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DPPviewer: A Visual Analytics Approach for Optimizing Production Chains on Digital Product Passports

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***Abstract*—The development of a Digital Product Passport (DPP) is an important step in the process of sustainable production and an increasingly mandatory tool for the manufacturing industry, particularly in the EU. However, DPPs have so far been understood in the industry as a purely technical implementation for the exchange of relevant data toward product manufacturing, which is not suitable for reading and understanding by humans. This paper, therefore, describes an approach for a visual analytics system that enables human decision making through the visualization and analysis of DPPs, with a particular focus on optimizing CO_2 efficiency. The system uses intuitive analytical visualizations to enable quick understanding and actionable insights. The main contribution is the concrete data processing and visualization of DPP information for human access, and is so far one of the first available approaches for a visual representation of DPPs in general.**

***Index Terms*—Visual Analytics, Industry 4.0, Internet of Things, Product Carbon Footprint, Circular Economy**

I. INTRODUCTION

In accordance with the EU's New Green Deal [1], a comprehensive CO_2 emission pricing model was introduced [2], [3], supported by initiatives such as the Circular Economy Action Plan, the EU Emissions Trading System, the European CO_2 Offset System, and the Carbon Border Adjustment Mechanism [2], [4], [5]. Among these measures is the development of a Digital Product Passport (DPP) [1], [6], which is sometimes referred to as a digital twin. This passport accompanies and documents a product throughout its life cycle [6]. The first applications of this technology are focused on batteries [7]. In addition to its environmental consequences, the new pricing model is anticipated to incentivize businesses to reduce emissions and enhance their sustainability by disclosing their efforts through DPP. As regulatory pressure increases, it is becoming likely that companies will be required to track emissions and maintain DPP throughout the entire product life cycle. Concurrently, businesses are struggling with the implementation and presentation of the complex topic in a manner that extends beyond documentation and reporting, but to support them in identifying key starting points for their further development and in strategic decision-making.

The described approach in this paper is significantly different to common Industry 4.0 approaches, since it not faces traditional plant analytics such as [8]–[11] where data is directly consumed from the shopfloor and visualized for analytical purposes or transmission to other production stakeholders. The intention is to make use of the data in DPP's which can contain any production-relevant information around the production itself and transportation, such as described in approaches like [12]–[14]. With the establishment of a broader offering of DPPs as documentation besides the products themselves, for instance in the form of an Asset Administration Shell, the understanding of its contained information for humans is important. But actually the industry focus lies on data definition, regulation, and exchange, but not on human accessibility. However, a graphically analyzable solution is urgently needed to understand the main points of origin of CO_2 emissions in a product to be manufactured and to make optimizations. This applies even more when a wide variety of components are incorporated into a product, as components from different manufacturers can already contain drastically different emissions.

The objective of this paper is, therefore, to advance the field of visual analytics in order to facilitate sustainable production through the use of the DPP. Consequently, this paper proposes an approach for a visual analytics system designed to enhance decision-making by visualizing and analyzing DPPs with a specific focus on optimizing the CO_2 efficiency. Furthermore, a system architecture is proposed, and an implementation of a proof of concept is designed to optimize production chains through the use of DPP. The system employs intuitive visualizations to facilitate rapid comprehension and actionable insights, enabling users to identify products with high emissions and isolate emission-intensive components. The approach presented here is one of the first ever to deal with the visualization and analysis of DPP data. However, such solutions are urgently needed for this domain in particular.

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II. THEMATICAL AND DATA FUNDAMENTALS FOR A DPP ANALYTICS SOLUTION

The DPP analytics requires an understanding of some relevant foundations, which are essential to be aware of for certain design decisions later in the design and implementation section.

A. Sustainability in Supply Chains

The concept of *sustainable development* emphasizes the importance of ethical and socially responsible practices, particularly regarding the future of young generations. The concept was first discussed in depth in the 1987 *Brudtland Report*, where it was defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [15]. Today, sustainable development has spread into multiple domains, including the business sector where it is generally divided into three pillars, also often regarded as the triple-bottom line [15]–[17]:

- *Environmental*: Preserving, protecting, and enhancing resilience of the natural environment [16]. Reducing greenhouse gas emissions, pollution, and resource usage [17].
- *Social*: Promotion of human rights, satisfaction of human needs, equity [15], [17]. Generate access to education, health care and create a fair work environment [15], [16].
- *Economic*: Promote long-term economic growth through financial sustainability [17]. Balance between growth, resources, social equity and finances. Responsible management, corporate responsibility. [16]

In the process of implementing these practices and making business operations more sustainable, the majority of options either directly or indirectly address the supply chain [18]. Particularly regarding environmental issues, supply chains frequently play a major factor. The emissions of greenhouse gases often originate in earlier stages of the supply chain [19] : "Having carried out an LCA, Scott [a paper production company] realized that many of its environmental problems were being 'imported' through the supply chain." [19] Often, environmental hazards in supply chains have their origins in countries with less comprehensive laws on sustainability and environmental protection [20]. Reasons can be plentiful: Raw materials might only or substantially cheaper be obtained from such countries, it may be cheaper for a company to intentionally greenwash a product to avoid the acquisition of carbon certificates (also called *carbon leakage*, the shifting of greenhouse gas emissions outside a country), or the company elects to stay in the dark by not conducting an LCA [19], [20]. To address such (and other) business practices, the European Parliament adopted the Corporate Sustainability Reporting Directive (CSRD) [21]. Starting 2024, companies have to report according to the European Sustainability Reporting Standard, which is closely aligned with the European New Green Deal and therefore the aim of a circular economy [21]. Further initiatives include the implementation of the Emissions Trading System [3] and Carbon Border Adjustment Mechanism which collectively serve as an effective instrument to mitigate outsourcing environmental issues, such as carbon leakage [22].

