# ONLINE SLEEP MONITORING SYSTEM

D.T2.1.3 - Design of platform

Version 1
09 2020

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# 1. Introduction

The online sleep monitoring system is a web-based application for modern remote (in-home) and non-invasive sleep assessment and monitoring for patients suffering from a variety of neurodegenerative disorders such as Alzheimer's disease and/or Parkinson's disease and many others. It takes advantage of the state-of-the-art approach towards using wearable technologies for measuring human wellbeing and fitness. Specifically, the designed online sleep monitoring system uses the actigraphy bracelet device to record a set of the body-level and other signals such as an acceleration of a hand in 3D (x, y, and z axes), temperature, light level, etc. in time. These signals are then safely stored and transferred to be processed and parametrised using specifically designed advanced digital signal processing algorithms to compute the hidden and possibly complex characteristics of the acquired data, and state-of-the-art machine learning techniques to predict, assess, and monitor the presence of sleep disorders. The system is designed to provide clinicians with a convenient way of measuring and analysing the sleep-related data.

This document aims at describing the most important information regarding the design of the online sleep monitoring system. It summarises the architecture of the system (a questionnaire, client-server application, etc.), the analytical modules at the backend level of the system, parameterisation of the signals acquired by the actigraph, prediction, and assessment of sleep as well as the frontend and visualisation parts. It also describes the graphical user interface and UX, data protection and security, testing, and other aspects of the application that played a key role in its design towards preparing a system that will provide us with the tool that helps the doctors around the EU (and hopefully the world) with faster, remote, and cost-effective identification and monitoring of sleep disorders that can be applied in day-to-day clinical practice.

# 2. Overview of the online sleep monitoring system

## 2.1. Motivation to introduce the online sleep monitoring system

The trend is clear, improved and more affordable medical care and better living conditions in developed countries have increased both health and life expectancy, from approx. fifty years in the early 1900s to over 80 years now. In one hand, this is desired, but on the other hand, this brings new important concerns and situations that need to be handled accordingly. In general, ageing is characterized by a progressive loss of physiological integrity leading to impaired function and increased vulnerability to death. This deterioration is the primary risk factor for major human pathologies, including cancer, stroke, diabetes, various cardiovascular disorders as well as a variety of neurodegenerative diseases such as Alzheimer's disease (AD) or Parkinson's disease (PD) [1, 2], etc. Moreover, approximately 7% of adults over 65 years suffer from dementia, and this number raises up to nearly 30% for adults over 85 years [3].

At present, dementia is an incurable disease associated with irreversible impairment and loss of cognitive abilities. The major symptoms of dementia include the progressive decline and eventual loss in cognitive skills, such as memorizing, thinking, reasoning, and speaking [4]. Alzheimer's disease is the most common neurodegenerative disorder characterized by the loss of memory and reduction in cognitive functions due to progressive deterioration of brain tissue, eventually leading to death [5]. AD accounts for approx. 60–70% of age-related dementia [6]. Currently, no treatments are available to stop, slow, or reverse the progression of this disease [7], whereas symptoms of AD gradually worsen with time. In its early stages, memory loss is mild, but with late-stage AD, patients lose the ability to carry on a conversation and respond to their environment. Parkinson's disease is the second most common neurodegenerative disorder [8] associated with the progressive loss of dopaminergic neurons in substancia nigra pars compacta [9]. The primary motor symptoms of PD consist of tremor at rest, muscular rigidity, progressive bradykinesia, and postural instability [9]. Patients with PD also develop additional non-motor symptoms such as dysarthria, depression, cognitive impairment [10], etc. It has been estimated that a quarter of patients with PD have dementia [11] while 80% eventually develop dementia in the long term [12].

By 2050, there will be around 10 billion people on earth, and the population ages, the number of older people who develop any/a combination of the previously mentioned problems will also increase [13]. Currently, older adults may experience healthcare in various settings, such as hospitals, assisted living facilities, or in some cases, they can be treated at home. These situations can affect the health and function of older adults and therefore require careful management to ensure proper care and improve or maintain quality of life for as long as possible. These facts will likely result in an immense health issue with increasing economic burdens to health care systems worldwide [14]. For this purpose, various in-home remote systems for the analysis, monitoring and treatment of various age-related diseases such as PD or AD are being developed all around the world. The hope that the entire world has it in the near future and we will be able to develop modern tools that will enable early and precise identification of such diseases and allow us to slow down the process of neurodegeneration and improve the patient's quality of life.

Recently, rapid eye movement sleep behaviour disorder (RBD) has been identified as a prodromal marker of PD [15, 16]. Moreover, it has been shown that RBD is a symptom that may precede PD by decades [17]. It is therefore getting more and more obvious that early identification of RBD will play a key role in the diagnosis of PD in its early (prodromal) stages that can be crucial for the development of disease-modifying treatment as it is known that the neurodegeneration may be treated and possibly stopped before the pathological cascades even start. Nowadays, the diagnosis and monitoring of sleep disorders and RBD, in particular, is conventionally performed overnight using polysomnography at a hospital/sleep clinic. Although polysomnography is the gold standard for sleep quality assessment, it can be invasive, disruptive to sleep as well as expensive. For this purpose, other approaches have been extensively investigated. One such approach is the use of actigraphy. The actigraphy is much more comfortable than polysomnography, the price of an actigraph is approximately EUR 300, and it can be used repeatedly while requiring battery exchange after several years. In addition to that, it is not bound to a patient's presence at a sleep clinic and therefore allows for in-home sleep assessment and monitoring. Hence it is no surprise that there are various applications for an online sleep monitoring tool such as the assessment of exploding head syndrome, sleep terror, narcolepsy, idiopathic hypersomnia, etc.

The concept of the online sleep monitoring system is to create a modern, web-based system that will provide clinicians with an intelligent platform to acquire, collect, and analyse data from actigraphs to indirectly predict, assess, and monitor sleep disorders in patients suffering from neurodegenerative disorders in relation with RBD. This concept is in line with the trend towards virtualisation of medical care via utilising wearable technologies, digital signal processing techniques and machine learning algorithms. The ultimate goal is to move as many parts of the events/procedures to patients' homes where they feel safe and comfortable. The achievement of this goal is going to bring down the costs related to the medical care that is of great importance for future generations that will have to face the increasing growth of the population. Furthermore, the online sleep monitoring system is not limited to any specific country as PD is the most common neurodegenerative condition after AD affecting an estimated 1.2 million people in Europe alone with the incidence of PD being forecasted to double by 2050 primarily as a result of the ageing population. Therefore, an actigraphy-based sleep monitoring tool has a high potential to be used in the entire EU, to make the acquisition, analysis, assessment, and monitoring of sleep data more accessible and easier to deploy aiming at day-to-day use in clinical practice.

## 2.2. Presentation of the use-case(s)

The online sleep monitoring system is designed to enable easy, in-home sleep quality measurement, assessment, and monitoring using affordable wearables and modern technologies. From the high-level perspective, the targeted use-case can be described as follows:

1. A patient at risk of having/developing sleep disorders (as mentioned in the previous section, this can be a prodromal market of developing a neurodegenerative disorder such as PD/AD, etc.) borrows an actigraph from a doctor.
2. Next, he/she wears it for a couple of days during sleep according to the instructions provided by the doctor to acquire large enough data sample to be analyzed by the sleep monitoring system to compute relevant features describing the potential sleep-related problems and to assess and/or monitor the quality of sleep aiming at early identification of the development of a sleep disorder.
3. Then, he/she uploads the sleep data via the web interface/or brings the actigraph to the doctor for the processing and prediction/assessment. And finally, he/she gets a detailed report about his/her sleep from the doctor that is going to act accordingly.

This simplified use case scenario can be seen in Figure 1 (1-2: data acquisition. 3: data storage, processing and analytics, 4: sleep report combining the output of the sleep monitoring system and the doctor's expertise in the given field).

