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Development of a Digital Product Passport for iPads to Enhance Student Sustainability Practices

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Abstract: This paper proposes a generic framework for the design and development of Digital Product Passports (DPPs) applicable across various products, sectors, and developers. The framework, established considering information requirements and existing approaches identified in DPP literature, comprises four key phases: (1) Defining the Foundations; (2) Design and Development; (3) Testing and Refinement; (4) Deployment and Evaluation. Its application is demonstrated through the development of a Digital iPad Product Passport for the University of Kentucky iPad initiative (UK-DiPP). An app-based UK-DiPP prototype is presented with three core intended functionalities: (1) Charging Pattern, (2) Battery Usage, and (3) iPad Lifecycle, aiming to promote sustainable charging practices, extend battery lifetime, support end-of-life (EoL) management, enhance sustainability awareness on campus, and mitigate the negative environmental impacts associated with iPad use and disposal. Challenges as a third-party DPP developer, including limited data accessibility and technical obstacles, are discussed with potential workarounds and solutions. This research contributes to the practical development and implementation of DPPs by offering a versatile framework and showcasing real-world application.

Introduction

The Digital Product Passport (DPP), introduced by the European Union (EU) under the Circular Economy (CE) Action Plan, aims to enhance transparency throughout a product's lifecycle covering pre-manufacturing (PM), manufacturing (M), use (U), and post-use (PU) stages (EC, 2020). The DPP is a tool for providing electronically accessible information about a specific product (e.g., origin, composition, maintenance and repair guidelines, and end-of-life (EoL) management options) to stakeholders across the entire value chain (EPC 2024). Relevant stakeholders, while complying with privacy and proprietary concerns, can access and exchange data through the DPP for agreed upon criteria (Adisorn et al., 2021). Through such data sharing, a DPP creates valuable feedback loops and supports the design, production, use, as well as EoL management of products in a more sustainable way.

While the concept is promising, fully-deployed DPPs remain limited due to various challenges. One issue is the lack of standardization and consistency in the development, management, and data sharing (Cetin et al., 2023). The feasibility and value of a standardized DPP to attain a unified format across sectors is debated due to concerns about complexity and resource demands (Voulgaridis et al., 2024). Several studies explored the information requirements for DPPs (Lopes and Barata, 2024; Plociennik et al., 2022; Adisorn et al., 2021) but also highlighted that these requirements can vary depending on the sector or product type. This raises the question of how to determine the most relevant information for a DPP tailored to a specific product. Intellectual property (IP) concerns further complicate data accessibility and availability, especially when developed by a third-party (Ducuing and Reich, 2023). Additional obstacles include poor platform interoperability (Jansen et al., 2023), data security and confidentiality (Berger et al., 2023), and trustworthy data exchange (Lopes and Barata, 2024). Despite its challenges, when developed, DPPs could help enhance sustainable production and consumption.

This research employs the concept of DPP to enhance campus sustainability and educate students on sustainable practices for their iPads at the University of Kentucky (UK). The UK iPad Initiative was launched in 2019 to make the UK an innovative campus in technology use, managed by the Smart Campus Program (SPC). UK provides an iPad to every incoming undergraduate student with more than 30,000 currently in use. While the SPC collaborates with a third-party service platform (GSX) to handle iPad service and repair, it lacks the capability to track or monitor usage data of these devices, such as charging patterns, energy consumption, battery usage, defects, or how/where they are disposed of at EoL after students leave campus.

This research was inspired by the need to gather and share iPad lifecycle information with students and other stakeholders on/off campus. Access to this lifecycle data can enhance SCP's ability to promote more sustainable iPad use. Information such as optimal charging practices, battery usage guidelines, energy consumption, repair & maintenance guidelines, EoL management, etc., can help extend iPad lifetime and mitigate negative environmental impacts associated with their use and disposal. In addition, this can also increase students' awareness about sustainability and help them make reasonable decisions not only when using iPads but also with other products and activities. Therefore, two Research Objectives (ROs) are formulated:

- ***RO1**: Establish a framework for developing a DPP*
- ***RO2**: Develop an app-based Digital iPad Product Passport for UK-iPads (UK-DiPP)*

The remainder of the paper first examines relevant prior work related to DPPs. Next, a framework to guide the development of DPPs is presented. This is followed by a discussion of the preliminary UK-DiPP app, including the challenges faced during development. Finally, the key takeaways and directions for future research are presented.

Related Work

This section provides a brief discussion of previous research on information requirements and approaches for developing DPPs. Detailed discussion of the DPP concept can be found in EPC (2024), Lopes and Barata (2024), and Adisorn et al. (2021).

