DTU Compute
Department of Applied Mathematics and Computer Science

Mobile Health Application - Heart Rate Measurements During Cold Water Immersion

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Contents

1 Introduction

Mobile technologies has become an essential part of everyday life and increasingly plays a role in how individuals engage with their health and well-being. Smartphones and wearable devices offer new opportunities for collecting, storing and reflecting on personal health data in real-world settings, outside traditional clinical environments.
This project explores the design and implementation of a mobile application situated within this personal health design space. The application allows users to record and review specific health-related activities, focusing on ease of use, clarity of feedback, and sustained engagement. By situating the system within the broader context of mHealth and persuasive design, the project seeks to investigate how simple recording tools can support personal reflection and long-term habit awareness.

2 Mobile Health & Related Work

Mobile health (mHealth in short) refers to the use of mobile and wearable technologies to support health, wellness, and medical interventions[1, 9]. Early mHealth systems emerged in the mid-2000s alongside the proliferation of smartphones and low-power wearable sensors, enabling continuous monitoring of physical activity outside clinical settings [10].Initial research primarily focused on feasibility-whether mobile devices could reliably collect physiological or behavioral data such as steps, movement patterns, or heart rate [3]. A landmark contribution in this field is the UbiFit Garden system presented by Consolvo et al. at the ACM CHI conference in 2008 [7].

Figure 1: The UbiFit Garden system [7]

UbiFit Garden combined activity recognition with persuasive design to encourage physical activity. Instead of explicit numerical feedback, the system used a glanceable, ambient visualization in which a virtual garden on the user's phone wallpaper grew as physical activities were completed. The study demonstrated that subtle, positive feedback could motivate sustained behavior change without being intrusive, highlighting the importance of design choices in mHealth interventions.
Following this work, research increasingly shifted from pure sensing toward behavior change support [9]. Systems such as Fitbit [2], Garmin [11], Strava [13] and later smartphone health platforms integrated goal-setting, progress tracking, and social comparison features. Studies in persuasive technology and behavioral psychology showed that features like rewards, streaks, and self-monitoring can significantly influence user engagement and adherence [5].
Maintenance plays a central role in long-term health outcomes. Although a broad consensus exists that healthy eating and regular physical activity contribute to improved health and longevity, many individuals struggle to sustain such behaviors over time. Research consistently indicates that awareness alone is insufficient to ensure lasting behavioral change. Even when structured health programs or new habits are introduced, adherence tends to decline substantially as time progresses.
This challenge of long-term adherence was documented in a 2018 [8]. It was concluded, that one group (who where not followed up on) was significantly less active, with respect to the trial program, that was followed up on. In a study from 2007, participants were previously recruited in 2004 and 2005 for one large managed care organization in Minnesota. They were (in the study from 2007) randomly assigned to either treatment or usual care [6]. It was concluded in this study, that the group that received the phone- and mail-based physical activity maintenance intervention, were maintaining the healthy habits significantly more, than the control group. This is one of many studies, that indicates, that rewarding/ reminding the user, will keep them motivated and/or help them continue the healthy habits. These findings underscore the importance of designing mHealth applications that not only record health data, but also support maintenance and motivation through carefully considered

interaction and feedback strategies.

In terms of cold plunges in general, more and more research is published, that reveals the benefits of bathing in colder temperatures. A new study from 2024 investigated the effect of 7 day cold plunges in young males [12]. The researchers examined how 7 days of cold-water acclimation at 14^{o}C for 60 minutes a day affected cell activity and inflammation. The study found, that by day 7, the cells were better suited for removing damaged components. They also found, that the cells were less prone to damage and premature death by the end of the week, because of adaptation, and also that some markers like TNF-α decreased, which suggests that the week helped calm inflammatory pathways; this can support recovery and immune balance. These are just a few of the benefits found from this study.

3 Analysis

As a preliminary exercise in the development of the project, we conducted an initial usage research and data elicitation activity. In this phase, we focused on gaining early insights into potential user behavior and contextual use of the system. Specifically, this involved a private recording session with an experienced practitioner, serving as an expert witness, as well as a personal attempt to recreate and reflect upon the preliminary "scenario" underlying the application concept as shown in table 1.

3.1 Expert Story

Prior to conducting the expert interview, several preparatory materials were developed to support a structured and systematic data collection process. These included an outline of interview questions, a rating scheme allowing the expert to evaluate different potential implementations of the application 11.5.1, and a supplementary survey instrument 11.5.2.