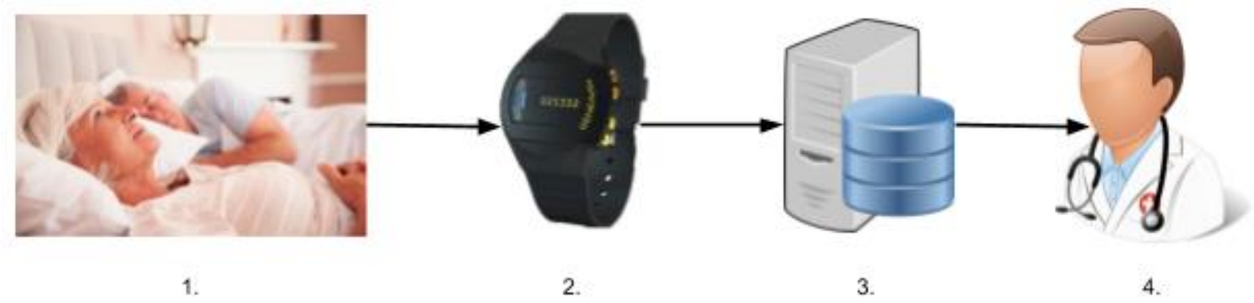


**Figure 1: Use-case scenario: sleep data acquisition (1-2), processing (3), and assessment (4).**

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**Table 1: Responsibility assignment matrix.**

| | subject | researcher | technician | coordinator |
|---|---|---|---|---|
| Actigraph configuration | I | R | | A |
| Data acquisition | R | A | | |
| Control visit | R | A | | I |
| Data downloading | I | R | | |
| Data preprocessing | | R | A | A |

| | | | | |
|---|---|---|---|---|
| Data upload to the system | | R | A | |
| Server configuration | | I | R | A |
| User-accounts management | | I | R | A |
| Data tagging | | | I | R |
| Machine learning model definition | | | I | R |
| Machine learning model training | | | R | A |
| Machine learning model application | | | R | I |
| Results interpretation | | I | R | R |
| Results publication | I | I | R | A |

After the system is deployed (in real clinical use), there can be another role. Besides a patient and a doctor, there is an administrator. This is a person who is responsible for the management of the system, e.g. creating/editing/removing of doctor accounts or patient accounts. The use case scenario is described in more details in the next sub-sections.

### 2.2.1. Use case: doctor

A doctor provides a patient with an actigraph and some instructions regarding wearing it. The patient wears the actigraph during sleep. After some certain number of days (depending on the kind of analysis) the patient uploads the data from the actigraph via the online web interface, or he/she sends/brings the actigraph back to the doctor (who uploads it on behalf of him/her). The doctor is then able to create a patient's profile in the system and to manage/edit this profile. The profile can be shared among several doctors. After the data are uploaded, the doctor can visualize them, compare (e.g. among several days or patients), parametrize (extract sleep measures), and apply the trained machine learning models (e.g. to detect sleep stages, specific sleep disorders, etc.). The system also enables to export the data into commonly used formats.

### 2.2.2. Use-case: patient

A patient wears a borrowed actigraph during sleep according to the instructions given by a doctor to collect sleep data for the consequent processing and analysis. After the data is collected, a patient is be able to upload the data into the system via his/her profile. If allowed by a doctor (who manages the rights along with an administrator (for more information, see below)), he/she can see a part of or the results of the analysis.

### 2.2.3. Use-case: administrator

An administrator has the same rights as the doctor(s) or the patient(s). Besides, he/she can create or manage profiles of doctors/patients, etc. He/she is also able to manage the user interface, processing pipelines, etc. In this regard, an administrator takes care of the system in terms of its functionality, security, management, etc. so that a doctor can focus on the medical tasks taking advantage of the system without additional burden related to the system's operation.

## 2.3. Electronic survey about digital innovations

During the design of the online sleep monitoring system, we created an electronic survey to capture the opinion of the general public about digital innovations in the field of medical care and health in general. The survey provided us with important information about the impact of technological innovation, future directions, the feeling about wearables, etc. This information was used to design the system in a way that will be easily acceptable and adoptable by the end-users, especially by elderly as they are in general not that used to modern wearable technologies and if they do not feel comfortable, safe, and they do not believe in the technologies, they are less likely to end up using it. The transcript of the survey can be seen bellow (The results/statistics about the survey will be summarized in the upcoming deliverable D.T2.1.4 that will present the testing of the system).

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Opinion about digital innovations in the field of medical care and health

Please think about science and technology

**Q1: In your opinion, 15 years from now, what impact will science and technological innovation have on medical care and health?**

| | | | |
|---|---|---|---|
| Negative impact | No impact | Positive impact | I don’t know |

**Q2: In your opinion, do the following technological innovations have an impact on medical care and health to date?**

| | | |
|---|---|---|
| Health-apps | Yes | No |
| Wearable devices, such as bracelets, step-counters, smart-watches, etc. | Yes | No |
| Telemedicine services, to monitor and manage the disease at home | Yes | No |
| Online social networks, to communicate, promote health, create networks of patients with the same disease | Yes | No |

**Q3: In your opinion, will the following technological innovations have an impact about medical care and health at three years?**

| | | |
|---|---|---|
| Health-apps | Yes | No |
| Wearable devices, such as bracelets, step-counters, smart-watches, etc. | Yes | No |
| Telemedicine services, to monitor and manage the disease at home | Yes | No |
| Online social networks, to communicate, promote health, create networks of patients with the same disease | Yes | No |

**Q4: In your opinion, what is the utility of health-apps and wearable devices on the following aspects of medical care and health?**

| | | | |
|---|---|---|---|
| To be engaged in one’s own health | Useful | Not useful | No effect |

| | | | |
|---|---|---|---|
| To improve patient-doctor communication | Useful | Not useful | No effect |
| To understand one's own health condition | Useful | Not useful | No effect |
| To reduce costs of healthcare | Useful | Not useful | No effect |
| To boost compliance | Useful | Not useful | No effect |

**Please answer the following questions about health-apps and wearable devices**

**Q5: Do you use some of the following health-apps and wearable devices?**

| | | |
|---|---|---|
| **Diet app**: to take note of calories, manage diet, receive text message of encouragement, for example to lose weight | Yes | No |
| **Informative app**: to search for information about health or disease | Yes | No |
| **Fitness app**: to monitor physical activity, collect data about running, walking or cycling | Yes | No |
| **Monitoring app**: to control the disease and symptoms through sensors or external devices measuring medical parameters to share them with the doctor, etc. | Yes | No |
| **Therapy app**: to increase compliance, receiving text message that remind you to take pills or complete therapy diaries | Yes | No |
| **Self-check app**: to check symptoms | Yes | No |
| **Services app**: to schedule visits/exams or view a medical report | Yes | No |
| **Fitness wearable**: to check physical activity | Yes | No |
| **Weight wearable**: to check weight | Yes | No |
| **Blood pressure wearable**: to check heart rate and blood pressure | Yes | No |
| **Glycaemia wearable**: to check blood sugar | Yes | No |
| **Sleep wearable**: to check rhythm and quality of sleep | Yes | No |

**Q6: In your opinion, which are the obstacles in using health-apps and wearable devices?**

| | | |
|---|---|---|
| Technical obstacles, for example not having a suitable device | Yes | No |
| Personal motivations, for example not being able to use them | Yes | No |
| Little faith in usefulness of data recorded | Yes | No |
| Low trust in confidentiality and privacy of data | Yes | No |
| Low trust in accuracy and reliability of data recorded | Yes | No |
| Lack of examples of their usefulness for medical assistance | Yes | No |

**Q7: In your opinion, on which health-apps and wearable devices might the developers focus to give more useful tools to improve medical assistance and health?**

| | | |
|---|---|---|
| **Diet app**: to take note of calories, manage diet, receive text message of encouragement, for example to lose weight | Yes | No |

| | | |
|---|---|---|
| **Informative app**: to search for information about health or disease | Yes | No |
| **Fitness app**: to monitor physical activity, collect data about running, walking or cycling | Yes | No |
| **Monitoring app**: to control the disease and symptoms through sensors or external devices measuring medical parameters to share them with the doctor, etc. | Yes | No |
| **Therapy app**: to increase compliance, receiving text message that remind you to take pills or complete therapy diaries | Yes | No |
| **Self-check app**: to check symptoms | Yes | No |
| **Services app**: to schedule visits/exams or view a medical report | Yes | No |
| **Fitness wearable**: to check physical activity | Yes | No |
| **Weight wearable**: to check weight | Yes | No |
| **Blood pressure wearable**: to check heart rate and blood pressure | Yes | No |
| **Glycaemia wearable**: to check blood sugar | Yes | No |
| **Sleep wearable**: to check rhythm and quality of sleep | Yes | No |

**Q8: In your opinion, which negative aspects could be related to a constant adoption of health-apps and/or wearable devices?**

| | | |
|---|---|---|
| Dependence | Yes | No |
| No privacy | Yes | No |
| Excessive control of one's own health | Yes | No |
| Increasing medicalization, for example through an over-use of drugs, supplements, medical devices or scheduling visits even if they are not needed | Yes | No |
| Compromising patient-doctor communication | Yes | No |

**Please answer the following questions about yourself**

**Sex: / M / F /**

**Age: /__/__/**

## 2.4. Separation of concerns

The online sleep monitoring system is designed as a modern client-server web application with all of the trending concepts (separation of concerns, model view controller architecture, modularity, flat design, etc.) in mind. The frontend part of the system serves for the purpose of interactivity and presentation of the results to a patient (and other people involved in the operations) as well as a gate into the system itself (used by all parties involved, e.g. patient(s), doctor(s) as well as administrator(s), and possibly others). The backend part of the system serves for the purpose of data storage, data processing, data analysis, data/user/access/rights, etc. management, results generation, communication with the frontend part, etc. It provides a computational power to the analysis and uses the frontend part to interact with the end-users.

