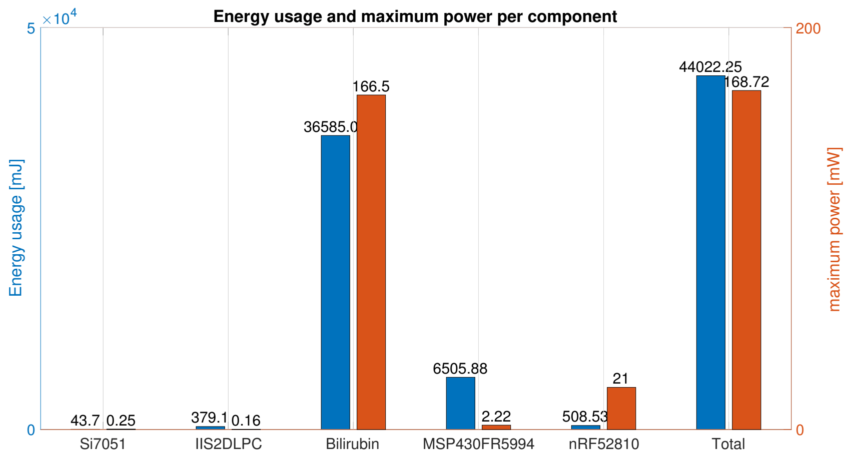

Figure 4.4: Energy usage and maximum power per component in the full system simulation without losses.

it can be concluded that the nRF52810 still draws a considerable amount of power for short periods of time. Additional graphs generated by the simulation can be found in Appendix D.3.

4.1.3. Conclusie

An energy model has been succesfully designed. It gives a clear overview of the energy consumption of every device and of every operating stage. It meets the expectations listed in Table 3.2

4.2. Implementation of the battery

As stated in Section 3.4, the CP1654A3 Battery manufactured by Varta has been chosen. This battery could be placed in a battery mount but this would result in an even larger total volume that will be occupied by the battery. It is also possible to buy the battery with pre-fixed solder tags or cables. The most suitable mounting for our sensor patch can be seen in Figure 4.5. The flags, which are mounted on the battery in the figure, are only 0.2 mm thick which means that the total construction remains very thin. This way, the battery can be properly mounted on the PCB of the sensor patch.

Now that the battery selection is confirmed, it is possible to estimate the total amount of energy in the battery. Figure 3.7 shows the discharge characteristics of the battery, it shows that the battery has an average voltage of 3.7Volt and can deliver 120mAh when discharged at a discharge rate of 0.2C (0.024A). According to the formula 4.1 the battery will then have about 1600J of energy. This will not be fully available. The hospital receives a warning when the battery dives under 20% (Requirement C.3). This means that the battery will probably be recharged from 20% SOC up to 100% SOC, which results in a smaller use of its capacity. A simple

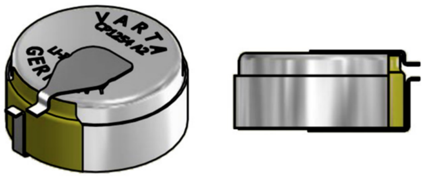

Figure 4.5: Possible battery mounting [39].

estimation that only 80% of the capacity is effectively used. This estimates the available energy on a value of $0.80 * 1600J = 1280J$. It can be expected that a Lithium-ion battery has an efficieny of 98%, according to J.T. Warner [41]. This reduces the available energy further to $0.98 * 1280J = 1254J$

$$E_{Battery} = V \cdot I \cdot t = 3.7V \cdot 0.024A \cdot (5h \cdot 3600s) = 1598.4J \tag{4.1}$$

4.3. Implementation of Power Management

A simple design with its requirements of the power management module is proposed in the previous Chapter 3. Devices such as voltage regulators, boost converter, battery charger, resistors, inductors and capacitors will be implemented in this section. The size and power consumption of the circuitry should both be minimized, because the sensor patch has limited area and energy on-board.

4.3.1. Implementation voltage regulation

Before the DC-DC step-down buck and buck-boost converter will be implemented, an interesting quote from Meng He on voltage regulators states that quiescent current needs to be considered in the implementation of converters: *"You can choose the processors and digital peripherals with the best low power specs, but victories can't be claimed until the right power regulator specs are locked down. In low power applications, never underestimate the specs and condition of quiescent current because it can be the main contributor to the overall power consumption of the system."* [17]. Quiescent current is the nominal current used while integrated circuits are "resting" and ready to work. The system is in an idle state and waiting for something to happen. Designers usually use quiescent current to gauge the power dissipation of a power supply at light load. This information will be of help to estimate the quiescent power consumption in the upcoming sections.

Buck converter

The design considerations have been mentioned in Section 3.5.1. The battery voltage, which can be seen in Figure 3.7, will stay in-between *3.35V* and *4.15V* during the 3 days of functioning. This voltage is the input voltage of the DC-DC buck converter. The allowable output voltage must be in-between *1.9V* and *3.6V*, according to Table 3.5. A low voltage is preferred over a high voltage at the output of the converter.
Therefore, the **ST1PS01AJR** step-down buck converter [34] has been chosen that regulates a constant voltage of *2.0V*. The schematic of the circuit is shown in Figure 4.6 and the value of the components are listed in Table 4.1.

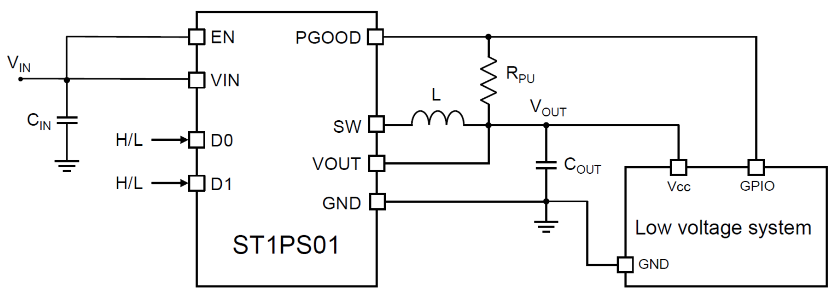

Figure 4.6: ST1PS01AJR Schematic

Table 4.1: Components for the 2.0V buck converter

Component	Value	Unit
C_{in}	10	μF
C_{out}	10	μF
L	2.2	μH
R_{PU}	1	MΩ

The component values are recommended by the datasheet and it will not influence the DC output voltage level of the buck converter. The output voltage can be set as 2.0V by feeding a 'HIGH' to D0 and a 'LOW' to D1. The output voltage will be connected to the devices listed in Table 4.2. The buck-converter can easily handle the maximum current as it is designed for a maximum of 400mA. The sensor patch is estimated to draw maximally 50mA.
The efficiency of the buck converter can be estimated with the aid of Figure E.1. The input voltage will stay in-between 3.2V and 4.15V, based on the characteristics of the battery 3.7. The output current is roughly estimated to stay in-between 100μA and 50mA, this means that the efficiency will always be more than 85%.
The quiescent current is estimated 500nA with an input voltage of 3.7V and an output voltage of 1.8V, according the the Datasheet [34]. This translates to a quiescent energy consumption of $3.7V * 500nA * 3600s * 24h = 160mJ/day$.
The size of the ST1PS01AJR chip is 1.44mm x 1.14mm x 0.60mm (L x W x H). For sake of simplicity, resistor will be sized 0.50mm x 1.00mm x 0.50mm and capacitors will be sized 1.00mm x 2.00mm x 1.00mm. The inductor normally is a large component, but in an environment where there is little current, it could be small. A reasonable size estimation is 3.00mm x 3.00mm x 1.50mm. This information is needed to estimate the dimensions for the total power management circuitry.

Buck-boost converter

The buck-boost converter is needed to step up or step down the DC battery output voltage to *3.7V* for the bilirubin sensor LEDs. This can be seen in Table 4.2.

Table 4.2: Voltage level per device

Voltage level per device	2.0V	3.7V
MCU (MSP430FR5994)	X	
BLE Module (nRF52810)	X	
Temperatue Sensor (SI7051)	X	
Respiration Rate Sensor (IIS2DLPC)	X	
Bilirubin sensor & LEDs	X	X

Due to a limited sensor patch area, IC variants of a boost converter switch are preferred. The design requirements of the boost converter were given in Section 3.5.1.
A buck-boost converter that meets the requirements is the **RP604Z37**[26]. It can produce a stabilized 3.7V at the output and the LEDs can draw at least 40mA if needed. The schematic of the circuit is shown in Figure 4.7 and the value of the components are listed in Table 4.3.