Such regulatory pressure from adjustment mechanisms and due diligence reports aims to create incentives for businesses to increase sustainability in supply chains beyond their potential long-term business-strategic interest [3], [21], [22].

B. Data Foundation of a DPP

The Asset Administration Shell (AAS), defined by Industrial Digital Twin Association e. V. (IDTA)[1], encompasses three file formats for the representation of asset information. The `.aas.xml` and `.aas.JSON` formats contain all text-representable (non-binary) information, incorporating the majority of data required for a DPP [23], [24]. These files can refer to external binary data via URI and organize the information in predefined structures called *submodels*, which are standardized through the IDTA in the form of templates [24]. The IDTA offers an explorer for such files, which enables the editing and browsing of those nested structures. A variety of submodel templates are available for specific types of information, such as carbon footprint data or a bill of materials, each with a dedicated submodel format [24]. The `.aasx` format is a zip-based container that encapsulates one or multiple `.aas.xml` or `.aas.json` files, along with any referenced files, making it ideal for packaging all data necessary for a complete AAS representation [23].

Two submodels are of particular importance to the system's functionality: the hierarchical structure model in the form of the *BillOfMaterial*-submodel) and the carbon footprint model [25], [26] (as specified in Figure 1). The hierarchical structure model incorporates a bill of materials into the asset, establishing a straightforward tree structure where each asset can be a parent or child node, commencing from a root node [25]. The carbon footprint model provides the environmental impact of the asset, which is divided into two distinct categories: the product part and the transport part. The product phase encompasses the CO2eq associated with the life cycle phases of the product. The model permits the consolidation of multiple phases into a single value, which may, on occasion, render it impossible to precisely reproduce the phase during which an emission occurred. The transport phase records the CO2eq associated with the transportation stage, including locations for takeover and handover (expressed as addresses or coordinates) [24], [25]. This information can be employed to facilitate distance-based calculations of CO2eq per kilometer.[2] At the project's inception, version 0.9 of the Carbon Footprint Model was employed. However, as the project neared its conclusion, version 1.0 was imminent, which would introduce substantial changes. Of particular note is the alteration of the transport carbon footprint, which became a distinct life cycle phase. This resulted in the removal of takeover and handover location

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[1] IDTA website: https://industrialdigitaltwin.org (accessed: 05/05/2025)

[2] If only an address is provided, a geocoding service (which turns addresses into coordinates) may be needed to calculate CO2eq/km. When multiple addresses are resolved, our system selects the address identified by the geocoding as the most probable.

data, which had a significant impact on certain features in this thesis, especially the CO2eq/km calculation.

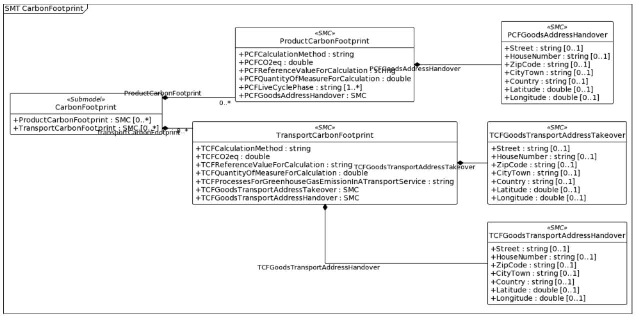


Fig. 1. UML diagram of the carbon footprint submodel version 0.9 depicts the distinction between the product and transportation components [26].

C. Methodology

The optimization of the manufacturing of products through their data often relies on visual analytics [8]. Because our data does not support fully automated optimization, a human-in-the-loop approach is necessary, aligning closely with the visual analytics methodology proposed by Shneiderman [27]. Shneiderman repeatedly emphasizes the importance of the "Overview first, zoom and filter, then details-on-demand" mantra. In addition, the visualization context [28] (see also Fig. 2) is important to consider so that users receive an effective graphical representation. The context of visualizations is characterized by the connection to the given data, the user, and the respective task. In our case, the data is taken from the DPP, the user is the analyst or customer who wants to understand the emissions more precisely and the task is characterized by the analysis, i.e. where which emissions occurred and where they can be reduced - for example by replacing upstream products or by optimizing the company's own product or delivery processes.

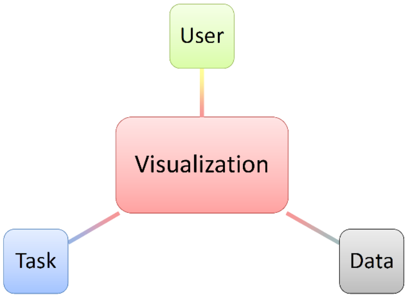


Fig. 2. The dependent objectives of the general visualization context, which consists of the three main objectives: user, task, and data. [28]

The system design, depicted in Figure 3, outlines the fundamental components of our visual analytics framework and its foundation on the principles proposed by Keim et al. [29]. The figure illustrates more visualization-driven and more data-driven analyses. The core modules, namely *Data*, *Models*, *Visualization*, and *Knowledge*, align directly with the framework put forth by Keim et al. [29], thereby enabling users to interact with and influence the program's flow at each stage.

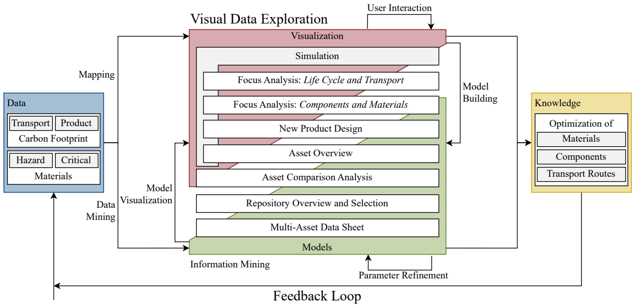


Fig. 3. Concept of DPP visual analytics system highlighting the seamless integration into Keim's approach on visual analytics. The arrows show the user's interaction routes with our visual analytics system.