As mentioned in the section 2.2 (presentation of the use case(s)), there are multiple steps from the perspective of the system's technical architecture and design such as data acquisition, data processing, machine learning (sleep prediction), etc., that are described in this document.

## 2.5. Data acquisition

ActiGraph is a device dedicated to providing end-users with highly accurate, innovative, cost effective and objective monitoring solutions for sleep monitoring (among other capabilities). There are many manufacturers on the market offering various actigraphs that differ in many sleep monitoring-related characteristics such as the internal memory, battery capacity, presence of an accelerometer, temperature measurement(s), etc., as well as other important factors such as the material/quality of the casing, data transfer possibilities, price, and many others. Before the system's designed, the following actigraphs were compared among each other in order to use the most suitable one given its characteristics and price.

The key characteristics (i.e. battery capacity, memory capacity, presence of the accelerometer(s), presence of the thermometer(s), etc.), and overview of the compared commercially available devices for sleep monitoring can be seen in Table 2:

1. Mbientlab 9-axis IMU [18].
2. Actigraph wGT3X-BT [19].
3. Activinsights GENEActiv [20].
4. Philips Respironics Actiwatch Pro [21].
5. Fitbit Charge 3 [22].
6. Mobvoi Tiewatch E [23].
7. Misfit Vapor [24].
8. Garmin Vivoactive3 [25].
9. Samsung Fit2 Pro [26].

**Table 2: Overview of the commercially available devices for sleep monitoring [18].**

| | Actigraph model name | Battery capacity | Memory capacity | Presence of accelerometer | Presence of thermometer |
|---|---|---|---|---|---|
| **Mbientlab** | 9-axis IMU | 7 days | 8 Mb | Yes | No |
| **ActiGraph** | wGT3X-BT | 25 days | 4 Gb | Yes | Yes |
| **Activinsights** | GENEActiv | 45 days | 4 Gb | Yes | No |
| **Philips Respironics** | Actiwatch Pro | 60 days | 32 Mb | Yes | No |
| **Fitbit** | Charge 3 | 7 days | Unknown | No | Yes |
| **Mobvoi** | Tiewatch E | 2 days | 4 Gb | Yes | Yes |
| **Misfit** | Vapor | 2 days | 4 Gb | Yes | Yes |
| **Garmin** | Vivoactive3 | 7 days | Unknown | Yes | Yes |
| **Samsung** | Fit2 Pro | 3 days | 4 Gb | Yes | Yes |

After the comparison, the lightweight, waterproof, wrist-worn actigraph GENEActiv from Activinsights [20] was chosen for the sleep data acquisition in the monitoring system. Among other benefits, it provides open-source analytics and open SDKs, it is ergonomic, and it has an aesthetically neutral design with maximum subject acceptance and wears compliance, which is also essential especially for elderly people. The GENEActiv actigraph can be seen in Figure 2.


**Figure 2: GENEActiv actigraph device (bracelet) [18].**

### 2.5.1. Actigraph bracelet

To describe the selected actigraph bracelet in more detail: GENEActiv is a reliable body-worn accelerometer that measures and tracks everyday living in all environments. It offers 0.5 Gb of raw data in an open format and comes as a fully waterproof instrument with one month of battery life. Unlike other accelerometers, the GENEActiv instruments are waterproof and can be worn 24 hours a day. A near-body temperature sensor confirms wear time, and an accurate and configurable clock allows data to be matched to a reported activity or other measures. The GENEActiv instruments are charged in a cradle connected to a USB power source. The cradle also allows them to communicate with the GENEActiv software, which is used to configure the instruments and download and manage the recorded data. The components of the GENEActiv Kit (USB cable, cradle, and the GENEActiv instrument itself) can be seen in Figure 3. The technical specification of the GENEActiv bracelet is described in Table 3.

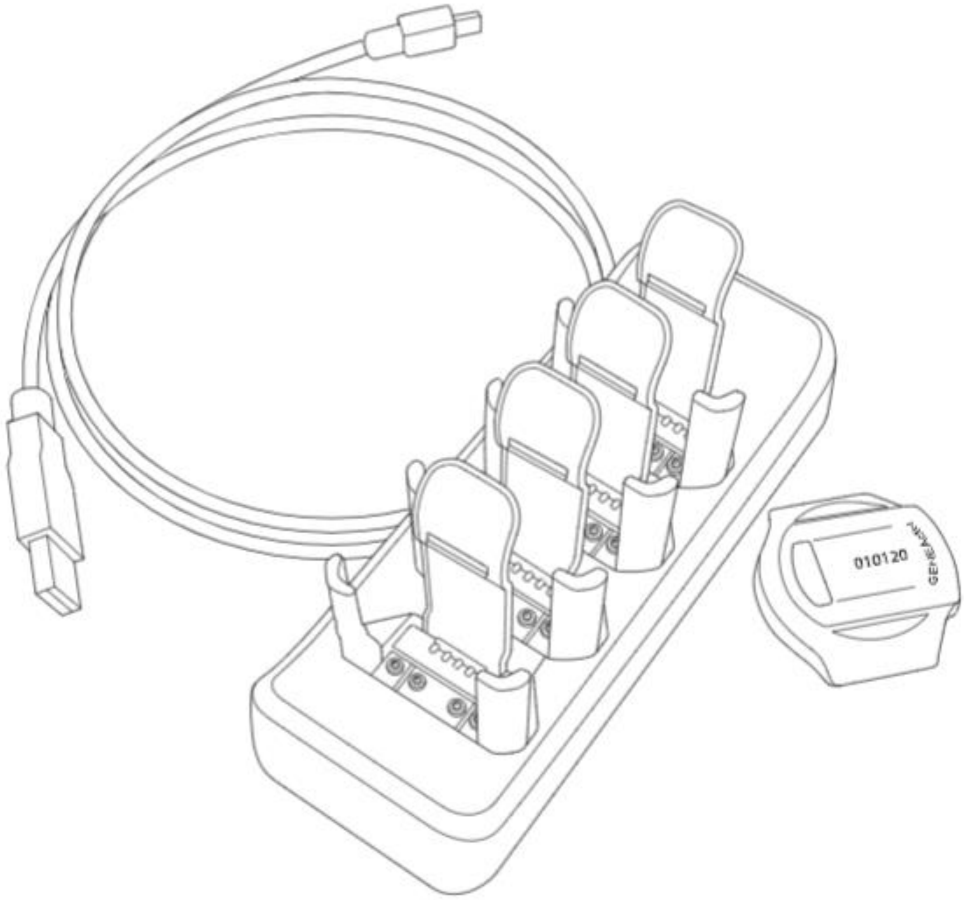


Figure 2: GENEActiv Kit (components: USB cable, cradle, actigraph bracelet) [18].

Table 3: Technical specification of the GENEActiv instrument.

| | |
|---|---|
| **Physical parameters** | |
| Size | 43mm x 40mm x 13mm |
| Weight | 16g (without strap) |
| Main housing material | PC/ABS (medical device grade) |
| Light guide material | PC (medical device grade) |
| Data contact material | Gold-plated |
| Fixings | 20mm heavy-duty spring bar |
| Strap | PU resin |
| Battery type | Rechargeable lithium polymer |
| **Environmental protection** | |
| Moisture ingress | Water-resistant to 10m (IP67 – 1m 24h) |
| Material ingress | Dust tight (IP67) |

| | |
|---|---|
| Operating temperature | 5 - 40°C |
| Mechanical impact | 0.5m drop resistant |
| **Measurement capabilities** | |
| Memory | 0.5Gb non-volatile |
| Logging frequencies | Selectable 10 - 100Hz |
| Maximum logging periods | 60days at 10Hz, 7days at 100Hz |
| **Internal clock** | |
| Type | Quartz real time clock |
| Frequency | 30.768Khz |
| Accuracy | +/- 20ppm [+/- 1.7s per day] |
| **Acceleration measurements** | |
| Sensor type | MEMS |
| Range | +/- 8g |
| Resolution | 12bit (3.9mg) |
| **Light measurements** | |
| Sensor type | Silicon photodiode |
| Wavelength | 400 - 1100nm |
| Range | 0 - 3000Lux typical |
| Resolution | 5Lux typical |
| Accuracy | +/- 10% at 1000Lux calibration |
| **Temperature measurements** | |
| Sensor type | Linear active thermistor |
| Range | 0 - 60°C |
| Resolution | 0 - 25°C |
| Accuracy | +/- 1°C |
| Measurement frequency | Every 30s minimum |
| **USB connection** | |
| Device | USB 2.0 full speed |
| Charge cradle | Format 4-unit cradle USB 2.0 high speed |
| Chare time | 90% at 2h, 100% at 3h |
| Data download time | Maximum 20min for 4 concurrent units |

### 2.5.2. Acquisition software

The data acquired by the GENEActiv bracelet is stored in the physical memory of the bracelet and can consequently be downloaded/viewed, etc. by the open source software: *GENEActivPcSoftware*. It provides users with sections for viewing device settings, configuring, and downloading and viewing data are accessed by single-clicking on the menu options (examples can be seen in Figures 3-5).