Table 4.3: Components for the 3.7V buck-boost converter

Component	Value	Unit
L	2.2	μH
C_{in}	10	μF
C_{out}	22	μF

The values of the components are recommended by the datasheet. The buck-boost converter can easily handle the maximum current as it is designed for a maximum of 400mA. The sensor patch is estimated to draw

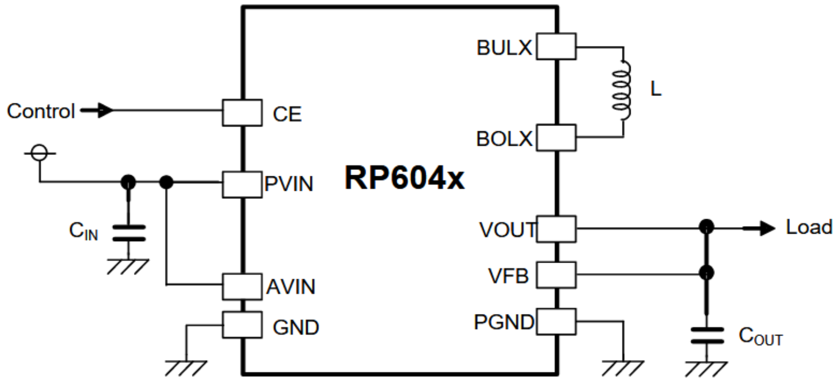

Figure 4.7: RP60437 Schematic

maximally 50mA.
The efficiency of the buck converter can be estimated with the aid of Figure E.2. The input voltage will stay in-between 3.2V and 4.15V, based on the characteristics of the battery 3.7. The output current is roughly estimated to stay in-between 10μA and 50mA, this means that the efficiency will always be more than 80%.
The quiescent current is estimated 0.3μA with an input voltage of 3.7V and an output voltage of 3.7V, according the the datasheet [26]. This translates to a quiescent energy consumption of $3.7V * 0.3\mu A * 3600s * 24h = 96mJ/day$. This does not look like a lot, but the RP60437 is designed for extremely low quiescent current. For comparison, the first buck-boost converter selected for the sensor patch was the TPS63060DSC [35]. This buck-boost converter has a quiescent current of approximately 37μA. This translates to a quiescent energy consumption of $3.7V * 37\mu A * 3600s * 24h = 12J/day$! Here, the importance of quiescent current is sketched.
The size of the RP604Z37 chip is 2.70mm x 3.00mm x 0.60mm (L x W x H). For sake of simplicity, resistor will be sized 0.50mm x 1.00mm x 0.50mm and capacitors will be sized 1.00mm x 2.00mm x 1.00mm. The inductor could normally be a large component, but in an environment where there is little current (maximally 50mA), it could be small. A reasonable size estimation is 3.00mm x 3.00mm x 1.50mm. This information is needed to estimate the dimensions for the total power management circuitry.

4.3.2. Implementation battery management

An implementation method of the battery management will be proposed in the following two paragraphs. The battery management is split up in two modules: the battery protection circuitry and the battery charger circuitry.

Battery protection

Section 3.5.2 concludes that a battery protection circuit must be implemented for safety issues. The requirements for the battery protection is as follows: over-charge protection, over-discharge protection, over-current protection and short circuit protection. These protections make sure that the battery will not exceed its safe-operating limits. As for every implementation method, the size of the circuitry and the power consumption should be minimized.
A single chip solution for all the requirements listed above is chosen, namely the **AP9211** [8]. This IC has a low quiescent current of 3.0μA.
The AP9211 needs an additional three components, according to its datasheet. A 400Ω resistor and a 100nF capacitor will stabilize the supply voltage of the AP9211. And a 2.9kΩ will monitor the charge/discharge current from a sensing terminal. These components are listed in Table 4.4.
The size of the AP9211 chip is 3.00mm x 2.10mm x 0.60mm (L x W x H). For sake of simplicity, resistor will be sized 0.50mm x 1.00mm x 0.50mm and capacitors will be sized 1.00mm x 2.00mm x 1.00mm.

Battery charger

Section 3.5.2 concludes that an integrated battery charger must be implemented for safety issues. The requirements for the battery protection is as follows: the battery charger should safely charge the battery. The speed of charging is not important. For sake of simplicity, the recommended battery charger for the CP1654A3 Li-ion battery according to its datasheet [40] is chosen. As for every implementation method, the size of the

circuitry and the power consumption should be minimized.
A single chip solution for all the requirements listed above is chosen, namely the **LTC4071** [3]. Its shunt architecture requires just one resistor from the input supply to charge and protect the battery in a wide range of battery applications. The value of this resistance has impact on the speed of charge. The lower the resistance, the faster the charging. Also, the faster the charging, the more heat is produced by the resistor. With the help of Figure 4.8 and Equations 4.2 and 4.3, a resistance value can be calculated that will not exceed the battery's maximum allowable charging temperature. This maximum allowable charging temperature is 45°C. The voltage characteristics of the battery can be seen in Figure 3.7 and it can be concluded that it will stay in-between 3.2V and 4.15V for every state of charge. Therefore, it is useful to charge the battery with a source voltage of 5.0V to limit the heat dissipation of the resistor. A high charging speed is not important, thus relatively low maximum of 50mA to charge the battery is reasonable. With this information, the resistance is $(5.0V - 3.2V)/(50 * 10^-3) = 36\Omega$. This means that the resistor dissipates maximally 90mW. It is important that this resistor will not be located next to the battery in the prototype design.

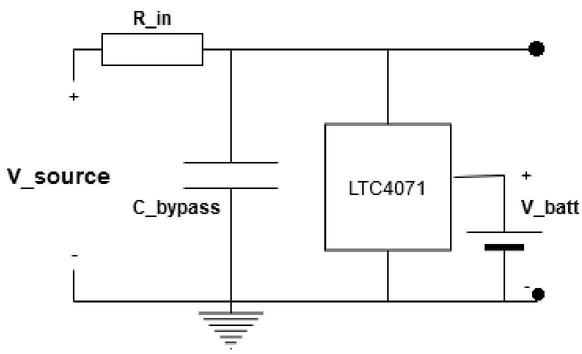

Figure 4.8: Lithium-ion Battery Charger

$$I_{charge} = \frac{V_{source} - V_{batt}}{R_{in}} \tag{4.2}$$

$$P_{diss} = \frac{(V_{source} - V_{batt})^2}{R_{in}} \tag{4.3}$$

It is also recommended to implement an input decoupling capacitor with a capacitance of 0.1μF to handle high peak load currents. These components are listed in Table 4.4.
The size of the LTC4071 chip is 3.00mm x 2.00mm x 1.10mm (L x W x H). For sake of simplicity, resistor will be sized 0.50mm x 1.00mm x 0.50mm and capacitors will be sized 1.00mm x 2.00mm x 1.00mm.

State of charge monitoring

As mentioned in Chapter 3, the state of charge of the battery will be monitored by the microcontroller. This is possible because an ADC is present in the microcontroller. The MCU gives a warning signal to the hospital when the SOC dives under 20%. The 20% SOC translates to a voltage level of approximately 3.50V. This translation is done as follows: Figure 3.7 shows the curve of Voltage vs Capacity of the battery. A C-rate of 0.1C is plausible since 1.0C equals 1 hour of discharge time and the discharge time of the battery will be at least 10 hours. The battery has a capacity of 122 mAh, thus 20% is 24.4mAh. The last 24.4mAh starts with a battery voltage of 3.50V.Keep in mind that the battery is full on 4.2V.
The ADC pin of the microcontroller is fed by the 2.0V output of the step-down buck converter. The microcontroller does not support a reference voltage above 2.5V for their ADC, so a voltage divider is needed in order to step down the voltage to something the ADC can work with. In this case, the maximum 4.2 will be stepped down to 2.45V by placing a 1.4MΩ resistor in series with a 1MΩ resistor. Notice that the values are high to limit the power consumption. The ADC of the MSP430FR5994 MCU is 12 bits. The state of charge monitoring needs 2 additional resistors for voltage division. These are listed in Table 4.4.

4.4. Dimensions of the circuitry

Table F.1 lists every component needed to implement the whole energy system. Requirement C.4 states that the power management circuitry, excluding the battery, may not exceed 30mm x 20mm x 4mm (L x B x H). A

Table 4.4: Additional components of the battery management module

Additional Components	Battery Protection	Battery Charger	SOC Monitoring
Resistors	1x 400Ω 1x 2.7kΩ	1x 36Ω	1x 1MΩ 1x 1.4MΩ
Capacitors	1x 100nF	1x 100nF	N/A
Inductors	N/A	N/A	N/A

simple estimation for estimating the component area goes as follows: calculate the square millimeters (mm^2) of every component by multiplying its length and width, then add every component area together to estimate to total area. This area can be compared with the maximally required 30mm x 20mm (L x B) = 600mm^2 from requirement C.4.
Adding all components' area from Table F.1 sums up to a total area of 50mm^2. This means that there is roughly estimated 550mm^2 area left for wiring each component and spacing between components. This area must be enough to wire every component correctly. The wiring plan is complex and not in the scope of this part. Also the height of 4mm is not a problem. It can be concluded that the power management system fits within its given area and thus requirement C.4 is met.