Regarding the data, we previously provided detail which data is available for analysis through the DPP. However, we restructured the data in the system design with the objective of enhancing the visualization process. For example, while hazardous and critical materials impact decision-making in disparate ways, they share a common visualization style, which allows us to consolidate them into a single material category. Conversely, although carbon emissions from manufacturing and transportation belong to the same data group, their optimization will on occasion necessitate different visual representations.

The knowledge module derives insights from analyses conducted during Visual Data Exploration. The system allows users to identify which materials, components, and transportation routes offer optimization potential. These can be integrated back into the data through the creation of new product passports with alternative materials or by using the simulation module, which enables parameter adjustments for existing assets and components.

The visual analytics system is designed in accordance with Shneiderman's mantra of "Overview first, Zoom and Filter, Details on Demand." Upon accessing the system, users are presented with an overview of the available data. This initial view allows them to assess high-level patterns, after which they can zoom in on specific assets of interest and filter out uninteresting items, for instance, when using the multi-asset data sheet. At any stage, users can request detailed insights as needed by viewing a single asset. While this applies Shneiderman's mantra on the macro level, it is also applicable at the micro level of each analysis, as will be discussed in the following sections, which introduce each component of the system. In addition, the three supplementary tasks proposed by Shneiderman are addressed: the relationships between items are displayed using a variety of trees or visualizations, a history is maintained, enabling the user to undo and redo modifications, and the user is able to extract new or modified data as well as export visualizations.

III. DESIGN & IMPLEMENTATION FOR VISUAL DPP ANALYTICS SOLUTION

Based on the foundations, we designed and implemented the analytics solutions.

A. Architecture

The architectural design is based on the storage of `.aas(x)` files on the server side. A lightweight server, constructed with Java (Spring Boot framework and AAS4J), hosts a partially IDTA-compliant AAS REST API, which is limited to the URL endpoints essential for frontend functionality. These endpoints facilitate the exchange of textual and binary data for an asset [30], enable the discovery of available AAS, and include a custom endpoint. The custom endpoint adds supports for the addition of external shells and is optional to guarantee that the frontend only requires an IDTA specification-compliant API for all features except this.

The web-based front end utilizes a number of libraries in order to guarantee functionality and user experience. Vue.js, an MVVM library, was selected for its intuitive structure and capacity to accommodate sophisticated, data-driven web applications. The MVVM pattern facilitates the separation of the application logic (*Model*), the user interface (*View*), and the management of the user interface state and behavior (*ViewModel*), thereby enhancing the manageability of the development and maintenance processes. While Vue.js is highly effective for rapid prototyping and production-ready implementations, it has inherent limitations in visualizing complex datasets [31]. To address this issue, we integrated D3.js, a powerful and flexible visualization library with an active community of users [32], [33]. However, D3.js requires a complex setup and lacks reusability for some visualizations [33]. To mitigate this, we incorporated *Observable Plot*, a D3-based library specializing in plot generation, with the aim of streamlining visualizations.

Figure 4 depicts the system's architectural configuration, which comprises a lightweight, Spring Boot-based Java backend that supports numerous AAS file formats and hosts portions of the IDTA API. Concurrently, a Vue.js frontend is employed, utilizing the MVVM model and integrating D3 and Observable Plot for data visualization within the *View* component.

B. View: Repository Listing

Firstly, it is essential that users become familiar with the data available to them, without feeling overwhelmed by an excess of details. In order to achieve this, users are initially presented with an overview of the entire DPP repository. Each passport displays key information, including its title, a brief description, and an image. This provides users with sufficient context to quickly identify a component.

As the repository grows, particularly if it encompasses all components of a complex product, efficient navigation becomes crucial. Therefore, we have incorporated a *quick search* functionality, which allows users to filter the repository instantly, and a *favorites* option, which enables them to mark and permanently highlight important items.

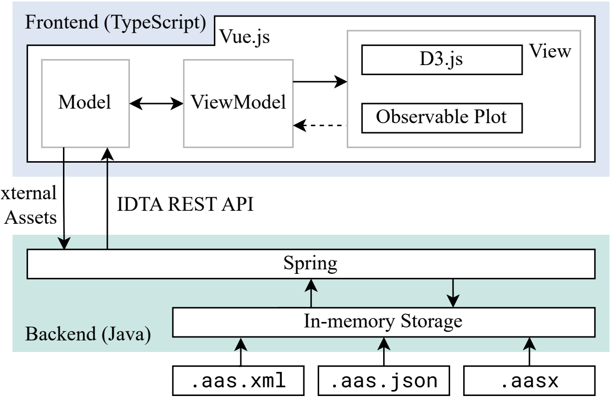


Fig. 4. Architecture of the proposed system, consisting of a backend connected via a REST API to an MVVM frontend.

Once users have gained an overview of the repository contents, they may also contribute by adding external product passports via an interface provided by the system.

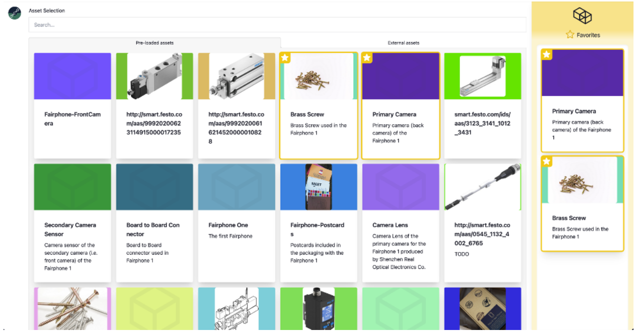


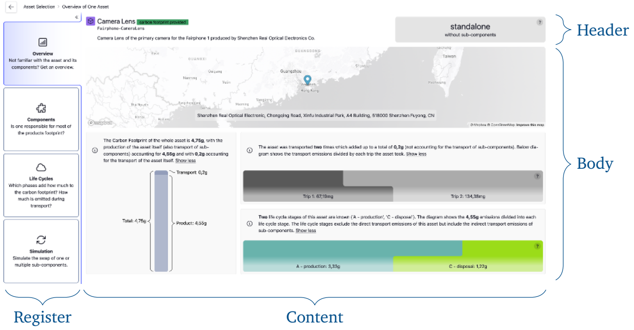
Fig. 5. Repository overview with its two columns: The left-hand column shows all the assets from the backend and allows loading external assets. The right-hand yellow column shows the user's favorites.