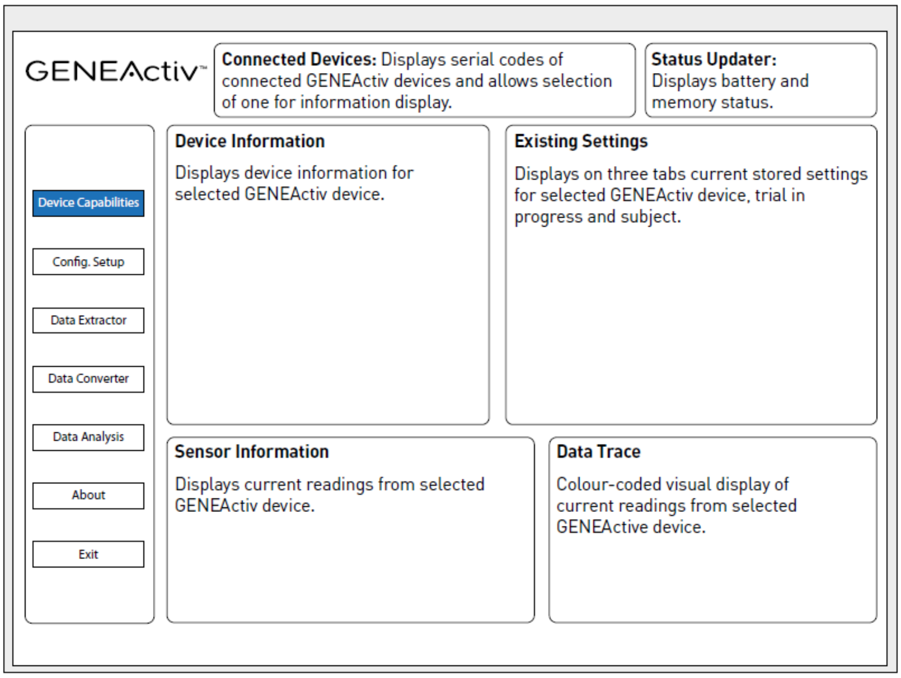


Figure 3: GENEActivPcSoftware: device capabilities [18].

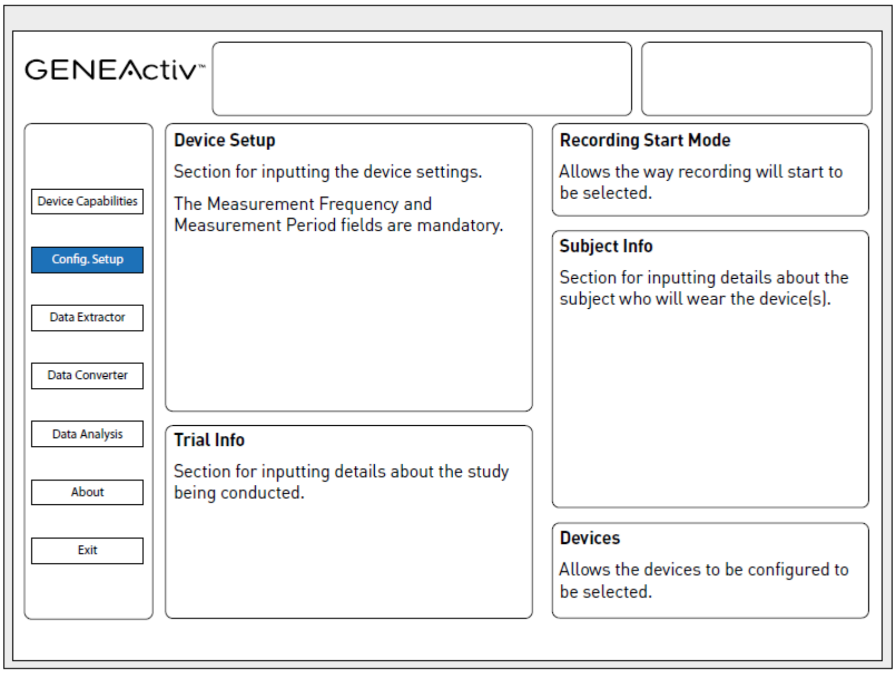


Figure 4: GENEActivPcSoftware: config setup [18].

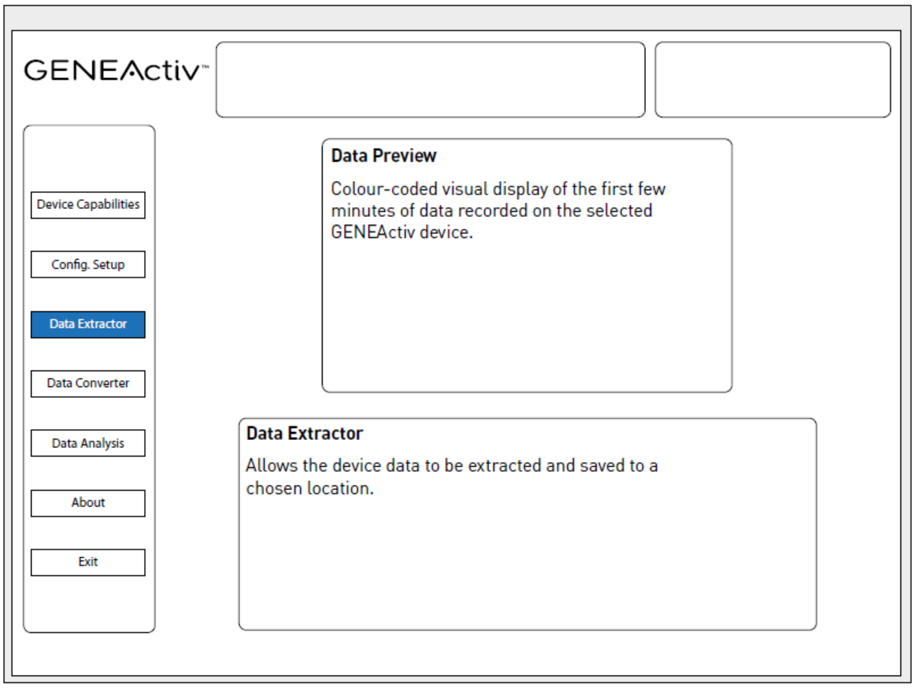


**Figure 5: GENEActivPcSoftware: data extractor [18].**

### 2.5.3. Acquired data

As could be seen in the technical specification, the GENEActiv actigraph bracelet provides raw data output including acceleration in 3 axes, physical activity intensity, sleep/wake measurements, etc. The raw data provided by the actigraph are the following [18]:

- acceleration in x-axis [g], range: (-8, 8), resolution: 0.0039g
- acceleration in y-axis [g], range: (-8, 8), resolution: 0.0039g
- acceleration in z-axis [g], range: (-8, 8), resolution: 0.0039g
- light level [Lux], range: (0, 5000), resolution: 5Lux
- temperature [°C], range: (0, 70), resolution: 0.1°C

The raw data series are stored in *.bin format (as a column delimited data) during the acquisition. Each row contains the previously mentioned information (row index, timestamp, acceleration in x, y, z axes, etc.). An example (9 randomly selected rows):

```
1 2013-06-11 02:50:58:505, 0.9573, 0.2857, 0.0989, 0, 0, 31.4
2 2013-06-11 02:50:58:516, 0.9573, 0.2779, 0.1067, 0, 0, 31.4
3 2013-06-11 02:50:58:528, 0.9612, 0.2741, 0.1107, 0, 0, 31.4
4 2013-06-11 02:50:58:540, 0.9651, 0.2974, 0.1185, 0, 0, 31.4
5 2013-06-11 02:50:58:551, 0.9495, 0.2779, 0.1107, 0, 0, 31.4
6 2013-06-11 02:50:58:563, 0.9495, 0.2702, 0.1224, 0, 0, 31.4
7 2013-06-11 02:50:58:575, 0.9534, 0.2779, 0.1028, 0, 0, 31.4
8 2013-06-11 02:50:58:586, 0.9690, 0.2702, 0.1028, 0, 0, 31.4
9 2013-06-11 02:50:58:598, 0.9534, 0.2935, 0.1302, 0, 0, 31.4
```

The raw data can be converted from *.bin format into a tabular for as *.csv that is easily accessible via standard tabular data processors. The system also expects the data to be downloaded from an actigraph and uploaded as a *.csv-formatted data for further processing.