The expert consultation yielded several insights that had not been previously considered and contributed to refining the project's design focus. In particular, the discussion helped identify which potential system features were of greatest relevance for the application. Based on this input, the implementation first priorities were narrowed to the recording of session duration, heart rate, and heart rate variability as these all performed above a score of 3 on the rating scheme. This prioritization did not preclude the potential implementation of additional features. However, it should be noted that the feature location of swim received comparatively low ratings in the survey. This outcome may be influenced by the expert's personal practice, as the expert primarily engages in cold water swimming at a single, consistent location.

3.2 Recreated User Story

To recreate the user scenario, it was personally enacted as accurately as possible on 8 January 2026. The process was documented through structured note-taking and photographic material to capture key aspects of the experience.

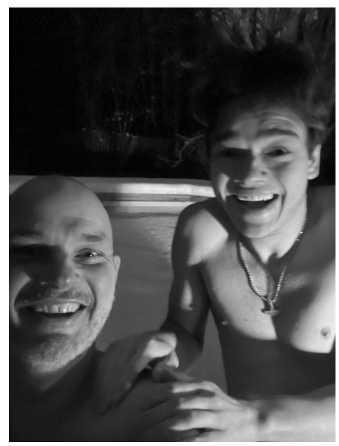

Figure 2: Winter bathing session with expert

An illustrative outcome of the recreated user story scenario was the difficulty encountered when attempting to stop the recording using the on-screen button. This challenge arose primarily due to reduced tactile control caused by cold exposure and wet fingers following submersion. As a potential mitigation strategy, the use of physical buttons on the side of the mobile device could be considered as an alternative mechanism for initiating and terminating recordings.

3.3 UML, Use Case & functional / non-functional requirements

Based on the analysis of the expert narrative and the reconstructed user story, a set of Unified Modeling Language (UML) diagrams were developed to support

the system design process. These include a use case diagram 12.0.1, a class diagram 12.0.2, a table of use cases 12.0.5, and a structured list of both functional 3.3.4 and non-functional requirements 3.3.5.
Our primary use case describes the interaction between a user and the mobile application during the recording of a cold water swimming event. The purpose of the use case is to support the user in documenting a swimming session in a simple and unobtrusive manner, while ensuring that the data is reliably captured for later review. The types of data is selected based on the projects initial idea, as well as the expert interview.

3.3.1 Use Case and scenario

The scenario starts when the user opens the application and selects the option to start a new recording. Upon activation, the system counts down from three, and then begins registering the event and records basic temporal information such as the "time spent swimming" and "HR values". No automatic interpretation or evaluation of the activity is performed at this stage, as the focus is on manual control and transparency.
The scenario concludes when the user stops the recording, which is preferably after ended session. At this point, the system stores the recorded event, including duration and any additional contextual information provided by the user, such as location or self-assessed experience. The recorded data is then made available for later access through the application's event overview.
Our use case is capturing data (heart rate, duration, location, etc.) during winter bathing, and thereby supports the overall goal of the system by enabling consistent and repeatable documentation of cold water swimming activities. As previously mentioned, it serves as a foundational interaction upon which additional feedback, visualization, or motivational features can be built, while maintaining a clear separation between data collection and interpretation.

3.3.2 Use Case Diagram

Using a use case diagram, the different actors that interact with the system were identified and structured. The primary actor is the user, who initiates and controls the recording of a cold water swimming session. In addition to the user, several external systems act as secondary actors, supporting the application's functionality. These include external weather services for retrieving ambient and water temperature data, a heart rate monitor for collecting physiological measurements. While the mobile phone itself is not a secondary actor it is also used for providing temporal information such as date and duration. The diagram illustrates how these actors interact with the system to enable session setup, data capture, recording, and user feedback, thereby providing an overview of the system's core functionality and external dependencies.

3.3.3 Class Diagram

The class diagram illustrates the structural composition of the system and the relationships between its core components. The central entity is the "Person class", which represents the user and maintains associations with recorded bathing events and accumulated streaks. Each "Badeevent" encapsulates data related to an individual cold water swimming session, including duration, temporal and spatial information, environmental conditions, water temperature, and physiological measurements such as heart rate and heart rate variability. External dependencies are represented through dedicated classes, including "Weather", "WaterTemperature", and a "HR Monitor", which provide contextual and physiological data via external APIs or devices. The Streak class combines multiple bathing events to support motivational features based on consistency over time. Together, these classes define the system's data model and clarify how internal entities and external services interact to support the application's functionality.