4.5. Conclusion

Extra circuitry next to the battery is designed and implemented to ensure proper functionality and safety. The integrated circuit LT4071 gives a wide voltage range in which the battery can be safely recharged and thus will not damage itself. The step-down buck converter, the ST1PS01, converts the battery voltage to a stabilized 2.0V. This voltage level feeds the MCU, BLE module and the sensors properly. The buck-boost converter, the RP604Z37, converts the battery voltage to a stabilized 3.7V to power the LEDs properly. The MCU monitors the State of Charge of the battery and sends a signal to the hospital when it dives under 20%. The dimensions of the power management circuitry is estimated on an area of 50mm^2 with a height of 2mm, excluding the wiring network and space in-between components. The battery is protected against over-charge, over-discharge, over-current and short circuit by the AP9211 single chip solution. It is concluded that the battery management meets all given requirements.

5
Overall design

This chapter discusses what the prototype should look and perform like. First, the physical characteristics will be discussed. Then a section will be devoted to how the system should be used.

5.1. Physical characteristics prototype

Figure 5.1, 5.2 and 5.3 show the top view, side view and bottom view respectively of the design of the sensor patch. The total size should be 3x7cm since this was recommended by Dr. Dudink [1]. The orange parts are flexible wires that interconnect the different parts. These flexible wires allow the prototype to be closer to the skin of the patient. Since the device needs to be reusable, it should be possible to clean the device. Therefore the device should be water- and alcohol proof. To this end, a silicon layer will be applied over the entire device. This will result in a flexible reusable device.
Additionally there will be 2 contact points on the silicon casing through which the battery can be charged.

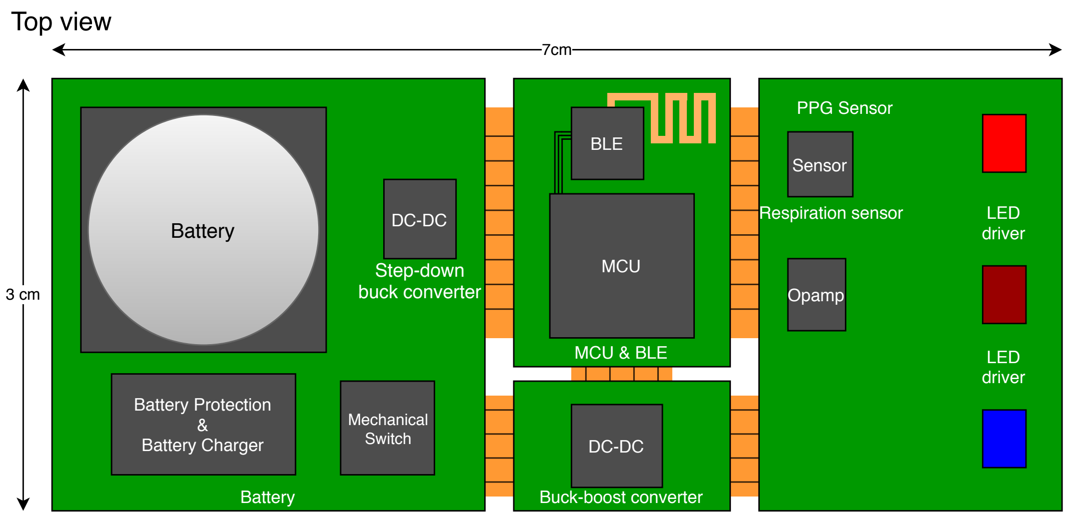

Figure 5.1: Top view of physical prototype

5.2. Results of final design

The photoplethysmography (PPG) sensor measuring heart rate, oxygen saturation and bilirubin levels has been designed to make accurate measurements theoretically possible. This was based on the following: sensor properties from papers describing similar PPG sensors, LED radiated power, attenuation and diffusion factors of the skin, photo-diode sensitivity and output currents and noise due to the amplification of the photo-diode output. However as no physical prototype has been made, no measurements could be per-

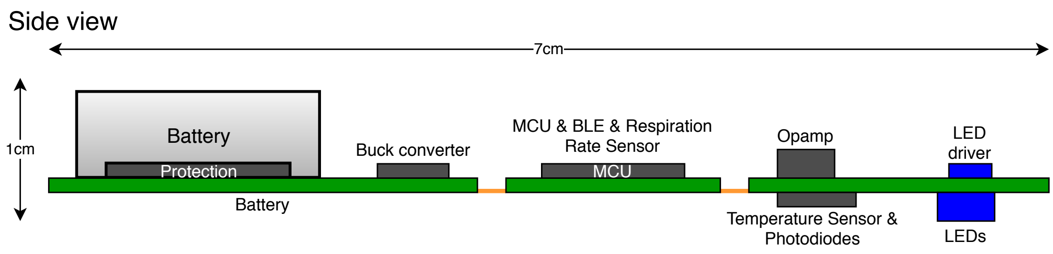

Figure 5.2: Side view of physical prototype

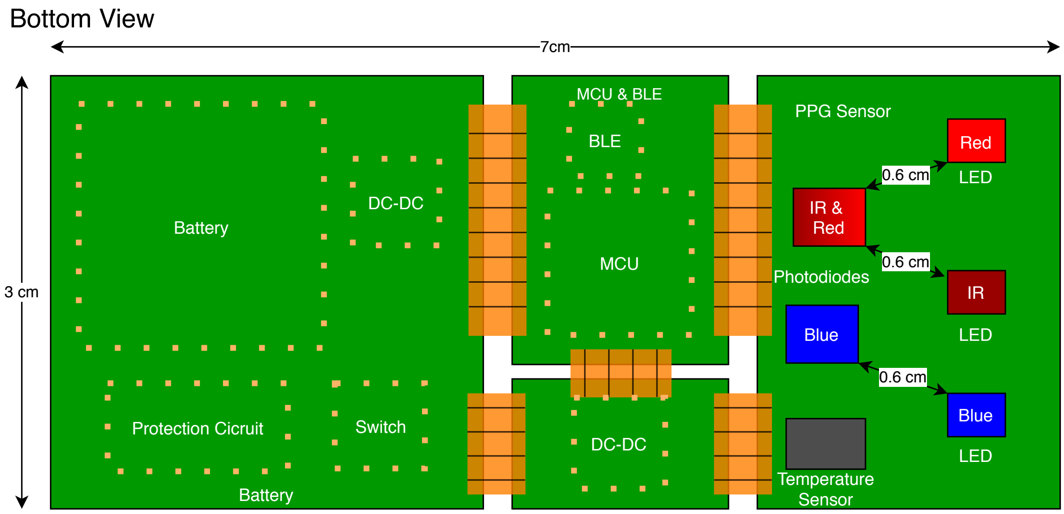

Figure 5.3: Bottom view of physical prototype

formed to proof the accuracy and measurement capabilities when performing measurements on patients.

The temperature sensor (Si7051) is able to perform accurate measurements within 0.1 degrees Celsius deviation between measured skin temperature and actual skin temperature. There is a correlation between skin temperature at the chest and internal core temperature [29]. Heart rate and chest movements are used for the correlation model and enable noninvasive methods to replace invasive methods to monitor patient core temperature.

The acceleration sensor (IIS2DLPC) produces 3 dimensional acceleration data with a acceleration resolution of 0.224mg. Using algorithms that remove large body movement components, a method for estimating respiration rate can be used to measure respiration rate [14]. Studies have shown that accurate respiration rates can be measured when using a 3D acceleration sensor with a sensitivity of 0.2mg and the appropriate signal processing techniques [25].
The total system consumes an estimated 52J in 3 days when it is attached to a newborn while measuring once every hour. This energy consumption is the sum of deep sleep, wake up, measurement, processing and transmission stages of every device separately. A visualisation can be seen in Figure 5.4. The sensor patch can last an estimated 3 weeks on one battery cycle.
The system is able to communicate its measurements wirelessly to a Bluetooth receiving device. This can either be a mobile phone, or some sort of base station which should be developed further.