DPP Information Requirements

Adisorn et al. (2021) examined existing regulated and voluntary information-sharing tools (e.g., Energy Label, Material Passport, Asset Administration Shell, etc.) to explore the design requirements for DPPs. Manufacturers and suppliers are identified as primary providers of specific product information, with information flow being either uni- or multi-directional. They identified key information categories to include the origin, composition, repair, dismantling, and product handling at EoL, covering entire product lifecycle. They also emphasized the need to assess information requirements in a sector- or product-specific manner, given the DPP's intended broad applicability.

Through a literature review and by engaging practitioners, Plociennik et al. (2022) identified generic information requirements for DPPs. These are categorized into four types: Manufacturing data; Usage data; EoL data; Lifecycle data. They emphasize that information requirements depend on factors such as the product's complexity, lifecycle complexity, its value (monetary or ecological), and harm potential.

Lopes and Barata (2024) conducted a systematic literature review and bibliometric analysis of 40 studies since 2021 to identify key guidelines for DPP structure and requirements. The most commonly listed information requirements identified, regardless of product type, were: Product information; Environmental information; Manufacturing data; Utilization data; Life-cycle data; Supply chain information; Guidelines, manuals, and compliance information. They also found that the need for a robust regulatory framework is the most commonly mentioned requirement for DPPs.

These studies present the current understanding of possible DPP information needs, while also highlighting the sector- and product-specific nature of these requirements. This variability indicates the challenge of determining suitable information a DPP should encompass for a specific product. The absence of standardization and consistency in the development process adds further complexity to creating a new DPP.

Existing Approaches to DPP Development

Langley et al. (2023) proposed a framework for orchestrating the development of DPPs, outlining eight guiding principles. These principles offer useful guidance for implementing DPPs, but remain broad, focusing on system-level insights rather than product-level specifics.

A standardized framework for designing and developing the DPP system within the manufacturing industry was introduced by Psarommatis and May (2024). While their seven-step framework provides a useful roadmap for implementing the DPP system, its focus is limited to only the manufacturing sector. This does not consider the broader scope of a DPP, which is to provide total lifecycle information as described previously. The framework is also described in broad terms, making its operationalization difficult. Another gap is the lack of guidance on identifying the necessary data and desired functionalities, especially given that information requirements vary depending on products or sectors.

Legardeur and Ospital (2024) presented a methodology for designing a generic DPP for the fashion and textile sector. While the proposed methodology addresses essential conceptual aspects, it lacks technical details, such as interface design (e.g., web-based or app-based), and data storage and sharing system.

Prior research provides valuable insights into DPP information needs and development. Nevertheless, challenges persist in identifying appropriate information types for specific products, and existing development approaches face limitations in practical implementation. The potential role of third-party developers, as well as the varying needs for a DPP among different user groups (e.g., consumers, suppliers, etc.), are also often overlooked in existing literature. Therefore, this research first focused on establishing a generic framework for developing a DPP (RO1) adaptable across various products, sectors, and developers. The findings from above studies and insights from other DPP-related initiatives such as the EU Batteries Regulation (EPC, 2023) and Ecodesign for Sustainable Products Regulation (EPC, 2024) were considered to establish and apply the framework for developing an app-based UK-DiPP (RO2).

Approach and Methodology

Framework for DPP Development

Figure 1 illustrates the proposed framework for developing a DPP, consisting of four key phases: (1) Defining the Foundations; (2) Design and Development; (3) Testing and Refinement; (4) Deployment and Evaluation. Phase 1 establishes the groundwork by identifying the purpose(s) of the DPP, defining the target end user(s) and sector(s), and determining relevant stakeholders involved. Phase 2 decisions build on these outcomes.