C. View: Asset Overview

The Asset Overview provides users with essential insight into a product or component. It displays basic data, including the asset name, description, and manufacturer location, while maintaining a strong focus on the component itself. This focus is underscored by clear, intuitively visualized sustainability data, which allows users to quickly assess the component's environmental impact. Additionally, the dashboard includes a preliminary breakdown of the asset's structure, showing the number of sub-components that make up the whole.

To facilitate rapid analysis, the dashboard employs straightforward yet effective visual representations. For instance, transportation and carbon footprints are presented in a comparable format, such as stacked bar graphs, enabling users to swiftly identify the factors contributing the most to emissions. Further insight is provided by detailed breakdowns:

transportation emissions are segmented by trip, displaying the emissions of each trip, while product emissions are categorized by different stages of the life cycle.



Camera Lens of the primary camera for the Fairphone 1 produced by Shenzhen Real Optical Electronics Co.

Shenzhen Real Optical Electronic, Chongqing Road, Xinfu Industrial Park, A4 Building, 518000 Shenzhen Fuyong, CN

The Carbon Footprint of the whole asset is **4,75g**, with the production of the asset itself (also transport of sub-components) accounting for **4,55g** and with **0,2g** accounting for the transport of the asset itself. Show less

The asset was transported **two** times which added up to a total of **0,2g** (not accounting for the transport of sub-components). Below diagram shows the transport emissions divided by each trip the asset took. Show less

Two life cycle stages of this asset are known ('A - production', 'C - disposal'). The diagram shows the **4,55g** emissions divided into each life cycle stage. The life cycle stages exclude the direct transport emissions of this asset but include the indirect transport emissions of sub-components. Show less

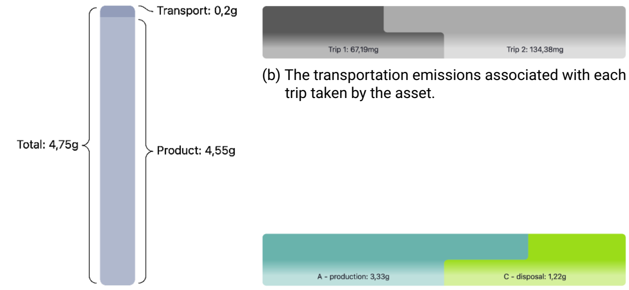
Fig. 6. Single-asset page layout which incorporates a side register for navigation within the same space, content for analyses or simulations, and a slim top bar for application-level navigation.

The single-asset analysis comprises four distinct views, each of which is designed to address a specific aspect of asset evaluation. The organization of these views is consistent, as demonstrated by the Overview page in Figure 6. The layout is divided into two primary sections:

- Side Register: The navigation is located on the left-hand side of the page and contains links to related analyses and simulations. Exploring these sections helps users understand the subject matter. Alternatively, descriptions can be hidden to conserve space. The essential navigation options, including a back button and breadcrumbs, are situated above the register for the user's convenience. The presented order of tabs on the left follows the process of Shneiderman's seeking mantra (see section II-C and [27]) and guides/supports the user through the different tasks (see also [34]).
- Content: The panel represents the central focus of each page and offers general information and detailed analyses. The content panel is also subdivided into two sections:
  - The *header* serves to organize and present essential information in a clear and concise manner. The component is consistent across all single asset analyses and displays essential information, thereby facilitating clear identification. It includes the asset's name, description, unique identifiers, and whether it has sub-components or is a standalone item.
  - The *body* section contains dynamic, view-specific content and analyses. Here, users can explore data visualizations, gain insights, and perform simulations tailored to each view. The remainder of this section will discuss these analyses in greater detail.

The layout maintains consistency across all pages within the single-asset analysis to provide users with clear and organized information about the asset's data.

As illustrated in Figure 6, the Asset Overview page offers users a concise presentation of essential information and straightforward, comprehensible visual representations that showcase the asset's characteristics. The body displays a map indicating the location of the manufacturer in addition to three visualizations. Each visualization is presented as a stacked normalized bar chart, selected for its clarity in highlighting proportions and identifying concerning distributions:



(a) A brief examination of the relative proportions of the product itself and its transportation.

(b) The transportation emissions associated with each trip taken by the asset.

(c) The life cycle phases of the asset and their emissions.

Fig. 7. The overview offers concise and intuitive visualizations, which facilitate a rapid comprehension of the asset's footprint.

- The left visualization (see Figure 7a) presents a breakdown of the asset's carbon emissions into transportation and production. This allows users to rapidly identify which of the two to focus on, thereby directing attention to the area requiring the most attention.
- The top visualization (see Figure 7b) depicts the number of trips necessary for production, along with the associated emissions. Users can promptly identify any trip with elevated greenhouse gas emissions, enabling them to conduct a further examination. Please note that the top row shows the correct proportion, while the row below is changed in its proportion to make the label readable.
- The bottom visualization (see Figure 7c) presents the carbon emissions across the various phases of the product's life cycle. This breakdown allows for the identification of the phase with the highest environmental impact. Please note that the top row shows the correct proportion, while the row below is changed in its proportion to make the label readable.

Each of the visualizations is accompanied by a concise description to facilitate accurate data interpretation. The descriptions can be minimized to maintain focus on the graphics themselves.