5.3. Conceptual use case

5.3.1. Data access

In terms of usability, there are a few factors which should be considered. Firstly, this system will measure and transmit sensitive medical data. Only doctors or nurses, who would otherwise work in the maternity ward of the hospital shall be allowed insight into this information. Parents should not be able to view the

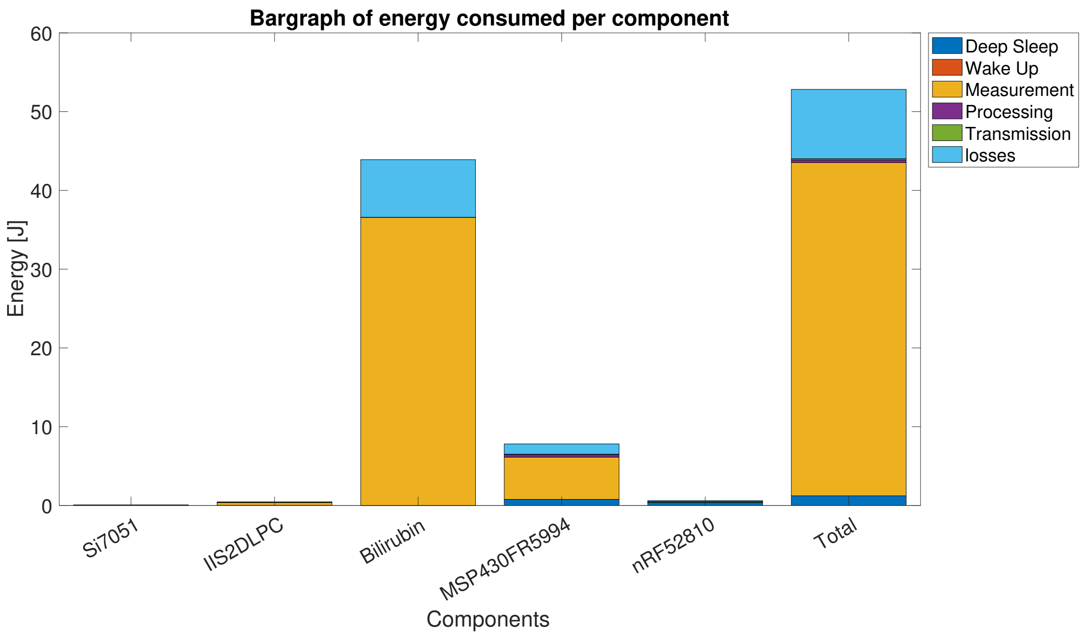

Figure 5.4: Energy usage per component divided per stage in the full system simulation.

measurements from the patch since they are not trained to interpret this medical information and the risk of unnecessary panic would be great. The purpose of this project is to replace maternity care and offer the possibility of medical monitoring from home, but this monitoring shall still only be interpreted by medical professionals.

5.3.2. Application of patch on skin

The first time the sensor patch is attached will be in maternity care. This will be done by a nurse. This way it is ensured that the sensor patch will be applied properly the first time, before the baby goes home. As described in further detail in Section 5.6, the patch will have an indicator which indicates if it is applied properly. Because of this indicator, parents at home could also reapply the patch properly in case this is needed.

5.3.3. Charging

The charging of the sensor patch will be done by trained individuals, to avoid accidental overcharging or damage to the system. This charging shall be done at the same location as the sterilisation of the devices as described in Section 5.4.

5.4. Sterilisation methods

The sensor patch can be categorised as a Semi-critical instrumentation, which means that it needs to be cleaned and disinfected [13]. Sterilisation often happens with alcohol and/or steam. The device will have a silicon layer around it as mentioned earlier. For this application, alcohol can be used to sterilise because silicone has good chemical resistance for alcohol [22].

5.5. Conclusion

As can be seen in Figure 5.1 the final design of the sensor patch does not exceed the required dimensions mentioned in 2. Furthermore, the designed sensor patch is able to measure the heart rate, temperature, oxygen saturation, respiration and bilirubin. The battery is able to supply enough power to perform measurements every 2 hours for 3 days. Moreover, the sensor patch is able to communicate wirelessly with an external device in order to send the measured data to a hospital where a doctor can access this data.

5.6. Future work

Some aspects of the design have not yet been addressed in this paper. In order to implement the sensor patch successfully, some aspects still need to be researched. They will be discussed in this chapter section.

Patch contact indicator

In order to receive accurate measurements from the sensor patch, it needs to be attached properly. Otherwise, the sensors might be too far away from the skin for accurate measurements. For this purpose, further work needs to be done into the development of some sort of indicator which will inform the user whether the patch is applied properly to the skin, so that the user can expect correct measurements.

PCB

A concept for the construction of a PCB and component placement has been made, however a design and testing procedure must take place in the future to realise a PCB with the correct placement and operation of components. The PCB design has to take into account aspects of comfort and durability to fulfil design requirements. Flexible PCBs or flexible cables need to be explored to see if the sensor patch can be somewhat flexible to make it fit better to the skin of the patient.

PCB housing

In order to protect the sensor patch from external influences, the patch needs a casing. This case must be completely closed and non transparent in order to block the ambient light which could influence the PPG sensors. However, this casing should not interfere with the Bluetooth communication. Furthermore, the casing should protect the electronics of the sensor patch from moisture like sweat. In order to increase user comfort the casing should be flexible. Also, charging points will need to be integrated in the PCB housing.

Method of attachment

No testing has been performed on how to apply the sensor patch to the patient. Some solutions have been conceived such as: using an adhesive material or tape to secure the sensor patch. These methods need to be explored and tested in the future to determine their capabilities of attaching the sensor patch for a period of three days. Water resistance can be a useful property for the method of attachment as this would enable the patient to take a bath while wearing the sensor patch and would prevent the patch from losing grip if the patient sweats.

Clinical trials

In order to calibrate the designed sensors, clinical trials on patients should be performed. The trials can be used to remove systematic errors in the measurements. Furthermore trials would also verify the performance of the sensors, for example the accuracy and repeatability of measurements. The trials will reveal potential issues in the design and may lead to the need of design alterations.

6 Conclusion and Future Work

6.1. Conclusion

The objective of the Bachelor Graduation Project was to develop a wireless sensor patch that monitors the health of the newborns. To this end, a theoretical design of the sensor patch is proposed to meet every requirement listed in the Program of Requirements (Chapter 2). This thesis focused on everything related to energy and power within the system. Energy storage, power and energy management and visualising data with the aid of a MATLAB model were the covered topics. The MATLAB model has been successfully designed. It gives a clear overview of the energy consumption of every device and of every operating stage.
The battery is chosen to be the CP1654A3. This battery is rechargeable and its dimensions are 16.1mm x 16.1mm x 5.4mm (L x W x H). The battery has an estimated 1254J of available energy that can be delivered over 3 days. The battery is able to provide a peak current of 360mA for 2s operating at 3.7V. The CP1654A3 battery meets the safety standards of hospitals, medical equipment and complies with safety legislation. The price is approximately cheaper than €50,-. It is concluded that the battery meets all the given requirements.
Extra circuitry next to the battery is designed and implemented to ensure proper functionality and safety. The integrated circuit LT4071 gives a wide voltage range in which the battery can be safely recharged and thus will not damage itself. The step-down buck converter, the ST1PS01, converts the battery voltage to a stabilized 2.0V. This voltage level feeds the MCU, BLE module and the sensors properly. The buck-boost converter, the RP604Z37, converts the battery voltage to a stabilized 3.7V to power the LEDs properly. The MCU monitors the State of Charge of the battery and sends a signal to the hospital when it dives under 20%. The dimensions of the power management circuitry is estimated on an area of $50mm^2$ with a height of 2mm, excluding the wiring network and space in-between components. The battery is protected against over-charge, over-discharge, over-current and short circuit by the AP9211 single chip solution. It is concluded that the battery management meets all given requirements. Chapter 5 concluded that all requirements for the total sensor patch were met. Therefore, all requirements listed in the Program of requirements (Chapter 2) are met.

6.2. Future Work

As stated in the previous section all of the requirements were met, but there is still room for improvement since this is the first iteration of the design. Therefore, several tasks can be done to improve sensor patch for the next iterations:

Energy Model

- It should be able to add components, like converters, into the energy model in order to take their losses better into account.
- It should be possible to select a battery and use it in the full system simulation so that battery specific losses are better calculated.
- A more general method can be designed and implemented to more easily and quickly compare different micro controllers and transmission modules.

Battery

- Examination of how much force is applied to the sensor patch, both during attachment and while the baby is carrying the device, can reveal whether pouch and prismatic batteries can be used and thus reduce the size of the battery.
- A better method to calculate the energy loss of a battery during peak currents could be explored as this could influence the battery choice.
- A temperature sensor close to the battery could be implemented in order to increase safety.
- If practice shows that the system works reliably, a smaller battery can be selected that exactly meets the energy needs calculated by the energy model.

Power management

- The voltage drops should be investigated more thoroughly. Every device or integrated circuit has decoupling capacitors to filter AC noise and to handle voltage drops.
- The state of charge monitoring should be further implemented with an algorithm in the MCU.
- Load switches should be selected in order to decrease deep sleep power further.
- The energy consumption per integrated circuit of the power management should be modeled and analyzed.
- The complex wiring network and placement of every component must be implemented correctly.