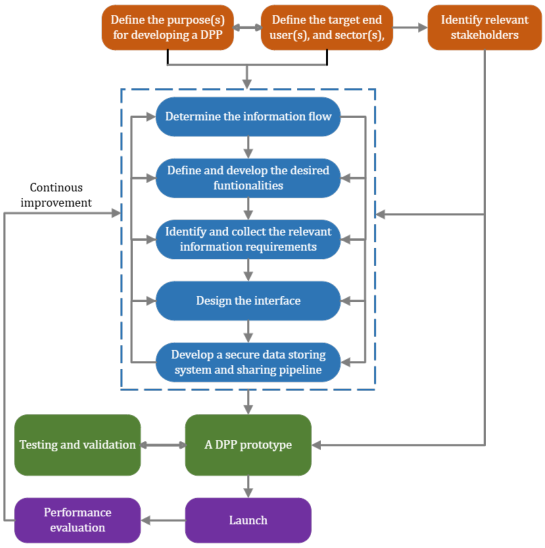

Figure 1. Framework for developing a DPP

Phase 2 focuses on creating the technical and functional backbone of the DPP. This includes determining the information flow (e.g., uni-, bi-, or multi-directional), defining desired functionalities, identifying requirements and collecting relevant information, designing the interface (e.g., web-based, app-based, etc.), and developing a secure data storing system (e.g., local, cloud-based, etc.) and the sharing pipeline. Each step in this phase is interconnected and iterative, requiring parallel consideration rather than a linear approach, as decisions in one area can influence others. For example, limited data availability or accessibility due to IP concerns may hinder achieving the initially defined DPP functionality. In such cases, the deliverable functionalities should be refined to align with the available resources. Engaging with relevant stakeholders in this phase is essential to verify identified information requirements and collected data accuracy, especially when a DPP is developed by a third-party. The outcome of Phase 2 is a DPP prototype. In Phase 3, this prototype is tested and validated to ensure it meets the desired functionalities and stakeholder expectations. Finally, Phase 4 involves DPP launch and performance evaluation (e.g., performance metrics, user feedback, etc.) for continuous improvement. Conducting regular reviews and integrating technological advancements are also crucial to maintain relevancy and effectiveness of the DPP.

Framework Application for Developing a Digital Product Passport for UK iPads

The framework is applied to develop a DPP for the iPads on UK campus (targeted sector) (UK-DiPP). Figure 2 illustrates the architecture of the UK-DiPP. The targeted end users are the students and employees on campus who own iPads. The purposes for passport development include promoting the sustainable charging and use of iPads, extending battery lifetime, supporting EoL management, increasing sustainability awareness on campus, mitigating negative environmental impacts associated with iPad use and disposal. Relevant stakeholders are the targeted users, the SCP staff, Apple, suppliers, and repair and EoL service providers.

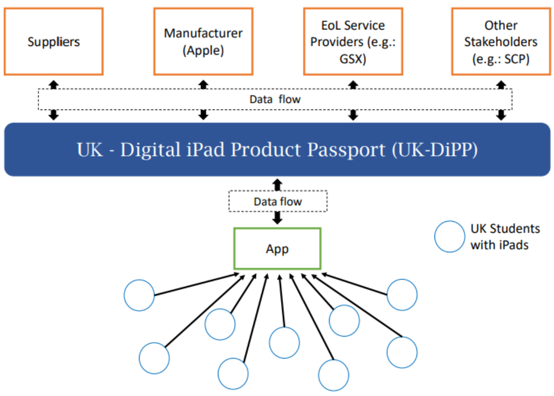

Figure 2. UK-DiPP Architecture

Building on these, Phase 2 was initiated. The information flow is multi-directional to enable data sharing among the relevant stakeholders. The desired functionalities include tracking and presenting charging patterns, monitoring and displaying the battery usage, and providing total iPad lifecycle information. Therefore, the relevant information requirements cover PM (e.g., the material origin and composition), M (e.g., energy usage, chemical usage, manufacturing waste, etc.), U (e.g., charging pattern data, battery usage, repair and service guidelines, etc.), and PU (e.g., take-back availability, EoL management, etc.) stages. An app-based interface was selected, alongside Firebase as the data storage system to ensure data security. The data-sharing pipeline is shown in Figure 2. An initial meeting was held with the Apple university representative to discuss access to data. A mutual non-disclosure agreement between UK and Apple could not be pursued at that time due to unforeseen circumstances. Therefore, it was decided that preliminary UK-DiPP development will be pursued with open-access data.

App Development Process

Figure 3 presents the app development process.

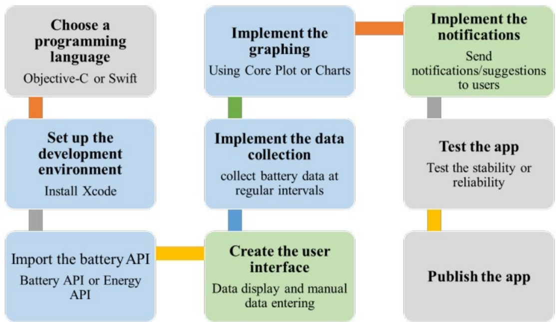

Figure 3. App development process

The app is developed using Xcode as the integrated development environment and Swift and SwiftUI for creating a modern, responsive user interface (UI). Firebase and Firestore are utilized for real-time data synchronization and storing, with Firebase Cloud Functions and Messaging enabling silent push notifications and background data collection. The app is designed to collect data from each user using anonymous identifiers, ensuring that no personally identifiable information is gathered during the process. The app follows the Model-View-ViewModel architecture, which ensures maintainable and scalable code by separating business logic, UI, and data management. The Model handles data processing and Application Programming Interface (API) calls, the View displays real-time battery data through interactive charts and tables, and the ViewModel dynamically updates data between the Model and View. A more detailed discussion of the app development is beyond the scope of this paper and not included due to word limitation.