3.3.4 Functional Requirements

- The system shall allow users to record a cold water swimming event.
- The system shall allow users to start and stop a recording session using a mobile interface.
- The system shall store the timestamp and duration of each recorded event.
- The system shall present previously recorded events in a chronological overview.

3.3.5 Non-Functional Requirements

- The system shall ensure that recorded data is stored locally on the user's device.
- The system shall provide a simple and intuitive user interface suitable for use in outdoor environments.
- The system shall respond to user input within a reasonable time frame under normal operating conditions.

3.4 MDR Considerations

The application developed in this project does not incorporate functionalities that fall under the scope of the Medical Device Regulation (MDR). It is therefore implemented as a private, non-medical service. Consequently, the application is not subject to the classification requirements outlined in MDCG 2019-11 [9].

4 User Experience

Based on the preceding analysis, the defined use case 12.0.1, and other usecases specified in the use case table 12.0.5, as well as the user story map 12.0.4, a series of user experience considerations were developed to inform and guide the design of the application. The focus was placed on ensuring that the interaction is simple, robust, and suitable for use in cold outdoor environments. To support this, wireframe and wireflow diagrams 12.0.3 were created to explore the overall structure and navigation of the application, while heuristic interface design principles were applied to evaluate and refine usability-related design decisions.

4.1 Wireframe and Wireflow diagrams

Wireframe and wireflow diagrams were used to represent the application's layout and interaction flow at an early stage of the design process. The wireframes provide a low-fidelity overview of the primary screens and interface elements, allowing key functionality to be evaluated without committing to visual design details. Wireflows were used to illustrate how users move between screens during core interactions, such as starting and stopping a recording or reviewing previously recorded sessions.

4.2 Heuristic interface design

The interface design was guided by established heuristic design principles 12.0.6. In particular, emphasis was placed on the visibility of system status and on aesthetic and minimalist design, as these principles were considered to have the greatest impact on usability and effective interaction with the application.

5 Software Architecture Design

The applications codebase is based on the Model-View-ViewModel (MVVM) structure, which is a way of structuring the code into smaller pieces. The pieces are as follows:

- **View** is in charge of displaying the images to the screen and telling the ViewModel the users input.
- **ViewModel** is the "middle" and in charge of translating View to Model, and Model to View.
- **Model** is holding all the data.

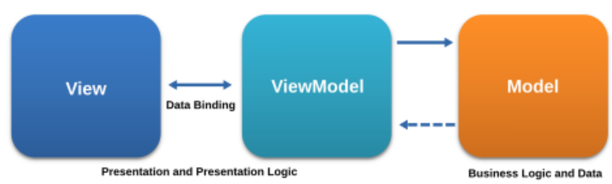

Figure 3: MVVM Structure [14]

Furthermore, we determined that adopting a BLoC (Business Logic Component) architecture would be beneficial for the overall software architecture. In our Flutter implementation, the BLoC structure enables the use of singleton components that can be accessed consistently across the application, thereby improving state management, reusability, and maintainability.

6 Implementation

The application was implemented using the Flutter SDK (version 3.35.3), including flutter/material.dart, and the Dart SDK (version 3.9.2), including dart:async. External dependencies used were movesense_plus (version

1.2.1), path (version 1.9.1), path_provider (version 2.1.5), sembast (version 3.8.6; used via sembast_io), and geolocator (version 14.0.2). Lastly the application was tested using a Movesense wearable sensor running the manufacturer's firmware version available at the time of testing.

7 Study

As an initial attempt to evaluate the functionality of the developed application, a preliminary study was conducted in which the scenario described in Section 11.4 was recreated. This test was carried out as a personal trial on the 20'th of January 2026, with the primary objective of assessing the application's ability to record heart rate data during cold-water immersion.

Figure 4: Testing the application during cold-water immersion

The resulting heart rate data obtained during the test is as follows:

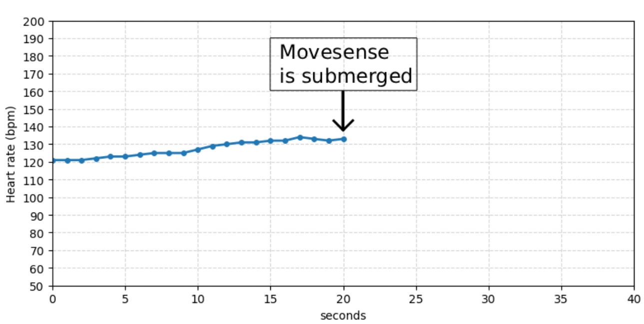

Figure 5: Heart rate (bpm) plotted as a function of time during the test

From the results of this preliminary study, it is evident that the experimental setup did not fully align with the intended study design. Specifically, the heart rate data stream was interrupted during the period of submersion. This behavior can be attributed to the physical limitations of Bluetooth Low Energy (BLE) communication, as Bluetooth signals cannot propagate effectively through water [4].