List of Figures

List of Tables

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A

Energy Estimation

It was first estimated that the sensor patch would consume no more than 0.25mW in deep sleep mode. Formula A.1 shows that this results in an energy consumption of 21.6J per day. The sensor subgroup estimated that their bilirubin sensor needs 10J per day and that other sensors never use more than 1.5J per day. The consumption of the microcontroller and transmission module has been estimated at 5J per day. Formula A.2 shows that this results in an estimated consumption of 47.6J, of course there is a big chance that there will be extra losses, so it was decided to have at least 50J per day available.

$$E_{DS} = 0.25 * 10^{-3} * 3600 * 24 = 21.6J; \tag{A.1}$$

$$E_{Estimate} = (E_{DS} + E_{Sensors} + E_{MCU\&Transmission}) = (21.6 + 10 + 1.5 + 5) * 1.2 = 47.63J; \tag{A.2}$$

B
GitHub link to the Energy Model

The Matlab code can be found on github with the following link: https://github.com/willemdl/Energy_Model

C

Battery choice

Table C.1: Comparison of lithium-ion chemistry's. [24, p. 82]

	Lithium iron phosphate	Lithium manganese oxide	Lithium titanium oxide	Lithium cobalt oxide	Lithium nickel cobalt aluminum	Lithium nickel manganese cobalt
Chemistry descriptor	LFP	LMO	LTO	LCO	NCA	NMC
Specific energy (Wh/kg)	90–120	100–150	60–80	150–200	200–300	150–280
Energy density (Wh/L)	190–300	250–360	170–230	400–600	490–675	325
Specific power (W/kg)	4000	4000	1000	1000	1000	1000–4000
Power density (W/L)	10,000	10,000	2000	2000	2000	2000–10,000
Volts (per cell)	3.3 V	3.7 V	2.3 V	3.6 V	3.6 V	3.7 V
Cycle life	5000–6000	300–700	>15,000+	500–1000	500	3000–4000
Self-discharge (% per month)	<1%	5%	2–10%	1–5%	2–10%	1%
Operating temperature range	−20°C to +60°C	−20°C to +60°C	−30°C to +75°C	−20°C to +60°C	−20°C to +60° C	−20°C to +55°C