D. View: Components Analysis

The components analysis offers users a comprehensive understanding of an asset's composition by presenting a detailed component tree and analyzing each part. This analysis enables users to identify individual components with unusually high emissions at any stage of the production chain, in alignment with the *Components and Materials Focus Analysis* module of the concept. The main panel features three visualizations, each designed to reveal different insights.

Fig. 8. An entire asset production chain is represented as a components tree, which depicts the hierarchical relationship between components and subcomponents.

The initial visualization, illustrated in Figure 8, depicts the asset and all its sub-components in a hierarchical tree structure. This visualization enables users to swiftly identify key information and determine the number of sub-components contained within each component. The component tree should contribute to the user's comprehension of the asset's overall structure.

The second visualization, depicted in Figure 9, focuses on the carbon footprint of only the asset itself. Generally, the provided footprints encompass the emissions associated with their constituents. This visualization excludes subcomponents' footprints, facilitating identification of those with elevated emissions only during their own processing steps. A simple bar chart was selected for this visualization to facilitate straightforward comparison and intuitive interpretation.

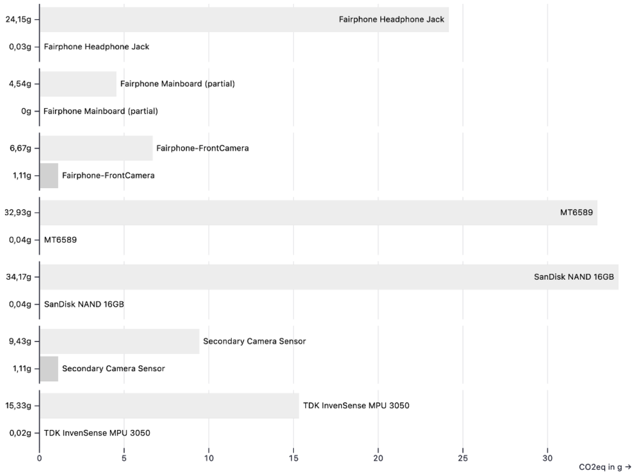


Fig. 9. Visualization of the product (lighter) and the transport carbon footprint (darker) of the asset and each component in the product chain without.

The third visualization, illustrated in Figure 10, is a Sankey diagram that depicts the distribution and flow of carbon emissions across components, differentiating between emissions resulting from the production process and those resulting from transportation. The diagram outlines the life cycle of each component, and additional details are displayed when the user hovers the cursor over an asset or connection. When the cursor is placed over an asset, the name and description of the asset are displayed, as well as a normalized stacked bar chart representing the product and transport carbon footprints of the asset. This is illustrated in Figure 11a. Similarly, when the cursor is placed over a connection, the linked components are displayed, and the manner in which the carbon footprint is divided between the parent and child components is indicated, as demonstrated in Figure 11b.

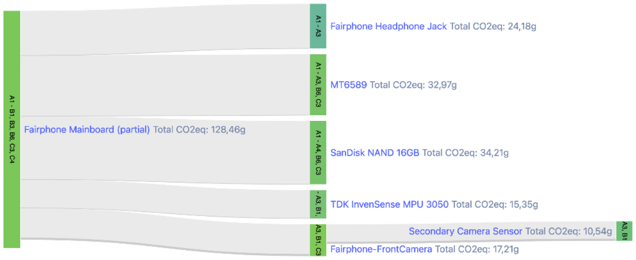
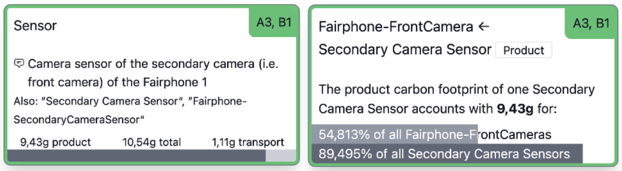


Fig. 10. Sankey diagram illustrating the distribution and *flow* of emissions throughout the production chain of an asset.



Sensor
A3, B1
Camera sensor of the secondary camera (i.e. front camera) of the Fairphone 1
Also: "Secondary Camera Sensor", "Fairphone-SecondaryCameraSensor"
9,43g product
10,54g total
1,11g transport

Fairphone-FrontCamera ←
Secondary Camera Sensor Product
A3, B1
The product carbon footprint of one Secondary Camera Sensor accounts with **9,43g** for:
54,813% of all Fairphone-FrontCameras
89,495% of all Secondary Camera Sensors

(a) Tooltip when hovering a node.

(b) Tooltip when hovering a connection.

Fig. 11. Tooltips providing the user with an overview of the distribution of emissions within the directly associated assets as well as further information about their association as served by the AAS.

Collectively, these visualizations facilitate the identification of critical emission sources, the comprehension of their interconnections, and the determination of the specific assets that contribute the most to the overall footprint.

E. View: Life Cycle Analysis

The life cycle analysis, which encompasses the *Life Cycle and Transport Focus Analysis* from the concept, presents two diagrams. One of these is the most sophisticated visualization in the analysis suite, offering granular details about emissions across each phase of the asset's life cycle, along with those of its direct sub-components.

By default, as illustrated in Figure 12, this visualization presents multiple stacked bars for each life cycle phase. The bars are indented, with the left-shifted, darker bars representing emissions from sub-components during a particular life phase and the right-shifted, lighter bars indicating emissions specific to the main asset (especially visible in the A2 or C3 columns in Figure 12 and A1 to A3 columns in Figure 14c).

The design permits the stacking of multiple sub-component bars, thereby enabling users to view emissions from a combination of components or multiples of the same component. Furthermore, the shading behind the life cycle phase label indicates the number of sub-components influencing that phase; darker shading signifies a higher number of contributing sub-components.