## 2.6. Data processing

Data processing involves the following steps: a) data cleaning, b) data pre-processing, and c) data processing. As stated above, data are gathered in the form of a time series stored in a *.bin format that is converted into a *.csv format. Data cleaning involves handling of missing values, corrupted values, etc. using the commonly used techniques in data science such as data imputation (median), etc. Next, data pre-processing involves the conversion of data units, and the data transformation (if necessary). Finally, data processing involves the selection of only sleep duration estimation-relevant data, i.e. acceleration in x, y, and z -axes, temperature, and the timestamp, and data-subsampling (from 85 Hz into one third; this is in line with the previous studies dealing with machine learning using actigraphy).

## 2.7. Data analysis

The accelerometer information (x, y, and z -axes) and the temperature are next used for the consequent data parametrization (extraction of relevant parameters that describe the information in a way that is not visible from its raw form). Each data vector (or series, i.e. information (x, y, and z -axes) and the temperature) is segmented using 30s (seconds) floating window to create a matrix of data segments. Each of the segments is then parametrized and handled individually. The parametrization involves computation of 45 statistical functionals that describe the statistical properties of the given time series data and some of the novel sleep parameters (features).

### 2.7.1. Conventional features

The following conventional parameters (features; statistical functionals) are used:

- min., max., relative position of min., relative position of max.
- range, relative range, relative variation range, interquartile range, relative interquartile range, interdecile range, relative interdecile range, interpercentile range, relative interpercentile range, Studentized range
- mean, means excluding 10/20/30/40/50 % of outliers, median, mode
- variance, standard deviation, median absolute deviation, relative standard deviation, index of dispersion
- kurtosis, skewness, Pearson’s 1st skewness coefficient, Pearson’s 2nd skewness coefficient
- 1st/5th/10th/20th/25th/30th/40th/60th/70th/75th/80th/90th/95th/99th percentiles

### 2.7.2. Novel features

The following novel sleep parameters (features) are used:

- total sleep time (total duration (min) of intervals scored as “sleep”)
- sleep efficiency index (total sleep time (min) divided by the total time in bed (min))
- sleep fragmentation index (number of intervals scored as “awake” (after sleep onset) relative to the total sleep time in hours)

- sleep onset latency (total duration (min) of intervals scored as “awake” before sleep onset)
- wake after sleep onset (total duration (min) of intervals scored as “awake” after sleep onset)
- sleep-wake ration (ratio of total sleep time and wake after sleep onset)

### 2.7.3. Feature matrix

Therefore, in total, there are 45 statistical parameters + 6 more advanced and novel sleep parameters for each of the segments, and this is computed for every time series that was mentioned, i.e. the matrix of parameters (also called “feature matrix” in the machine learning community) then contains all parameters (features; i.e. indirectly characterizing a subject’s sleep quality, etc.) used for sleep-related predictions.

## 2.8. Sleep prediction

Next, each parameterized 30s timeframe (feature matrix) is put into a pre-trained binary classification model that predicts if a subject is sleeping at that moment in time or not. After this step, the system has a time series of sleep predictions. To avoid misclassification, the system applies further logic that, for instance, takes care of rare, short-time misclassifications of a person being awake while sleeping, etc.

The prediction is made by a state-of-the-art machine learning algorithm, belonging to the so-called gradient boosting framework, named XGBoost [27]. XGBoost provides an extreme parallel tree boosting that solve many data science problems in a fast and accurate way and is currently one of few algorithms capable of competing with deep neural networks (deep neural networks, however, need to be trained on massive datasets, which is still not suitable for medical application because they work with small datasets most of the time). XGBoost is also robust against outliers, it can handle missing (censored data), it provides feature importance computation (feature ranking; some features are expected to be more important than others and capturing such importance is likely to bring clinical relevance to the predictions), and it is also optimized to run on both CPUs as well as GPUs.

# 3. System architecture

## 3.1. Hardware

### 3.1.1. Server-side

From the perspective of server-side hardware, the system is runnable on a consumer-level computer, and it does not require a powerful server(s) or cloud infrastructure. Therefore, a server that is to be used in the real use should satisfy at least the following hardware/computational requirements (as can be seen, unless a very high demand is expected, consumer-side hardware is capable of running the server-side of the sleep monitoring system with no issues):

- CPU - Intel Core i7 4710HQ, 4 × 3,5GHz
- GPU - NVIDIA GeForce GTX 860M (2GB)
- RAM - DDR3 (16GB)

It is also recommended that SSD (128GB) and HDD (1000 GB) is used to mimic the development environment. However, this is not crucial as the previous parameters, and it can change as long as the data storage is not going to become a bottleneck.

### 3.1.2. Client-side

From the perspective of client-size hardware, the system is not challenging to be deployed in real day-to-day use. The data acquisition part in terms of downloading data from the actigraph can be managed at any consumer-level computer running on the Windows operating system supporting the *GENEActivPCSoftware* application. Next, the data can be easily uploaded to the server using any device with a standard internet browser and the internet connection (PC, notebook, tablet, etc.).

## 3.2. Software

### 3.2.1. Software architecture

Server-side is a critical part of the entire system. It takes care of the data storage, data processing, data analysis, presentation of the results, user management, etc. It is designed and developed using a Linux-based operating system (Fedora) running in a virtual environment set-up on the Windows 10 operating machine. The reasons for this set-up are the following: a) virtualization, b) security, c) easy migration, etc. The software architecture and implementation of the server-side are designed according to the modern trends of vast modularisation and use of the microservices. It consists of several logical modules that cooperate to support all necessary functions provided by the online sleep monitoring system. The overview of the software architecture can be seen in Figure 6 (e.g. presentation module, analytical module, data administration, etc.).

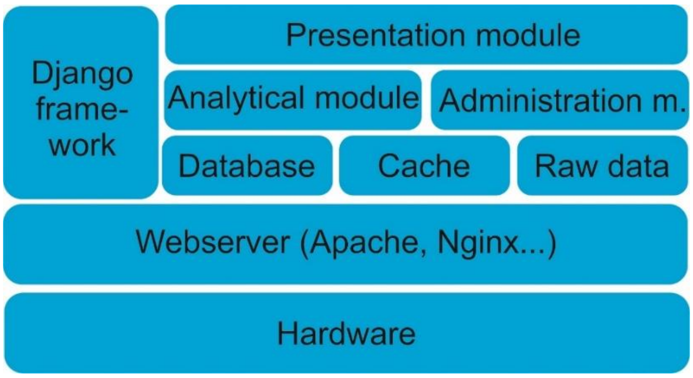


**Figure 6: Overview of the software architecture (server-side).**

### 3.2.2. Programming language and web development framework

The entire server side is programmed in Python programming language (v. 3.7 stable [28]). The Core of the software architecture is the Django web framework [29]. Django is a high-level free and open-source Python Web framework designed to be easy to use, fast, reassuringly secure, and exceedingly scalable. An essential feature of the framework is its object-relational mapper. By defining models, the single source of information about the data stored in the database is created.

Figure 7 shows the UML diagram of the Django models. This defines the structure accordingly. Due to the object-relational mapper, the database model is created, and the data are stored in the selected database. In case of a change in the model definition, the migration script is created automatically, and the database is migrated on-demand [29].

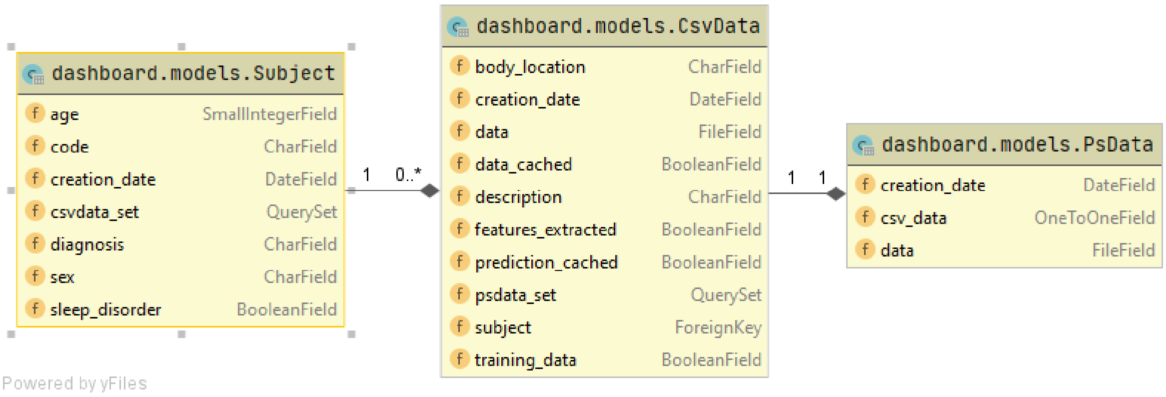


**Figure 7: UML diagram of the data models.**

Django framework itself depends on the Python runtime and some other Python packages. In the designed system, the last available version of the Django framework (in the stable version) was used, to ensure all of the necessary security patches were installed correctly, i.e. the high level of security is ensured. It was emulated as a virtual environment via Conda [30]. The list of all the dependencies is listed in Table 4.