Although this limitation compromised the original intent of the study, it revealed an important design constraint of the system. The findings indicate that the Movesense device cannot be fully submerged while maintaining continuous heart rate data transmission. This highlights a critical consideration for future system design and study protocols, namely that sensor placement and communication constraints must be carefully accounted for when conducting measurements in an underwater environment.

8 Discussion

Despite its usefulness, the current implementation presents several limitations. Firstly, the application is limited to the iOS platform and has only been tested on iPhone devices. Apart from the limited accessibility this makes, it is also something to take into account in future development, since the UI could be non-suitable for other devices 8.1.

Secondly, the application requires manual configuration of the Movesense device identifier (UUID) directly within the source code. Due to the absence of a device discovery or search feature, users must know their specific device UUID in advance, which increases the technical barrier for non-technical users.

The above is discussed more in detail in the following sub sections.

8.1 Future work

Since our project is very minimalistic, it is very easy to direct it in different directions and improve the functions. It is both possible to make it more detailed for the user, as well as make it more medically helpful. This all comes down to priorities, but we have highlighted a few main ones.

8.1.1 Usability

But most fundamentally, future development efforts should focus on improving accessibility, usability, and scalability. A key priority would be the implementation of cross-platform support, enabling deployment on both iOS and Android devices. Furthermore, the introduction of an integrated device discovery and pairing mechanism would significantly enhance usability by removing the need for manual UUID configuration. This could be achieved through Bluetooth scanning and user-friendly device selection interfaces.

Additional future work could include more advanced data visualization, such as detailed heart rate graphs and session summaries, as well as extended physiological metrics derived from the recorded pulse data. Cloud synchronization and secure data export mechanisms could also be explored to support longitudinal studies and multi-user data analysis. Furthermore a completed integration of a ”streak-system” was not implemented, but could also further enhance user engagement for the app. Together, these improvements would increase the applicability of the application in both personal health tracking and research-oriented contexts 8.1.2.

8.1.2 Clinical use

The developed application has not been designed with direct clinical use in mind and has therefore not been classified as a medical or clinical device. As such, it is not intended for diagnostic purposes or for guiding clinical decision making. Nevertheless, one can foresee the usefulness of a tool for tracking and studying physiological responses associated with winter bathing and cold-water immersion.

By systematically recording heart rate data, session duration, and contextual information, the application enables structured observation of individual responses over time. In a broader clinical or research-adjacent context, such data could contribute to studies on cardiovascular stress responses, autonomic adaptation, or tolerance to cold exposure. Furthermore, the collected data may be of interest in exploratory or preventive healthcare settings, for example in monitoring lifestyle interventions, supporting patient self-observation, or providing supplementary information in supervised rehabilitation or wellness programs. While further validation and regulatory considerations would be required for clinical deployment, the application illustrates how mobile health technologies can support data-driven insight into physiological responses outside of traditional clinical environments.

9 Conclusion

The developed mobile health application demonstrates how wearable sensor data can be collected, structured, and stored. By integrating real-time heart rate monitoring with temporal and geographical contextual data, the application enables structured documentation of individual cold-water bathing sessions. This provides value both for personal self-monitoring and for added user-engagement, as users are able to review historical swims and extract quantitative measures such as duration and average heart rate.

10 References

References

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11 Appendix

11.1 Appendix A – Distribution of Contributions

	Empirical work	Writing the report
Olivia	Created and finalized interactive Figma. Created View files for all pages in app.	Created Use Case diagram, Class diagram, Wireflow diagram, User Story Map. Found literature and wrote on: mobile health and related work [2], analysis [3], UX [4], software architecture [5], discussion [8].
Emil	Created Viewmodels, Models, BLoC structure. Conducted study and expert interview.	Found literature and wrote on: introduction [1], mobile health & related work [2], analysis [3], UX [4], implementation [6], study [7], discussion [8], conclusion [9].