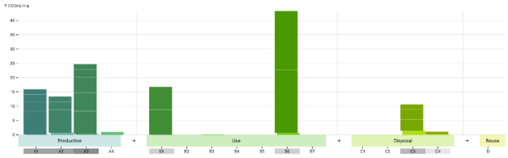
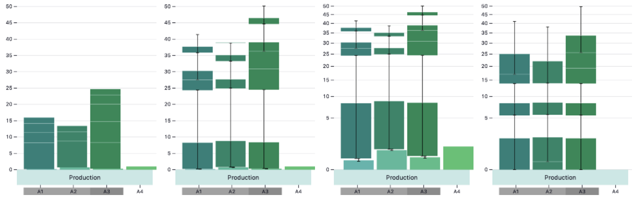


Fig. 12. Visualization depicting the emissions of an asset and its constituent components per life cycle phase grouped into its respective stages.

To enhance interactivity, a tooltip, as illustrated in Figure 13, provides precise emission values upon request. If a given value encompasses multiple life cycle phases, said value is distributed across the corresponding bars by default. However, users may elect to enable min/max intervals for more detailed information, as illustrated in Figure 14b. In such instances, the minimum value may could be 0, signifying a scenario in which all emissions occur during other phases. Conversely, the maximum value indicates a scenario in which all emissions occur within the current phase. Regardless of these settings, the bars continue to display the average.

SanDisk NAND 16GB
components CO2eq 22,034g
🟩 B6 - usage energy consumption

Fig. 13. Tooltip providing the user with precise information regarding the carbon footprint of the assets or sub-component.



(a) Default (b) With min/max option (c) With distorted scale and min/max (d) Hidden asset with distorted scale and min/max

Fig. 14. Various options revealing further information but therefore requiring greater effort to interpret correctly.

To enhance the visibility of very small values, the chart offers an optional square-root transformation, as provided by the Plot library and illustrated in Figure 14c. This transformation enhances readability by distorting the scale and moving small values to the bottom, thus rendering them more prominent. Furthermore, users may elect to conceal the asset's emission bars as depicted in Figure 14d, thereby creating additional space for the display of smaller component values. This visualization enables users to rapidly identify the life cycle phases that are the most emission-intensive and to identify whether the asset or its sub-components are primarily responsible for these emissions.

It is crucial to highlight that the emissions associated with the transportation of sub-components are incorporated into the overall asset life cycle. However, the data provided does not allow for the reproduction of the transportation footprints of sub-components within the parent, thus limiting the effectiveness of the visualization.

The second visualization, illustrated in Figure 15, is centered on the transportation-related emissions of the asset and its components. Each row in the chart corresponds to a specific component and includes a stacked bar, with each segment representing a distinct transportation route. The shading of each segment indicates the quantity of CO2eq per kilometer: darker shading represents higher emissions, while gray shading denotes unavailable data. This visualization allows users to identify transport routes with high emissions, which may be linked to carbon-intensive modes such as air transportation. This makes it easy to pinpoint components with significant transport emissions and potential areas for emission reduction.

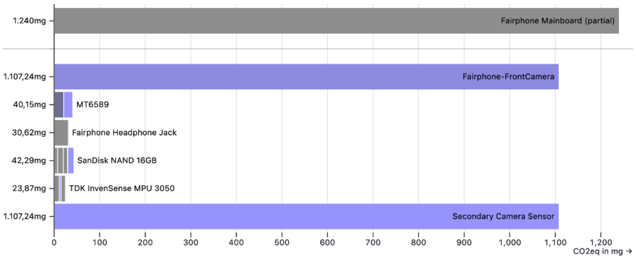


Fig. 15. Visualization depicting the transport routes of the asset and all its components, with the color intensity reflecting higher CO2eq/km values (or, if gray, indicating a lack of data).

The aforementioned visualizations facilitate a detection of emission hotspots across the life cycle phases and transport routes, thereby facilitating the implementation of targeted sustainability improvements.

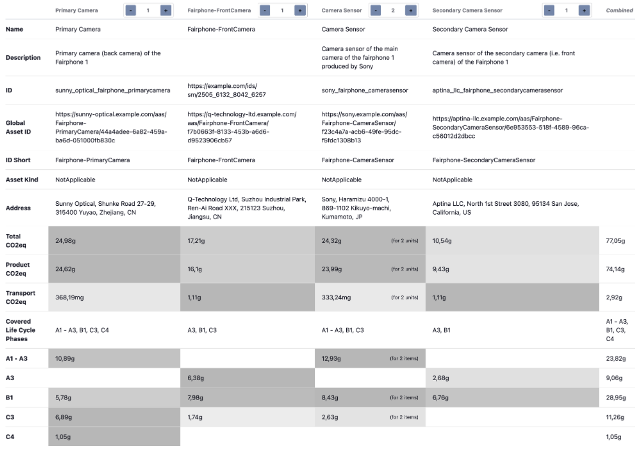
F. View: Comparison & Data Sheet

The Comparison View or also named Data Sheet is a comprehensive, single-page table designed for the convenient viewing and analysis of details regarding a selected asset. It implements the *Multi-Asset Data Sheet* module of the concept. The sheet includes essential meta-information such as the asset's name, description, identification numbers, and relevant addresses. Below, the focus shifts to environment-related attributes, including total CO2eq associated with the product, its transportation, and each specific phase of its life cycle.

On the right side of the asset table, users can find a button to add additional assets for comparison. New assets appear in the table alongside a *Combined* column, which aggregates values across rows, allowing users to see the cumulative impact of all selected assets. Rows with numeric values are normalized across all assets, with a visual color gradient that ranges from darkest (highest values) to lightest (lowest values), which enables the user to identify any outliers at a glance.

Additionally, the Data Sheet incorporates a functionality that enables users to dynamically adjust the multiplication factor in the header row of each asset, thus allowing them to scale numeric values as required. This functionality, when used in conjunction with the Combined column, facilitates the interactive creation of new hypothetical assets or scenarios.