**Table 4: Python package dependencies of the system.**

```
dependencies:
- asgiref=3.2.7=py_0
- blas=1.0=mkl
- ca-certificates=2020.4.5.1=hecc5488_0
- certifi=2020.4.5.1=py37hc8dfbb8_0
- cycler=0.10.0=py37_0
- django=3.0.3=py_0
- et_xmlfile=1.0.1=py37_0
- freetype=2.9.1=ha9979f8_1
- graphviz=2.38=hfd603c8_2
- icc_rt=2019.0.0=h0cc432a_1
- icu=58.2=ha925a31_3
- imbalanced-learn=0.6.2=py_0
- intel-openmp=2020.1=216
- jdcal=1.4.1=py_0
- joblib=0.14.1=py_0
- jpeg=9b=hb83a4c4_2
- kiwisolver=1.2.0=py37h74a9793_0
- libpng=1.6.37=h2a8f88b_0
- llvmlite=0.31.0=py37ha925a31_0
- matplotlib=3.1.3=py37_0
- matplotlib-base=3.1.3=py37h64f37c6_0
- mkl=2020.1=216
- mkl-service=2.3.0=py37_0
- mkl_fft=1.0.15=py37h14836fe_0
- mkl_random=1.1.0=py37h675688f_0
- numba=0.48.0=py37h47e9c7a_0
- numpy=1.18.1=py37h93ca92e_0
- numpy-base=1.18.1=py37hc3f5095_1
- openpyxl=3.0.3=py_0
- openssl=1.1.1g=he774522_0
- pyparsing=2.4.7=py_0
- pyqt=5.9.2=py37h6538335_2
- python=3.7.7=h60c2a47_2
- python-dateutil=2.8.1=py_0
- python_abi=3.7=1_cp37m
- pytz=2020.1=py_0
- qt=5.9.7=vc14h73c81de_0
- retrying=1.3.3=py37_2
- scikit-learn=0.22.1=py37h6288b17_0
- scipy=1.4.1=py37h9439919_0
- seaborn=0.10.0=py_0
- setuptools=46.2.0=py37_0
- sip=4.19.8=py37h6538335_0
- six=1.14.0=py37_0
- sqlite=3.31.1=h2a8f88b_1
- sqlparse=0.3.1=py_0
- tbb=2020.0=h74a9793_0
- tornado=6.0.4=py37he774522_1
- vc=14.1=h0510ff6_4
- vs2015_runtime=14.16.27012=hf0eaf9b_1
- wheel=0.34.2=py37_0
- wincertstore=0.2=py37_0
- xlrd=1.2.0=py37_0
- zlib=1.2.11=h62dcd97_4
- pip:
  - cffi==1.14.0
  - cryptography==2.9.2
  - django-braces==1.14.0
  - django-extensions==2.2.9
  - pycparser==2.20
  - pyopenssl==19.1.0
```

- pandas=1.0.3=py37h47e9c7a_0
- parameterized=0.7.0=py37_0
- pip=20.0.2=py37_3
- plotly=4.6.0=py_0
- werkzeug==1.0.1
- xgboost==1.0.2

### 3.2.3. Database

The Django models described in the previous sub-section are modelled as the database schemas. The system needs to process private data really securely. Therefore, the encrypted SQLite database was used. This database is natively supported by the Django framework, and it supports all the use cases [31]. The schemas modelled in the SQLite database are listed in Figure 8. The details were displayed for *dashboard_csvdata* (schema for the data coming from actigraphs with all the associated metadata and properties).

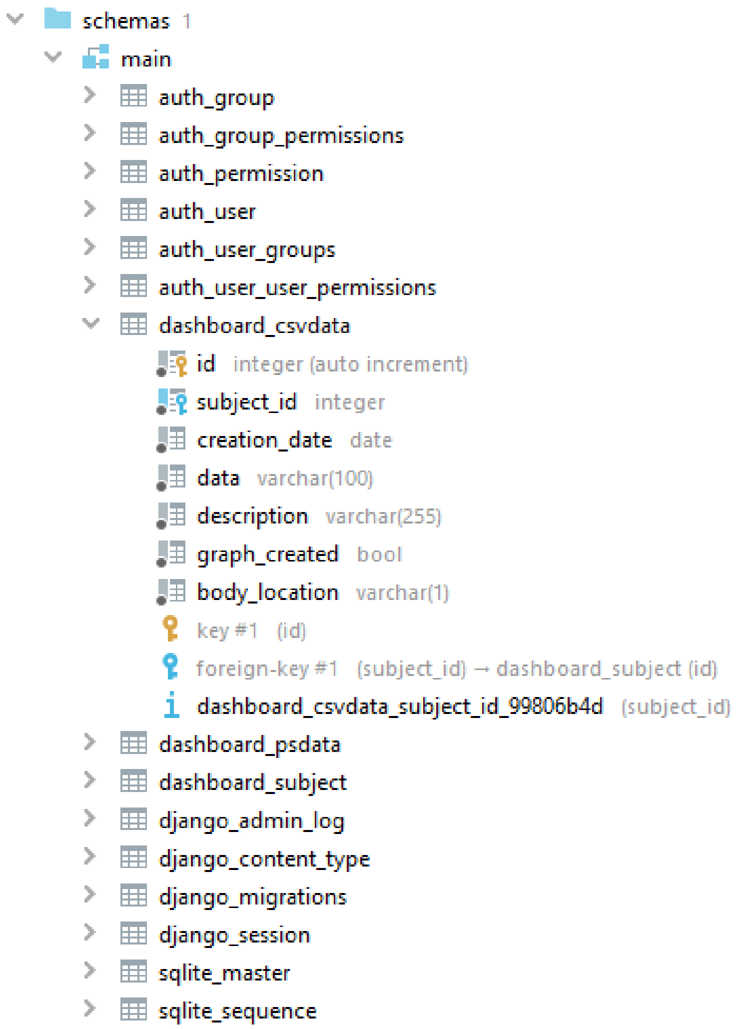


**Figure 8: Database schemas.**

### 3.2.4. Data module and processing

It is not optimal to store raw data from the actigraph in the database structure. It would be time-consuming and really slow. Therefore, the database objects store just a path to the raw data file located on the server. Naturally, the data are transferred to the server securely via encrypted https connection. It would be possible to store them on a different server and perform the secure multiparty computation for advanced security. The data are stored in the CSV files. Validation is performed on the data when they are uploaded, so it is not possible to upload a malware file on the server.

### 3.2.5. Cache

To speed up the system and also to make it more useable, the often-used data are stored in the system's cache. Such data are especially the feature matrices, computed in the data analysis module, the hyper-parameters, etc. They are stored as serialized Python objects via the pickle package. It did the work with them really fast. Hence it took milliseconds to deserialize the data, but it can take even half an hour to compute them. The size of the serialized files is optimized, that the files are significantly smaller than the raw data files. The final feature matrix is stored in the form of Microsoft Excel .xlsx file. It is a format that can be read by a human, and it is a widely supported format, so it is possible to exchange the analytical module.

### 3.2.6. Analytical module

The data analysis was described in the system overview (section 2.7). It is the most complex module. It is responsible for the prediction of sleep and final diagnosis according to raw data from the actigraph and from other metadata at the system's disposal. This module uses all of the data modules (database, cache, and raw data), and then it presents its results via the presentation module (described in the subsequent sub-section).

Figure 9 represents the structure of the analytical module. Obviously, the names of the files describe their functionality and the functionality of the entire module itself. To control the functionality of the module, a webpage was created. It enables authenticated administrators to perform high resource-consuming operations like training the machine learning models, pre-processing the data etc. It is accessible after administration login via Utils tab.

It is essential to log, which operations were performed with the personals data and by whom. Moreover, all that information and much more could be found in logs. Logs are stored in a text file with timestamps. An example was shown in Figure 10. There are visible warnings that state operation with personal data. First, anyone can see a blocked attempt to access private data; second, there is authorized access.