Preliminary Results

The results presented are preliminary, as the development is on-going due to challenges and limitations in accessing the necessary APIs and collecting the required data (further discussed in the Discussion section). Figure 4 demonstrates the user interface of the UK-DiPP prototype. The core functionalities described below are intended for this passport but are not yet fully developed. Additionally, some images in this section are mock-ups created for illustrative purposes (Figures 5, 6, 7, and 8).

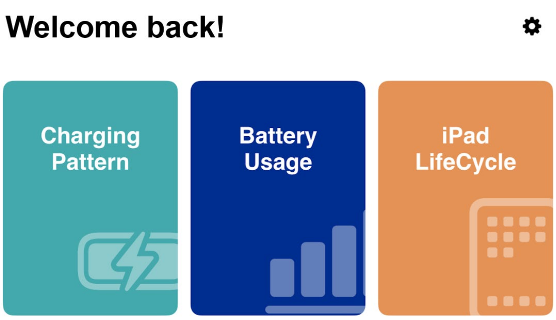

Figure 4. UK-DiPP: Prototype

- **Charging Pattern** (Figures 5 and 6): This feature monitors and displays the daily and weekly iPad charging patterns, including charging start time, duration, and a weekly summary of on-peak and off-peak charging duration. On-peak hours are periods of high electricity demand (higher costs), while off-peak hours are times of lower demand, typically at night, with reduced electricity rates (LGE-KU, 2024). These hours also differ based on seasons. This feature is aimed at guiding users toward more energy-efficient and cost-effective charging practices. This not only helps the users lower their electricity bills but also reduces strain on the power grid during peak periods. Suggesting optimal times for charging and showing daily as well as weekly energy consumption are considered for future implementations.

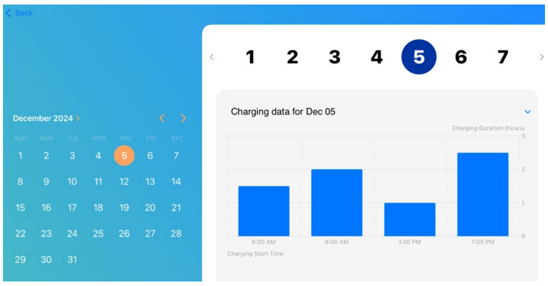

Figure 5. UK-DiPP: Daily Charging Pattern

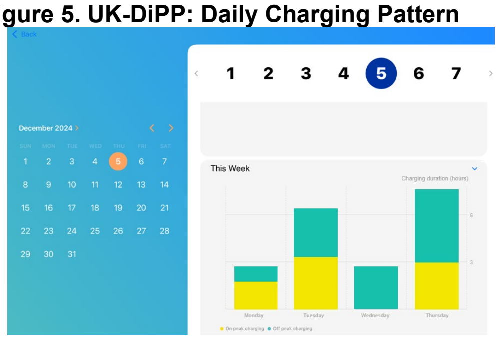

Figure 6. UK-DiPP: Weekly Charging Pattern (Yellow: On-Peak, Green: Off-Peak)

- **Battery Usage** (Figures 7 and 8): This feature promotes optimal battery health to extend its lifetime, reduce the need for frequent replacement and mitigate the negative environmental impacts associated with battery manufacturing and disposal. It monitors users' battery management on a daily and weekly basis by tracking how long the battery remains within different levels (0-20%, 20-40%, and 40-100%). Maintaining the battery level above 20% is critical for preserving its longevity, as frequently dropping below this threshold can reduce its life over time (Faisal et al., 2021; Su et al., 2019; Keeli and Sharma, 2012). The passport will send notifications when the battery falls below 40%, encouraging them to charge before it reaches the critical 20% threshold.