In conclusion, the Data Sheet enables not only a comprehensive comparison of multiple assets, but also facilitates the exploration of adjustments through the provision of tools that support informed decision-making towards more sustainable asset configurations.



	Primary Camera - 1 +	Fairphone-FrontCamera - 1 +	Camera Sensor - 2 +	Secondary Camera Sensor - 1 +	*Combined*
Name	Primary Camera	Fairphone-FrontCamera	Camera Sensor	Secondary Camera Sensor	
Description	Primary camera (back camera) of the Fairphone 1		Camera sensor of the main camera of the fairphone 1 produced by Sony	Camera sensor of the secondary camera (i.e. front camera) of the Fairphone 1	
ID	sunny_optical_fairphone_primarycamera	https://example.com/ids/sm/2505_6132_8042_6257	sony_fairphone_camerasensor	aptina_llc_fairphone_secondarycamerasensor	
Global Asset ID	https://sunny-optical.example.com/aas/Fairphone-PrimaryCamera/44a4adee-6a82-459a-ba6d-051000fb830c	https://q-technology-ltd.example.com/aas/Fairphone-FrontCamera/f7b0663f-8133-453b-a6d6-d9523906cb57	https://sony.example.com/aas/Fairphone-CameraSensor/f23c4a7a-acb6-49fe-95dc-f5fdc1308b13	https://aptina-llc.example.com/aas/Fairphone-SecondaryCameraSensor/6e953553-518f-4589-96ca-c56012d2dbcc	
ID Short	Fairphone-PrimaryCamera	Fairphone-FrontCamera	Fairphone-CameraSensor	Fairphone-SecondaryCameraSensor	
Asset Kind	NotApplicable	NotApplicable	NotApplicable	NotApplicable	
Address	Sunny Optical, Shunke Road 27-29, 315400 Yuyao, Zhejiang, CN	Q-Technology Ltd, Suzhou Industrial Park, Ren-Ai Road XXX, 215123 Suzhou, Jiangsu, CN	Sony, Haramizu 4000-1, 869-1102 Kikuyo-machi, Kumamoto, JP	Aptina LLC, North 1st Street 3080, 95134 San Jose, California, US	
Total CO2eq	24,98g	17,21g	24,32g (for 2 units)	10,54g	77,05g
Product CO2eq	24,62g	16,1g	23,99g (for 2 units)	9,43g	74,14g
Transport CO2eq	368,19mg	1,11g	333,24mg (for 2 units)	1,11g	2,92g
Covered Life Cycle Phases	A1 - A3, B1, C3, C4	A3, B1, C3	A1 - A3, B1, C3	A3, B1	A1 - A3, B1, C3, C4
A1 - A3	10,89g		12,93g (for 2 items)		23,82g
A3		6,38g		2,68g	9,06g
B1	5,78g	7,98g	8,43g (for 2 items)	6,76g	28,95g
C3	6,89g	1,74g	2,63g (for 2 items)		11,26g
C4	1,05g				1,05g

Fig. 16. Data sheet comprised of four distinct assets, with the *Camera Sensor* featuring two instances that are included in the combined calculations performed on the right.

G. Current Prototype

The current prototype includes the features listed here. The data is recorded individually for each workpiece in a separate DPP [35] via process mining, and can be analyzed with our prototype. We provide further information on our website: https://www.policymodelling.com/dppviewer.

IV. DISCUSSION

The prototype is currently being used in our project, primarily to display and evaluate the partners' DPPs to be exchanged in the project for us as users. We have also started talking to the partners about optimization options in production. The feedback to the prototype has been positive because it provides a generally understandable overview of emissions from production and the production chain based on DPPs.

One major problem at present is the DPP data for pre-products from suppliers. This is because there is usually no information or only very rough information in traditional formats such as PDFs. Even if it can be assumed that the industry standard will still be adopted, the practical application benefits are still limited and are therefore restricted to evaluating the production emissions of the current producer only (and therefore without preliminary products). However, solid comparisons can already be made between different productions.

At times, the potential of DPPs and, consequently, also of graphical analysis solutions for DPPs can only be guessed at, especially if the entire value chain can be evaluated. However, it is difficult to say whether this goal is realistic and will work beyond the EU.

V. CONCLUSION

The DPP represents an excellent opportunity for advancing sustainability efforts, as its implementation is actively being pursued by the EU. This ongoing legislative push makes DPP particularly promising for production chain optimization, as companies will need to develop and integrate it in compliance with new regulations. The IDTA Asset Administration Shell is the most comprehensive and most chosen approach so far to practically provide a DPP along a produced product, but its intention lies in offering a practical data exchange solution between technical systems along the production chain, but not with a focus on human accessibility to the containing data and information.

In this paper, we described a solution on how to make use of Digital Product Passport data to offer a human-understandable view and analysis capabilities of Product Carbon Footprint information in such an Asset Administration Shell. The solution gives stakeholders, but also potential customers, easy and visual access to information on how many and where in the production chain the CO_2 emissions have been generated.

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REFERENCES

[1] European Commission, "The European New Green Deal," Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 12 2019, COM(2019) 640 final. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

[2] ——, "Carbon border adjustment mechanism," European Commission, Brussels, 2020. [Online]. Available: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

[3] European Parliament and European Council, "Directive 2003/87/ec of the european parliament and of the council of 13 october 2003 establishing a scheme for greenhouse gas emission allowance trading within the community and amending council directive 96/61/ec," 10 2003. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32003L0087

[4] European Commission, "A new circular economy action plan for a cleaner and more competitive europe," Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 03 2020, COM(2020) 98 final. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0016.02/DOC_1&format=PDF

[5] Directorate General for Communication, "Reducing carbon emissions: EU targets and policies," European Parliament, Strasbourg, 10 2023. [Online]. Available: https://www.europarl.europa.eu/pdfs/news/expert/2018/3/story/20180305STO99003/20180305STO99003_de.pdf