The visualization of the webpage is displayed in Figure 11. It was created by the presentation module.

```
logic
    features_extraction
        __init__.py
        data_entry.py
        extract_features.py
    machine_learning
        __init__.py
        classification_metrics.py
        learn.py
        predict.py
        settings.py
        visualisation.py
    preprocessing
        __init__.py
        preprocess_csv_data.py
        preprocess_data.py
        preprocess_ps_data.py
    reults_visualization
        sleep_graph.py
    __init__.py
    cache.py
    utils_check.py
    utils_delete.py
```

Figure 9: Structure of the analytical module.

```
WARNING 2020-09-26 21:15:45,014 views 2032 11096 Blocked request to access subject Test data for user guest
INFO 2020-09-26 21:15:45,014 basehttp 2032 11096 "GET /dashboard/Test/ HTTP/1.1" 302 0
INFO 2020-09-26 21:15:45,062 basehttp 2032 11096 "GET /dashboard/index HTTP/1.1" 200 6789
INFO 2020-09-26 21:15:48,359 basehttp 2032 11096 "GET /admin/ HTTP/1.1" 200 2322
INFO 2020-09-26 21:15:51,026 basehttp 2032 11096 "GET /admin/logout/ HTTP/1.1" 200 1554
INFO 2020-09-26 21:15:53,982 basehttp 2032 11096 "GET /admin/ HTTP/1.1" 302 0
INFO 2020-09-26 21:15:54,025 basehttp 2032 11096 "GET /admin/login/?next=/admin/ HTTP/1.1" 200 2239
INFO 2020-09-26 21:15:57,891 basehttp 2032 11096 "POST /admin/login/?next=/admin/ HTTP/1.1" 302 0
INFO 2020-09-26 21:15:57,957 basehttp 2032 11096 "GET /admin/ HTTP/1.1" 200 8039
INFO 2020-09-26 21:16:01,844 basehttp 2032 11096 "GET / HTTP/1.1" 200 6896
INFO 2020-09-26 21:16:04,164 basehttp 2032 11096 "GET /dashboard/subjects HTTP/1.1" 200 21898
WARNING 2020-09-26 21:16:06,816 views 2032 11096 User root access details of subject Test
INFO 2020-09-26 21:16:06,823 predict 2032 11096 Data 185936__044351_2019-02-11_15-15-05.csv need to be preprocessed
```

Figure 10: Example of the analytical module logs.

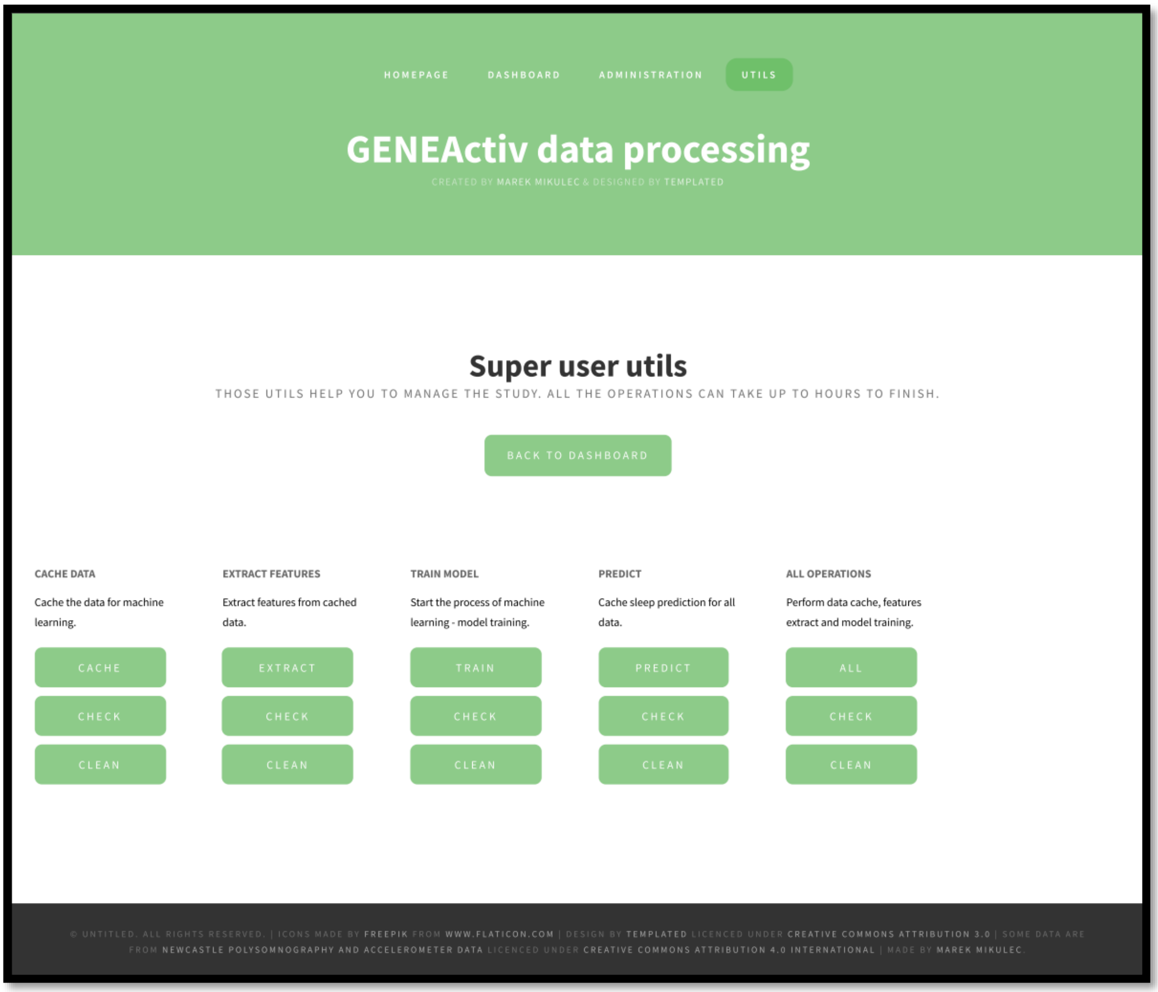


Figure 11. Visualization of the analytical module.

### 3.2.7. Administation module

The Administration module is designed to manage the system via a user-friendly UI. It is possible to create, read, update, and remove new users, subjects, data etc. The logic of the module is implemented in the standardized Django manner. Therefore, it is considered secure, there is built-in protection against XSS (Cross-site scripting), CSRF (Cross-site request forgery), SQL Injection etc. The standardized interface provided by Django was used. An example is shown in Figure 12.

One essential part of the system is the ability to create users and assign them roles. Use-cases are modelled via this module. The system administrator is the most privileged user account. It can create user groups and create user accounts for the others. Permissions need to be set up correctly, it is a crucial security aspect of the entire system.