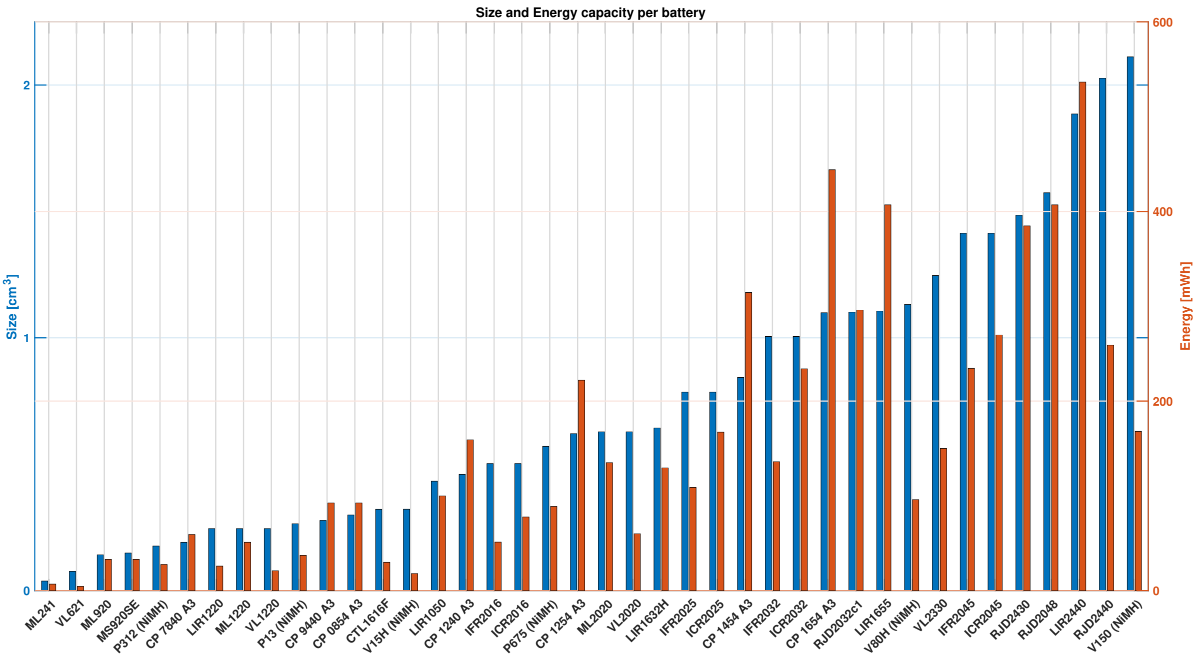

Figure C.1: Bargraph of the size and energy capacity of all the batteries

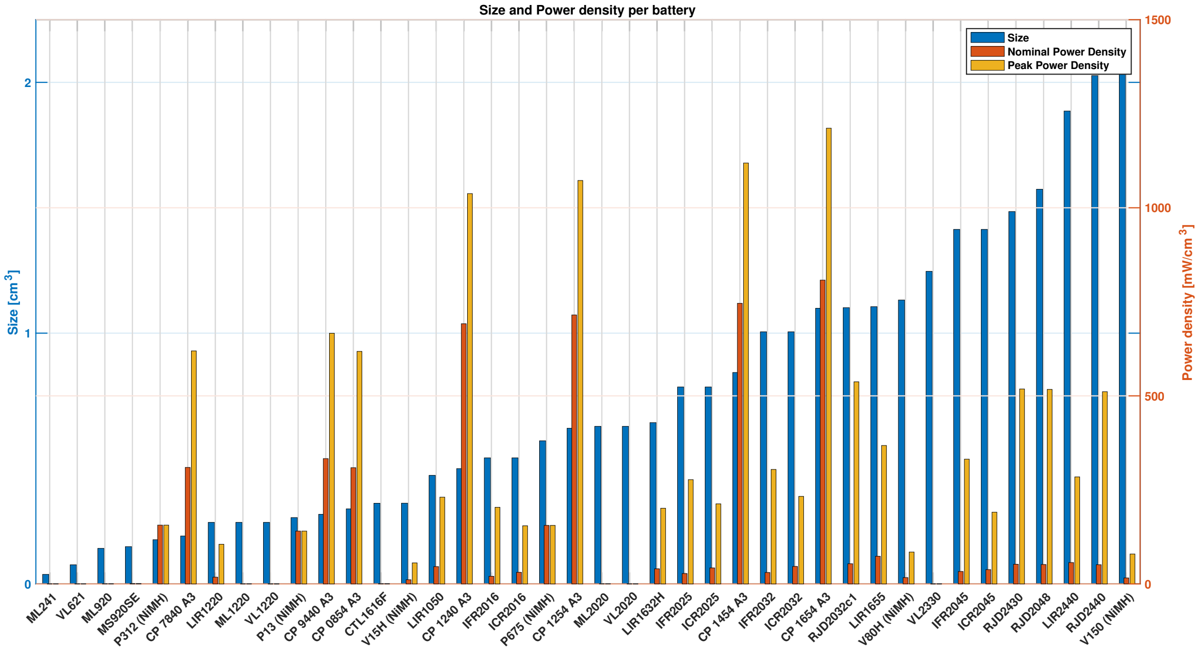

Figure C.2: Bargraph of the size and power density of all the batteries

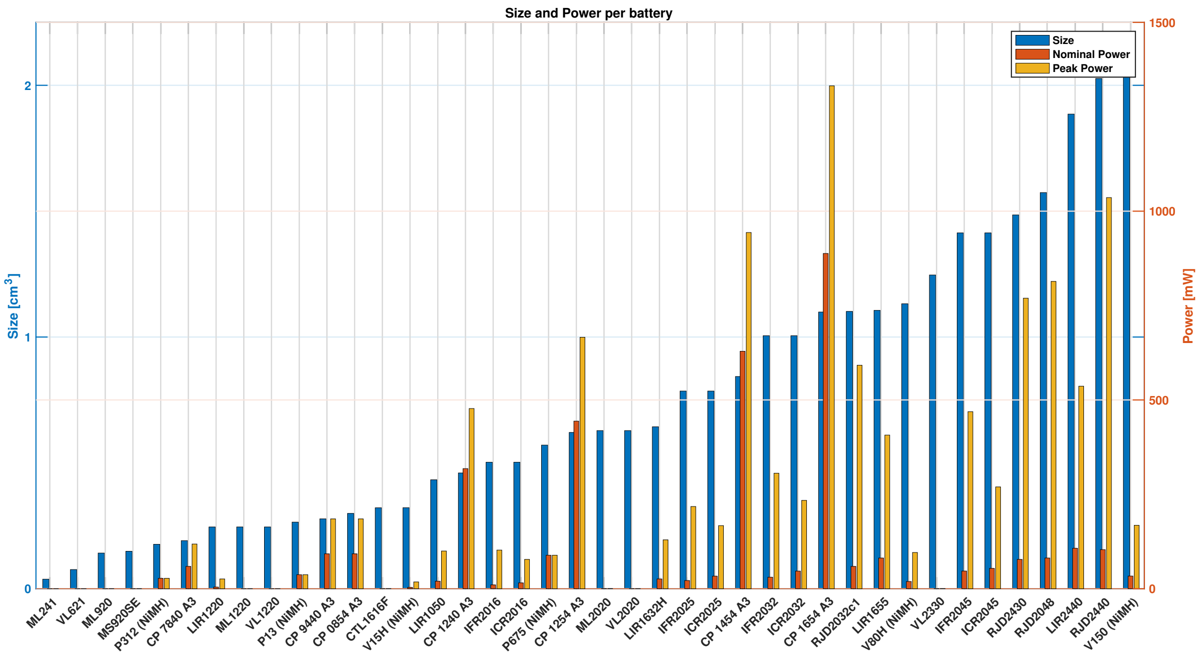

Figure C.3: Bargraph of the size and nominal&maximum power of all the batteries

D Energy Model

D.1. Sensor simulation Results

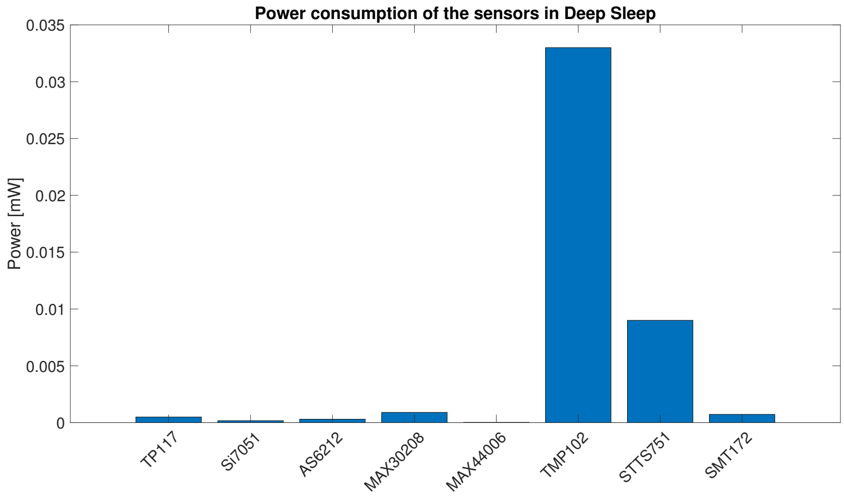

Figure D.1: Bargraph of the power consumption of sensors in deep sleep.

Table D.1: Table of the temperature sensors which have been used for the sensor simulation.

index	description of the parameter	unit	TP 117	Si 7051	AS 6212	MAX 30208	MAX 44006	TMP 102	STTS 751	SMT 172
3	default measurement rate.	[N / day]	24	24	24	24	24	24	24	24
4	Voltage at which the sensor operates.	[V]	3.3	2.8	3.0	1.8	18.000	3.3	3.0	3.3
5	Current drawn during measurement.	[mA]	0.1350	0.0900	0.0400	0.0670	0.0100	0.0070	0.0500	0.0600
6	Time it takes to do 1 measurement.	[s]	0.0155	0.0070	0.0360	0.0150	0.4000	0.0260	0.0840	0.0018
7	Time to process the data of 1 measurement based on a clock frequency of 32Mhz.	[s]	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
8	current drawn during standby / deepsleep.	[mA]	0.0001	0.0001	0.0001	0.0005	0.0000	0.0100	0.0030	0.0002

D.2. Parameters used for the Full system simulation

In order to calculate the energy consumption of a component, certain properties must be known. In the tables below it is indicated which parameters per sensor, MCU and transmission module have to be filled in so that they can be used in the simulations. In addition, the parameters of the components used are displayed in adjacent columns. The index column shows the index used in the Matlab code to address the specific parameter. This doesn't start on 1 because in one of the earlier versions the name was saved there, the saving of the names has been changed later and the indexing of the parameters hasn't been changed yet because many places in the code are affected by this change.

Table D.2: Table of the structure of the parameter variable of the Sensor class.

index	description of the parameter	unit	Si7051	IIS2DLPC	Bilirubin
3	default measurement rate.	[n times per day]	24	24	24
4	Voltage at which the sensor operates.	[V]	2.8	1.8	3.7
5	Current drawn during measurement.	[mA]	0.09	0.09	45
6	Time it takes to do 1 measurement.	[s]	30	30	3
7	Time to process the data of 1 measurement based on a clock frequency of 32Mhz.	[s]	0.0010	0.0010	0.0010
8	current drawn during standby / deepsleep.	[mA]	0.0001	0.0001	0

Table D.3: Table of the structure of the parameter variable of the MCU class.

index	description of the parameter	unit	MSP430FR5994
2	Default measurement rate.	[n times per day]	24
3	Voltage at which the microcontroller operates.	[V]	3.0
4	Current drawn when active.	[mA/MHz]	0.185
5	Extra time in active mode.	[s]	2.0
6	Wake up time.	[s]	0.0010
7	Current drawn during standby / deepsleep.	[mA]	0.001
8	Base clock frequency.	[MHz]	4.0

Table D.4: Table of the structure of the parameter variable of the Transmission class.

index	description of the parameter	unit	nRF52810
2	default transmission rate.	[n times per day]	24
3	Voltage at which the transmission module operates.	[V]	3
4	Current drawn during Tx.	[mA]	7
5	Time of Tx.	[s]	0.0015
6	Current drawn during Rx.	[mA]	7
7	Time of Rx.	[s]	0.0005
8	Current drawn during other time.	[mA]	4
9	Time of other "standard" operation.	[s]	0.25
10	Current drawn during deep sleep.	[mA]	0.0005

D.3. Full system simulation

noemen welke sensoren gebruikt zijn, welke tijd de simulatie gerund is dagen , interval ieder uur, losses0.20

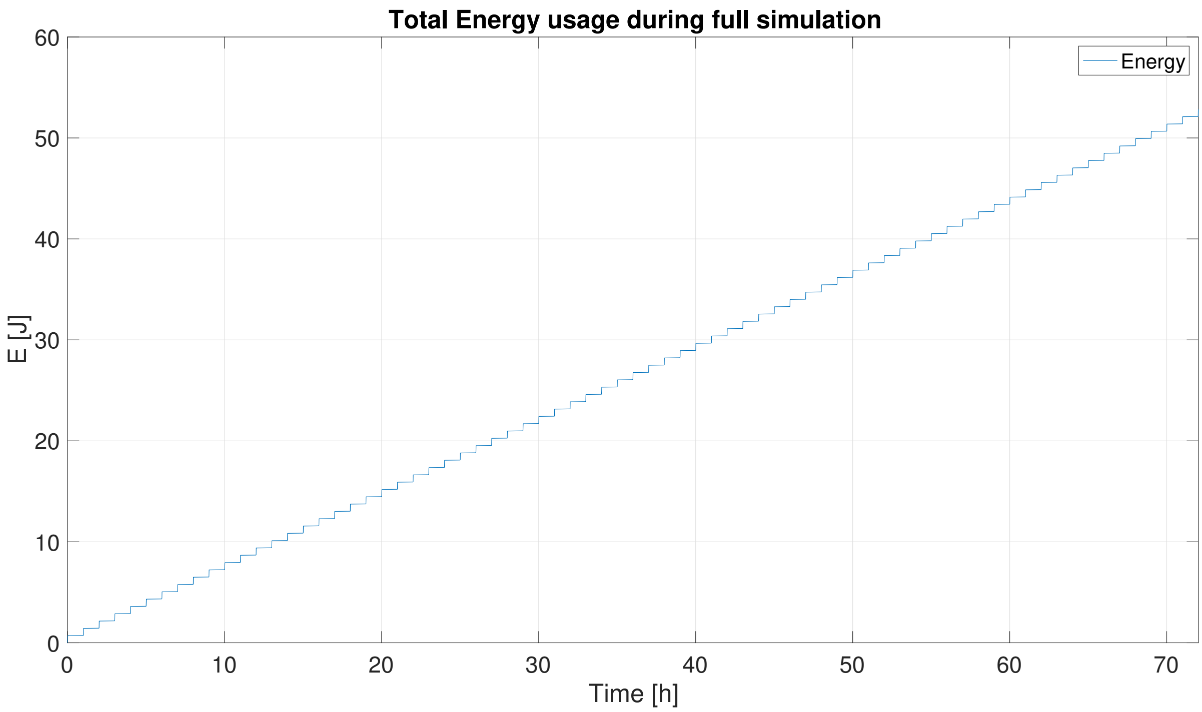

Figure D.2: Total energy usage in the full system simulation of the sensor patch.