11.2 Appendix B – Use Of Generative AI

Declaration of Use of Generative AI Tools
☒ I/we have used generative AI as a tool or aid (please tick the box) ☐ I/we have NOT used generative AI as a tool or aid (please tick the box). In this case do not fill out the rest of this template.
List the GAI tools used (include version): ChatGPT 5.2

I/we have used GAI tools in the following way (please tick the boxes):

Examples of Use of Generative AI Tools
☐ For sparring in formulating the research question
☐ For sparring in selecting theory and method
☐ For feedback on own text
☒ For generating alternative phrasings
☒ For getting started with writing
☐ For better understanding a topic
☐ As an aid in reading background material
☒ Proof reading of the report handed in
☐ For identifying knowledge gaps
☐ As help to initiate my/our search
☒ For programming tasks
☐ For analyses of data
☐ For interpretation of data
☐ For creating figures
☐ Other use (please specify):

We used AI for supplying our written work in terms of phrasing, writing and proof reading. For programming we used it to help problem solving and design implementation.

11.3 Appendix C – Links to Online Resources

The following online resources were used or produced as part of the project:

- **Overleaf project:** https://www.overleaf.com/read/gdgvqccqpbnh#83d56c
- **GitHub repository:** https://github.com/Thorald/MHealthApp
- **Video demonstration of the application:** https://www.youtube.com/watch?v=x1Mmn4pJQYs
- **Presentation slides:** https://docs.google.com/presentation/d/1TP5HSqSEEzfxsz3T2mp2Jqg8b71XEs1bU edit?usp=sharing

11.4 Appendix D - Scenario

Scenario name	Cold water swim
Participating actors	Jane, Doe
Flow of events	1. Jane drives down to the sea. 2. Jane puts on her recording device and turns on her phone. 3. Jane opens the app and starts recording the bathing event. 4. Jane slowly enters the water and continues recording. 5. Jane exits the water and stops the recording.

Table 1: Scenario

11.5 Appendix E - Expert Interview Materials

11.5.1 Scoring sheet

Data type	**Rating (1–5)**
Duration	
Location	
Heart rate	
Heart rate variability	
Weather conditions	
Water temperature	
Self-assessed experience	

Table 2: Desired data to be recorded during cold water swimming sessions, rated on a scale from 1 (not important) to 5 (very important).

11.5.2 Survey

Question	**Response options**
Frequency of participation	Daily; Several times per week; Once per week; Less than once per week
Motivation for participation	Physical health; Mental well-being; Stress reduction; Social/community aspects; Other
Duration of practice	Less than 3 months; 3–6 months; 6–12 months; More than 1 year
Current activity tracking	Yes, digitally (app or device); Yes, manually (notes or logbook); No
Perceived app motivation	Not motivating; Slightly motivating; Moderately motivating; Very motivating

Table 3: Questionnaire items and response options related to cold water swimming practices.