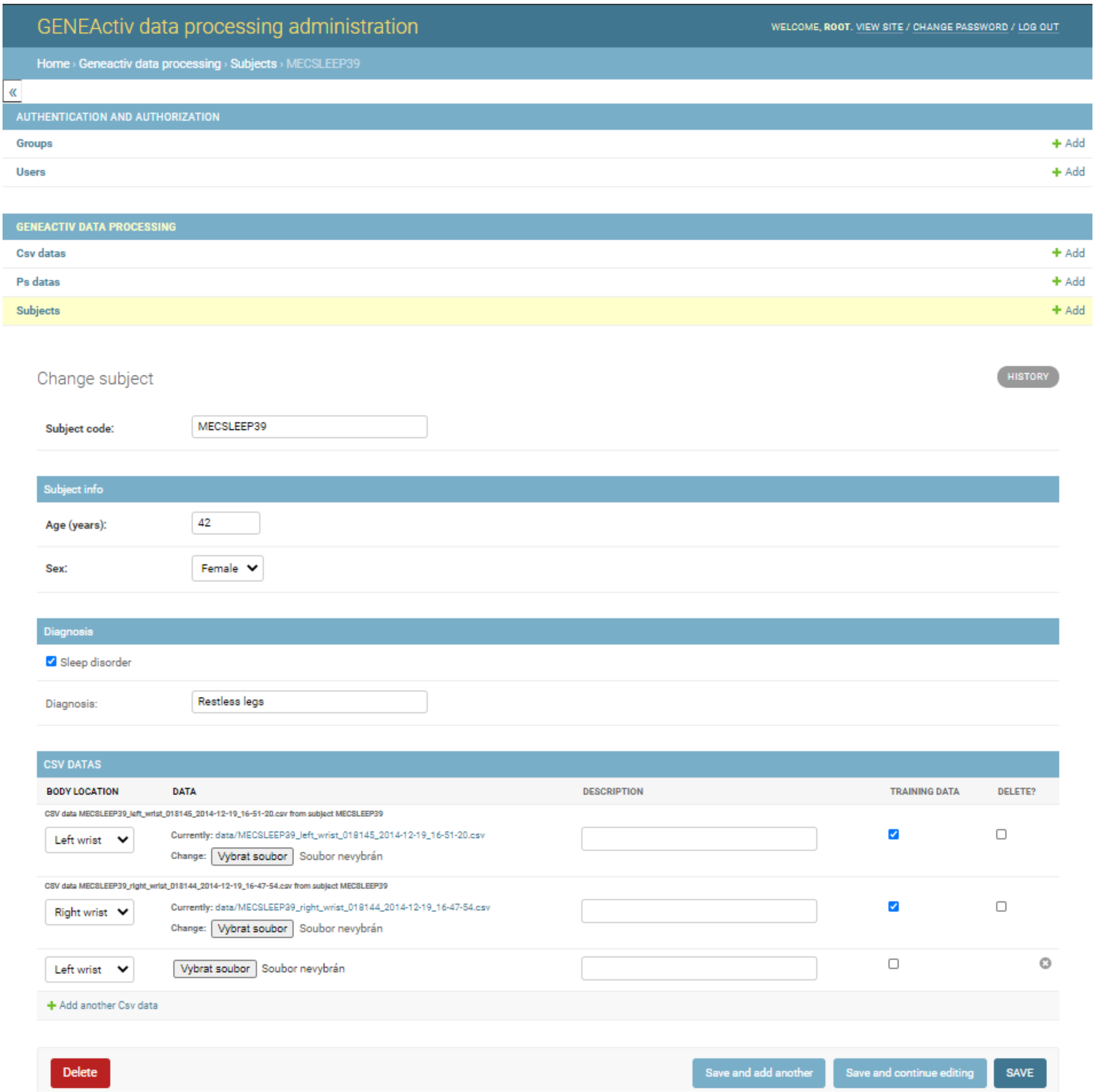


**Figure 12: Visualization of the administration module.**

### 3.2.8. Presentation module

This module implements mostly the view and partly the controller part of the Model-View-Controller architecture of the system. It uses a modern open-source CSS template that is very user-friendly on the mobile devices as well as on a big screen (PC, etc.). During the design, the key focus was put on the creation of an intuitive and easy to use UI so that even non-technical users can navigate in the system and present all the information in a meaningful way.

A special focus was put on the creation of client-server architecture when really “thin” client is needed, and the thick server takes responsibility for the whole system. The presentation module is done as a webpage enables to use of devices like smartphones to interact with the system in a comfortable manner.

The view is divided into four tabs. The first tab presents the base information about the project. The second tab displays the list of all subjects in the system. It is possible to view the details and the results of the analytical module in the detail view of the subject, but only to the user with such permission. These views are displayed in Figure 13 and 14.


**Figure 13: The first view of the presentation module: dashboard.**

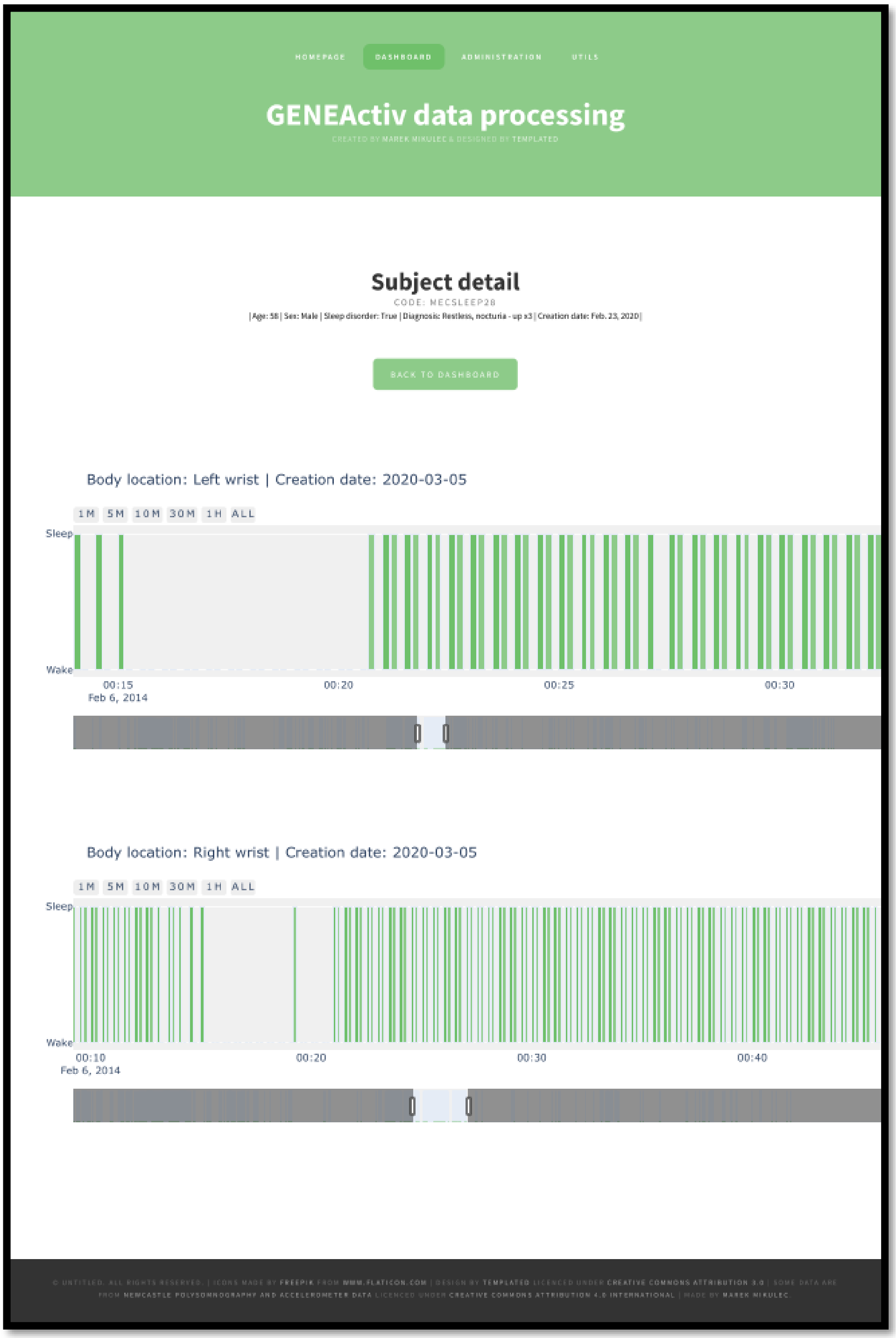


**Figure 14: The second view of the presentation module: details of a subject.**

The third tab is the administration. The presentation of this view was already shown in Figure 12. And the last tab is the Utils tab. It presents the control for the analytical module. Hence some of the operations took longer time to perform, the views were implemented to render asynchronously.

### 3.2.9. Client-side

From the client-side's perspective, the system requirements are the following:

1. A person responsible for data uploading (researcher, technician, doctor) needs a PC compatible with *GENEActivPcSoftware* (so that it is possible to upload data from the actigraph into the system itself). The PC should have USB connector(s) and run on Windows 7 and higher. Next, a standard web browser capable of rendering HTML 5 content is needed.
2. A subject only needs a consumer-level device such as PC, notebook, tablet or even smartphone (the system's website is developed to use the responsive design to maximize the user experience that is especially helpful for elderly people that may not be used to modern technologies on the web) and a standard web browser capable of rendering HTML 5 content to access the system's website.

# 4. Conclusion

This document summarizes the design of the online sleep monitoring system. It consists of three chapters (excluding this one), i.e. introduction, overview of the system, and the architecture of the system. The system is designed to fulfil the requirements and needs of the potential users. It was designed to provide a modern and user-friendly UI with the extensive focus on UX. One of the key concerns is the ability of the system to ensure privacy and data security. The system is designed in a modular way taking an advantage of state-of-the-art principles in web designs such as the separation of concerns, MVC architecture, flat and responsive UI, etc. It consists of separate modules for data processing, data analysis, data presentation, administration, etc. The analytical module employs the conventional as well as novel digital signal processing techniques (parametrization) to quantify data acquired by the actigraphs and to describe the user's sleep. This data (features) are then used to train the robust gradient boosting classifier (XGBoost) that is used by the system to predict the sleep patterns and eventually the presence of a sleep disorder. Finally, the system is therefore designed in a way that is in line with the trend toward virtualization of medical care and in-home examination, assessment, and treatment of neurodegenerative disorders.

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