- **iPad Lifecycle:** This feature intends to provide comprehensive lifecycle information of an iPad, covering the PM, M, U, and PU stages. However, as a third-party developer, access to such information is limited. Therefore, this category presents static information gathered from publicly available sources, prioritizing those provided by Apple. It starts with the pre-manufacturing stage, detailing the materials used in iPads. The manufacturing stage shows data such as clean energy use during manufacturing. The use-stage information includes guidelines on maximizing battery longevity, tips for optimal device performance, and instructions for repair and service. Finally, it outlines the EoL options, explaining how iPads can be recycled or reused, and who handles this process.

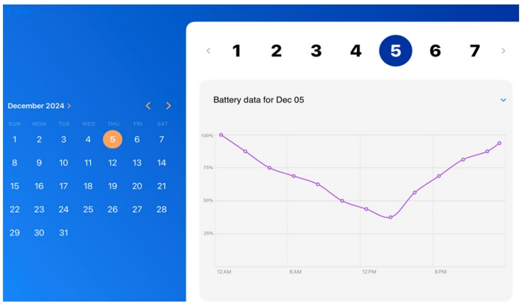

Figure 7. UK-DiPP: Daily Battery Usage

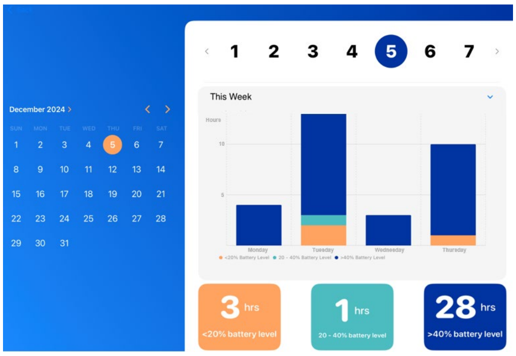

Figure 8. UK-DiPP: Weekly Battery Usage

Discussion

This section discusses the challenges and limitations faced in developing the desired functionalities for the UK-DiPP. Unlike typical DPPs created by Original Equipment Manufacturers (OEMs) for their products, the UK-DiPP is developed by a third-party. Therefore, the challenges outlined here are distinct from those typically encountered by OEMs.

One significant challenge faced in this research is the restricted access to APIs as a third-party developer. While Apple devices provide basic battery level and activity data through their default settings, this information lacks details on on-peak and off-peak charging durations and does not offer detailed insights into battery usage. The UK-DiPP app aims to address these gaps with its Charging Pattern and Battery Usage features. Implementing these features in real-time requires direct access to specific battery APIs, which are classified as private and inaccessible to third-party developers.

Another obstacle is the limitation on background data collection. Without access to battery APIs, the app needs to run continuously in the background to collect and display battery and charging data in real-time. However, Apple policies restrict third-party apps from operating continuously in the background to preserve battery life and prevent misuse. As a result, while the UK-DiPP functions as expected when open, the process stops when the app is closed or moves to the background.

To address this limitation, the use of silent push notifications via the Apple Notification Service is being explored. These notifications would wake the app at specific intervals to allow for data collection and chart updates. However, this approach is inherently limited by Apple's restrictions on the frequency of push notifications. Excessive notifications risk throttling or blocking by Apple, which would further limit the app's ability to provide consistent background updates. Consequently, this solution would only support periodic rather than real-time data collection, undermining the app's intended functionality.

A third challenge lies in the limited access to lifecycle information for iPads, which complicates the development of the app's iPad Lifecycle feature. Given these constraints, the team is exploring collaboration with Apple to gain access to restricted APIs or developing a custom approach that aligns with Apple's policies while meeting the app's requirements.

Conclusions and Future Work

This paper proposes a generic framework for designing and developing DPPs that can be applied across diverse products and sectors, established based on current literature and initiatives. Using this framework, the UK-DiPP was designed, and a prototype was developed. Despite challenges such as limited data access and technical constraints, the preliminary UK-DiPP demonstrates the potential for promoting sustainable usage behaviors of iPads, extending their lifetime, supporting EoL management, and enhancing sustainability awareness on UK campus. The UK-DiPP can also contribute to mitigating environmental impacts associated with iPad usage and disposal. This research further advances the practical implementation of DPPs by offering a versatile DPP development framework and showcasing its application in real-world contexts.

Future work will focus on addressing technical barriers to fully develop the desired functionalities of UK-DIPP. Testing and validation will involve UK students with iPads to ensure the app meets its intended purposes and user needs. After refinement, the UK-DiPP will be launched on the App Store, followed by performance evaluations to support continuous improvement. A detailed analysis of students' charging habits and battery usage will also be conducted to enhance the SCP's ability to promote more sustainable iPad use on campus.

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