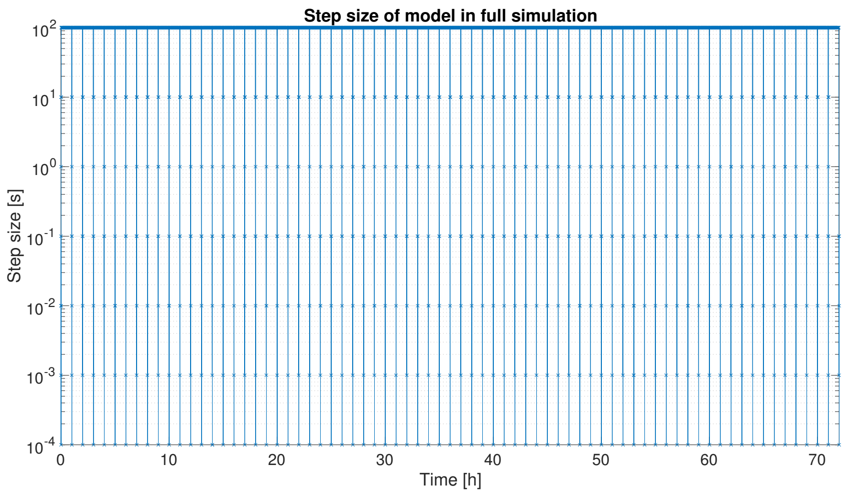

Figure D.3: Change in step size in full system simulation of the sensor patch for 3 days.

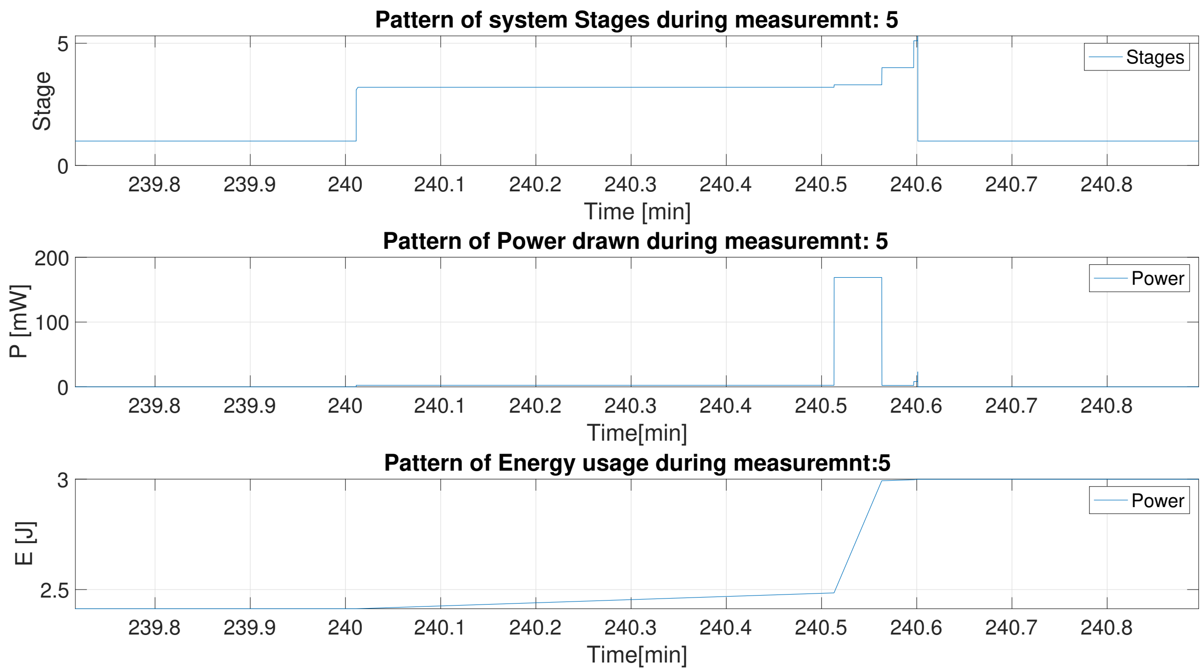

Figure D.4: Plots of one specific measurement during the full system simulation of the sensor patch.

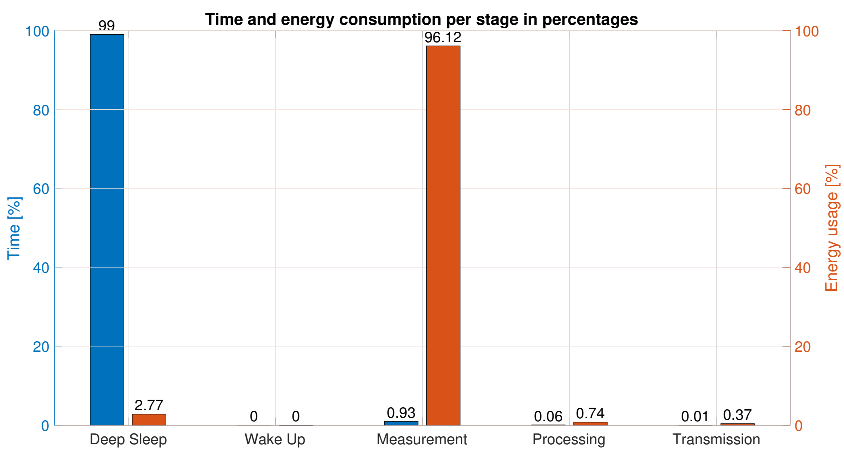

Figure D.5: Distribution of time and energy (in percentages) over the different stages in the full system simulation of the sensor patch.

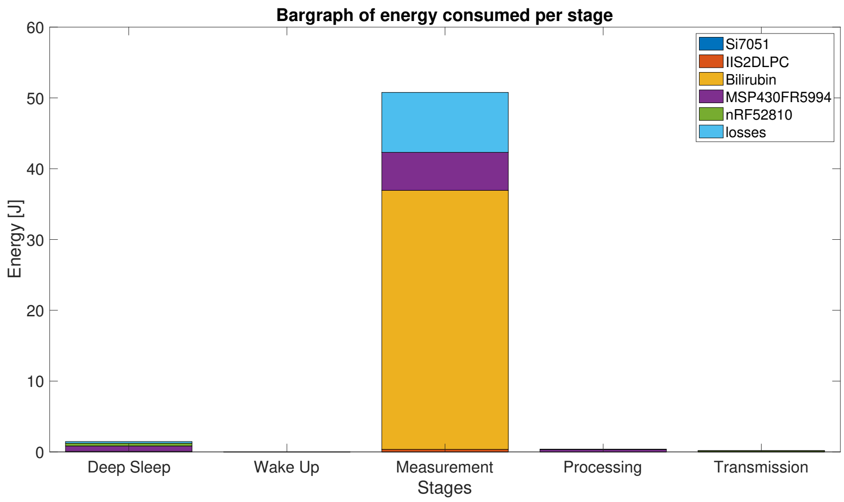

Figure D.6: Energy usage per stage divided per component in the full system simulation.

D.4. overige

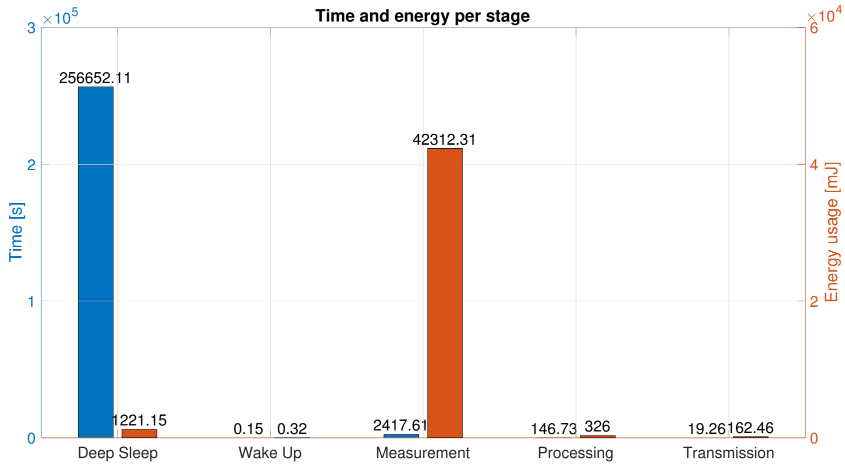

Figure D.7: Distribution of time and energy over the different stages in the full system simulation of the sensor patch.

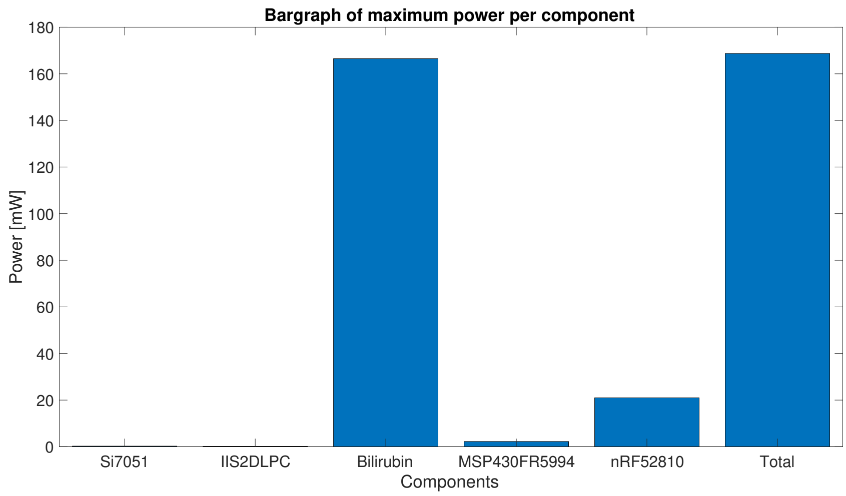

Figure D.8: Maximum power drawn per component in the full system simulation.