12 UX design (actors, use cases, flowcharts, UI design, etc.) Software Architecture diagrams

12.0.1 Use Case diagram

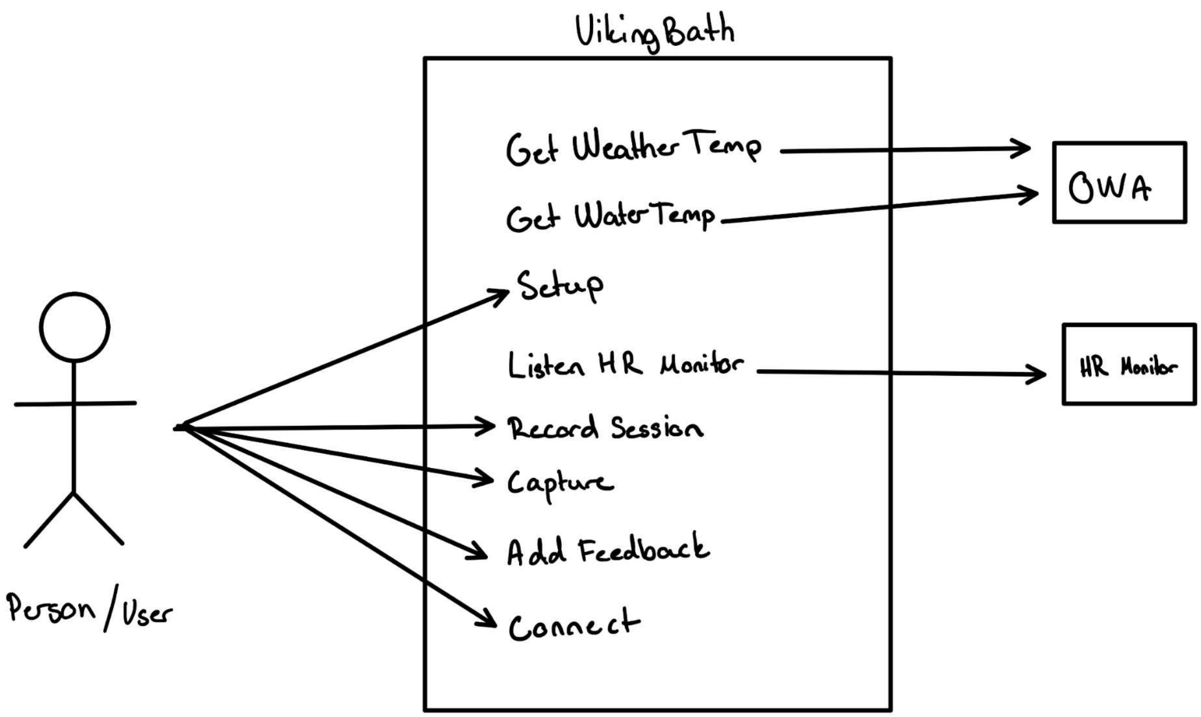

Figure 6: Use Case Diagram

12.0.2 Class Diagram

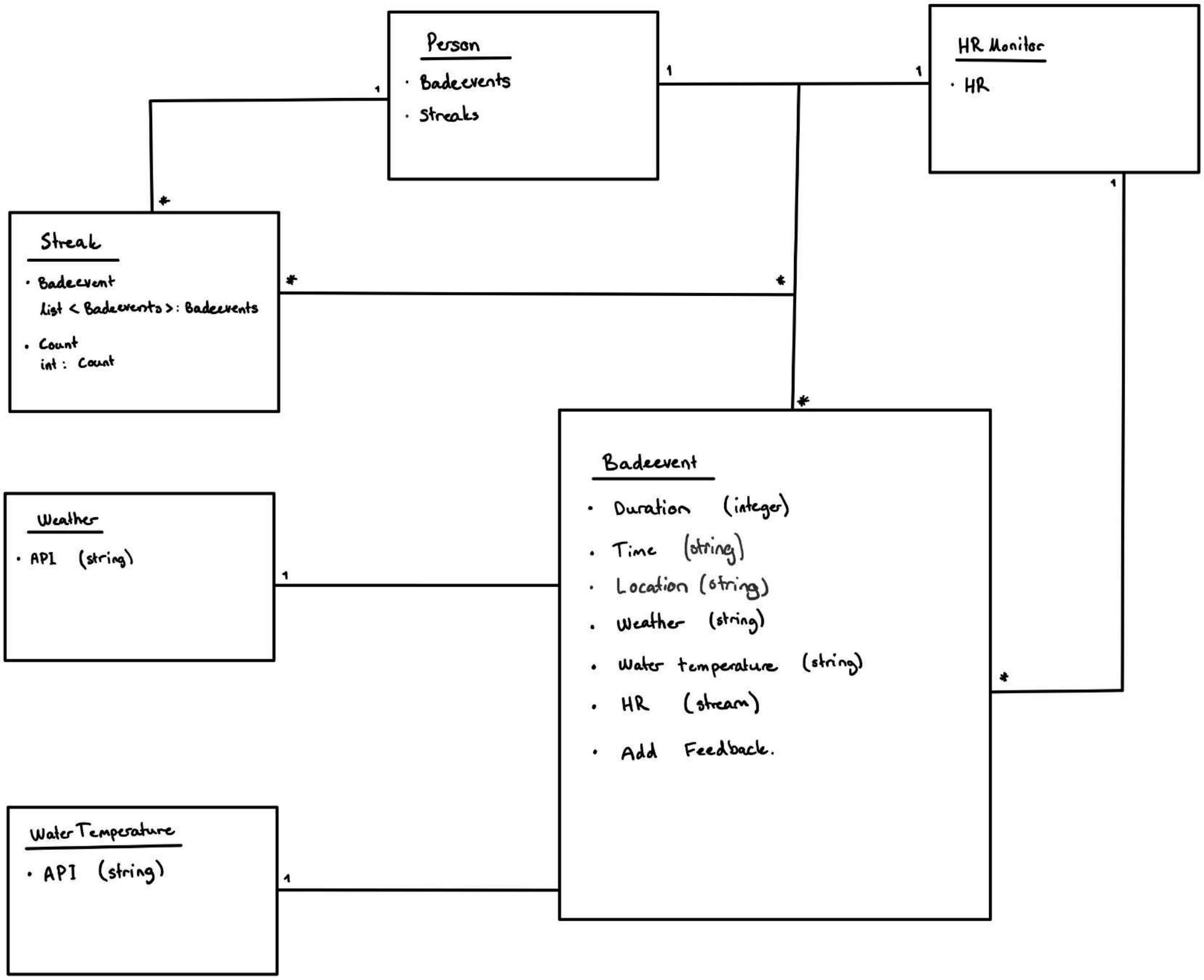

Figure 7: Class Diagram

12.0.3 Wireflow

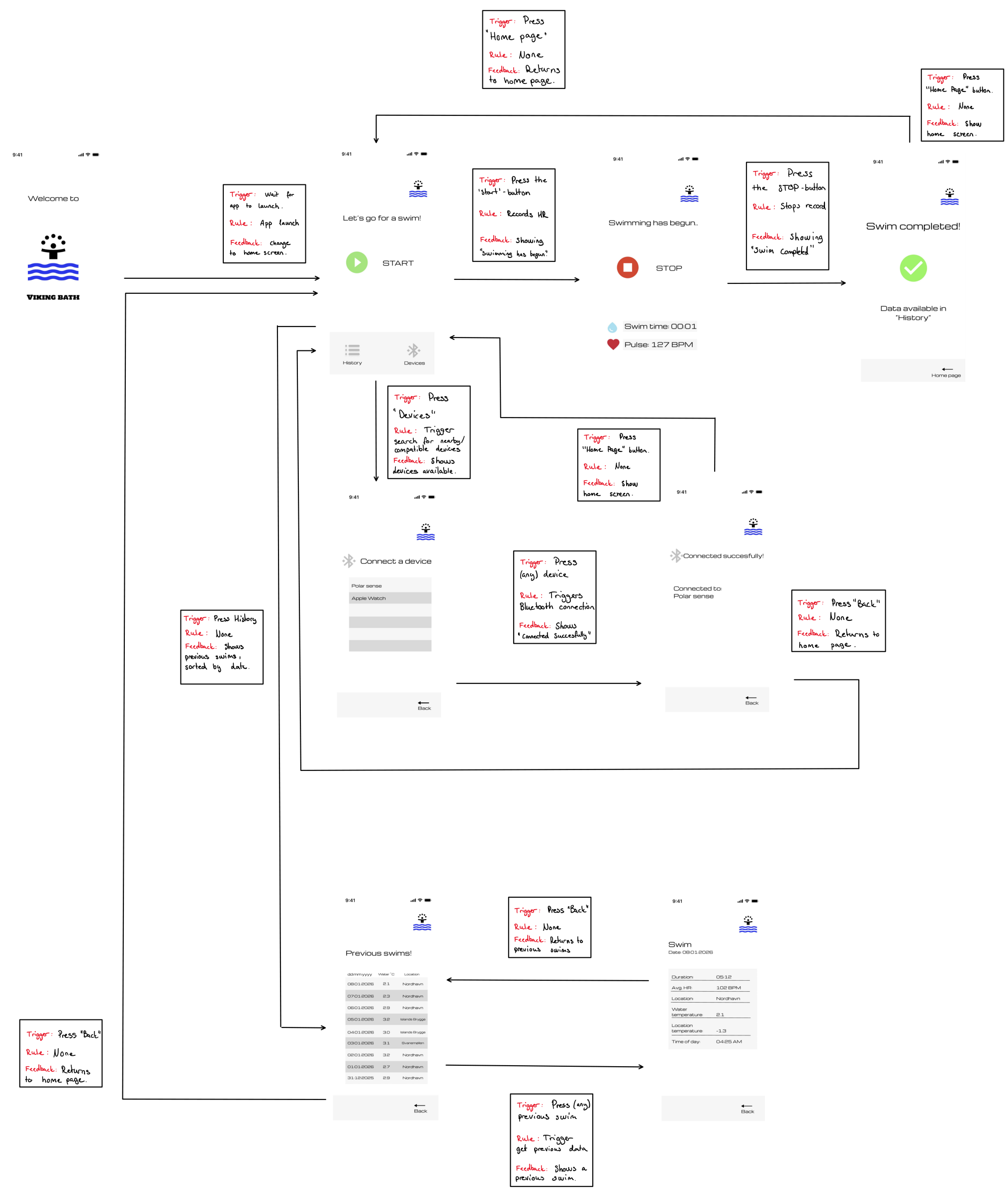

Figure 8: Wireflow

12.0.4 User story map

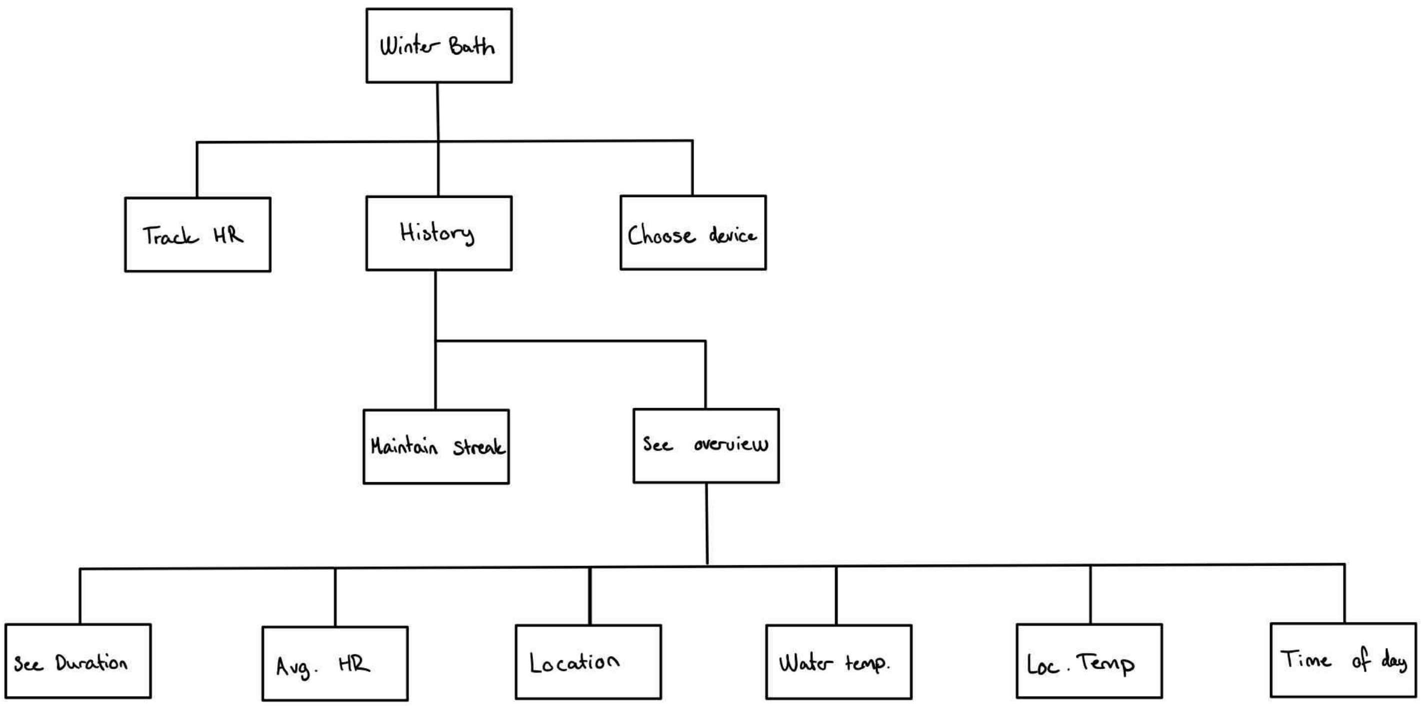

Figure 9: User story map

12.0.5 Use Case Table

Use case name	Record Cold Water Swimming Session
Primary actor	User
Secondary actors	Weather service (DMI); Water temperature service (OpenWeather API); Heart rate monitor;
Preconditions	• Application is installed on the mobile device • Heart rate monitor is available
Main flow	1. User opens the application 2. User performs initial setup and connects to the heart rate monitor 3. User starts recording the session 4. System listens to and records heart rate data 5. User enters and exits the water 6. User stops the recording 7. System retrieves weather temperature from the external API 8. System retrieves water temperature from the external API 9. System stores date, duration, and recorded data 10. User can review all previous swims and view recorded data
Postconditions	• A cold water swimming session is stored • Duration, date, weather, water temperature, and heart rate data are saved
Exceptions	• Heart rate monitor connection fails • External API data is unavailable • User cancels the session before completion

Table 4: Use case specification for recording a cold water swimming session

12.0.6 Heuristic usability

Figure 10: Heuristic Usability