E

Converter Effciencies

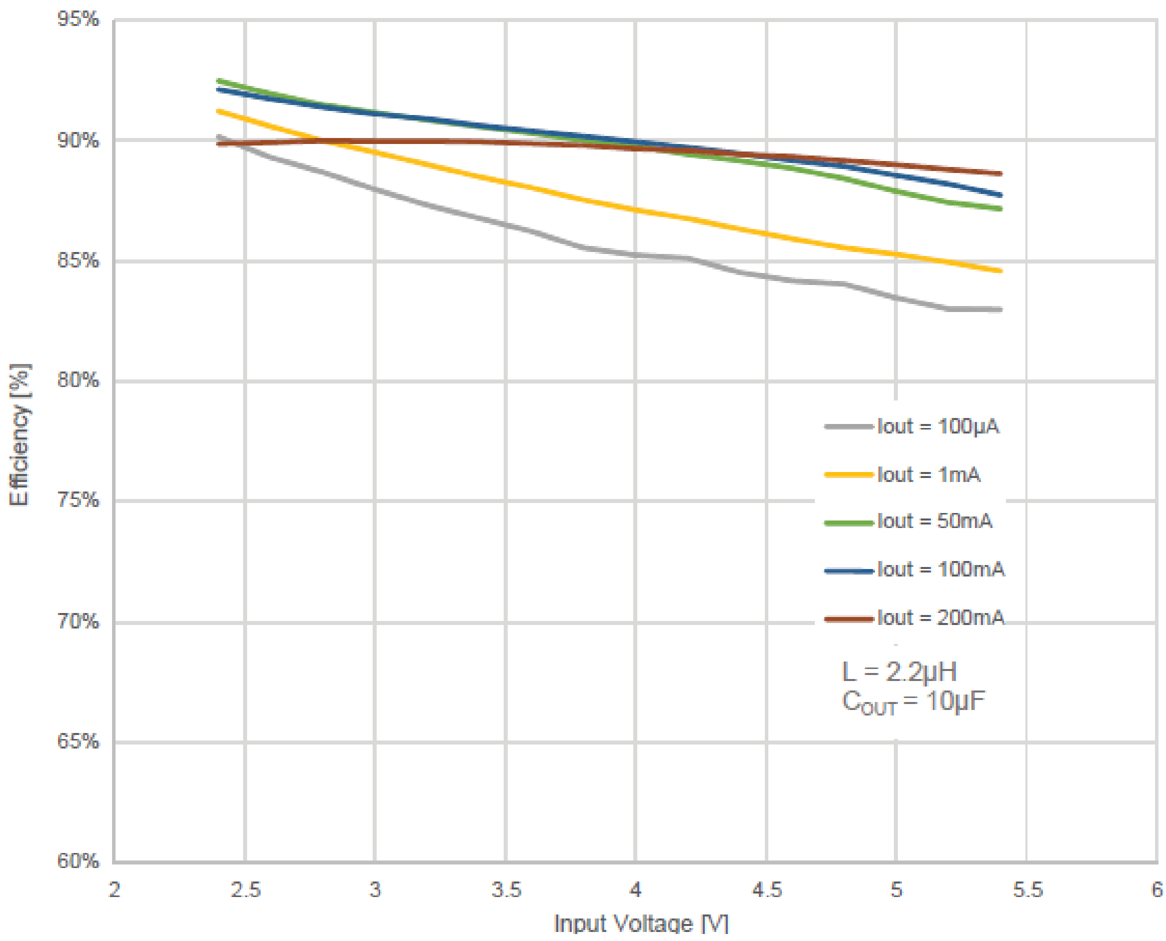

Figure E.1: Buck converter: Efficiency vs. Input voltage, Output voltage = 1.8V

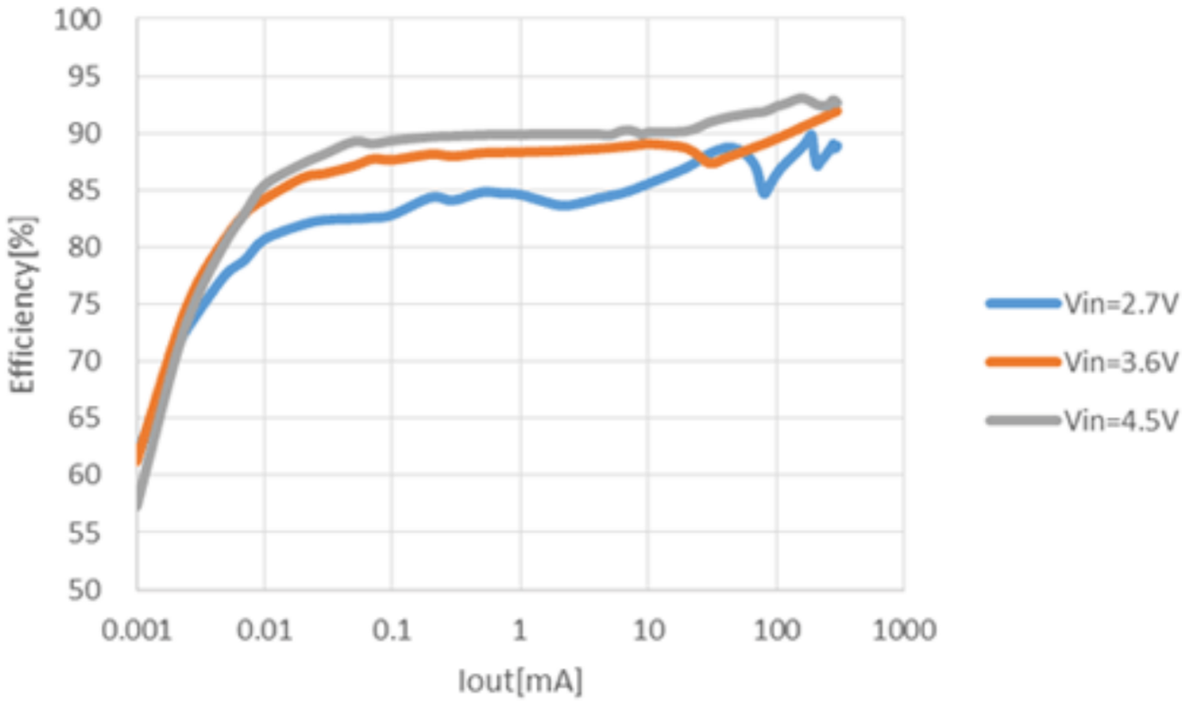

Figure E.2: Buck-boost converter: Efficiency vs. Input voltage, Output voltage = 5.0V

F

List of Components

Table F.1: The components needed to implement all circuitry

Components	Qty	Dimensions (L x W x H) [mm]	Price estimation [€/qty]
Battery CP1654 Li-ion battery	1	16.1 x 16.1 x 5.40	50 (max)
Power Management			
Buck converter:			
ST1PS01AJR step-down converter	1	1.44 x 1.14 x 0.60	1.18
1.0MΩ Resistor	2	0.50 x 1.00 x 0.50	0.01
10μF Capacitor	1	1.00 x 2.00 x 1.00	0.08
2.2μH Inductor	1	3.00 x 3.00 x 1.50	0.25
Buck-boost converter:			
RP604Z37 buck-boost converter	1	3.00 x 3.00 x 0.80	1.43
22μF Capacitor	1	1.00 x 2.00 x 1.00	0.08
10μF Capacitor	1	1.00 x 2.00 x 1.00	0.08
2.2μH Inductor	1	3.00 x 3.00 x 1.50	0.10
Battery protection:			
AP9211 Protection IC	1	3.00 x 2.10 x 0.60	0.37
LTC4071 Battery Charger	1	3.00 x 2.00 x 1.10	2.51
36Ω Resistor	1	0.50 x 1.00 x 0.50	0.01
400Ω Resistor	1	0.50 x 1.00 x 0.50	0.01
2.7kΩ Resistor	1	0.50 x 1.00 x 0.50	0.01
1.0MΩ Resistor	1	0.50 x 1.00 x 0.50	0.01
1.4MΩ Resistor	1	0.50 x 1.00 x 0.50	0.01
100nF Capacitor	2	1.00 x 2.00 x 1.00	0.08
TOTAL	19		56.2