[6] A. Neligan, C. Schleicher, B. Engels, and T. Kroke, "Digital Product Passport as Enabler for the Circular Economy," Institut der deutschen Wirtschaft Köln e. V., Berlin/Cologne, Tech. Rep. 47/2023, 09 2023. [Online]. Available: https://www.iwkoeln.de/en/studies/adriana-neligan-barbara-engels-thorsten-kroke-digital-product-passport-enabler-of-the-circular-economy.html

[7] European Parliament and European Council, "Regulation (eu) 2023/1542 of the european parliament and of the council of 12 july 2023 on batteries and waste batteries, repealing directive 2006/66/ec and amending regulation (eu) no 2019/1020," *Official Journal of the European Union*, vol. L 191/1, 07 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

[8] D. Burkhardt and G. Ristow, "Enabling smart manufacturing with visual analytics for plant workers," in *Datenbanksysteme für Business, Technologie und Web (BTW 2025)*, ser. Lecture Notes in Informatics (LNI) - Proceedings, Volume P-361, M. Klettke, R. Schenkel, A. Henrich, D. Nicklas, M. E. Schüle, and K. Meyer-Wegener, Eds. Bonn: Gesellschaft für Informatik, 2025, pp. 665–678. [Online]. Available: https://doi.org/10.18420/BTW2025-33

[9] T. Post, R. Ilsen, B. Hamann, H. Hagen, and J. C. Aurich, "User-guided visual analysis of cyber-physical production systems," *Journal of Computing and Information Science in Engineering*, vol. 17, no. 2, p. 021005, 02 2017. [Online]. Available: https://doi.org/10.1115/1.4034872

[10] S. Liu, D. Weng, Y. Tian, Z. Deng, H. Xu, X. Zhu, H. Yin, X. Zhan, and Y. Wu, "Ecoalvis: Visual analysis of control strategies in coal-fired power plants," *IEEE Transactions on Visualization and Computer Graphics*, vol. 29, no. 1, pp. 1091–1101, 2023. [Online]. Available: https://doi.org/10.1109/TVCG.2022.3209430

[11] H. Schöning and M. Dorchain, *Big Smart Data – Intelligent Operations, Analysis und Process Alignment*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2024, pp. 611–630. [Online]. Available: https://doi.org/10.1007/978-3-662-58528-3_70

[12] W. Ochoa, F. Larrinaga, and A. Pérez, "Architecture for managing aas-based business processes," *Procedia Computer Science*, vol. 217, pp. 217–226, 2023, 4th International Conference on Industry 4.0 and Smart Manufacturing. [Online]. Available: https://doi.org/10.1016/j.procs.2022.12.217

[13] V. Berchtenbreiter, T. Schröder, F. Gast, O. Kohn, M. Stolze, and M. Weigold, "Machine component monitoring in data and service ecosystems enabled by the asset administration shell," *Procedia CIRP*, vol. 130, pp. 1474–1479, 2024, 57th CIRP Conference on Manufacturing Systems 2024 (CMS 2024). [Online]. Available: https://doi.org/10.1016/j.procir.2024.10.269

[14] Z. Bradac, P. Marcon, F. Zezulka, J. Arm, and T. Benesl, "Digital twin and aas in the industry 4.0 framework," in *IOP Conference Series: Materials Science and Engineering*, vol. 618. IOP Publishing Limited, Bristol, United Kingdom, 2019. [Online]. Available: https://doi.org/10.1088/1757-899X/618/1/012001

[15] World Commission on Environment and Development, *Our Common Future*. Oxford: Oxford University Press, 1987.

[16] IPCC, *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Integovernmental Panel on Climate Change*, R. Watson and Core Writing Team, Eds. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2001. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_TAR_full_report.pdf

[17] J. Elkington, *Cannibals with forks : the triple bottom line of 21st century business*. New Society Publishers, 1998.

[18] P. H. Walker, P. S. Seuring, P. J. Sarkis, and P. R. Klassen, "Sustainable operations management: recent trends and future directions," *International Journal of Operations & Production Management*, vol. 34, no. 5, 2014. [Online]. Available: https://doi.org/10.1108/ijopm-12-2013-0557

[19] J. Elkington, "Towards the sustainable corporation: Win-win-win business strategies for sustainable development," *California management review*, vol. 36, no. 2, pp. 90–100, 1994.

[20] R. Dai, R. Duan, H. Liang, and L. Ng, "Outsourcing climate change," *European Corporate Governance Institute–Finance Working Paper*, no. 723, 2021. [Online]. Available: https://dx.doi.org/10.2139/ssrn.3765485

[21] European Parliament and European Council, "Directive (eu) 2022/2464 of the european parliament and of the council of 14 december 2022 amending regulation (eu) no 537/2014, directive 2004/109/ec, directive 2006/43/ec and directive 2013/34/eu, as regards corporate sustainability reporting," 12 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464

[22] ——, "Regulation (eu) 2023/956 of the european parliament and of the council of 10 may 2023 establishing a carbon border adjustment mechanism," *Official Journal of the European Union*, vol. L 130/52, 05 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R0956

[23] Plattform Industrie 4.0, "Specification of the asset administration shell: Part 5 - package file format (aasx)," 04 2023. [Online]. Available: https://industrialdigitaltwin.org/wp-content/uploads/2023/04/IDTA-01005-3-0_SpecificationAssetAdministrationShell_Part5_AASXPackageFileFormat.pdf

[24] Industrial Digital Twin Association, "Specification of the Asset Administration Shell - Part 1: Metamodel," Frankfurt a.M., 03 2023. [Online]. Available: https://industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01001-3-0_SpecificationAssetAdministrationShell_Part1_Metamodel.pdf

[25] ——, "Hierarchical Structures enabling Bills of Material Specification," Frankfurt a.M., 06 2024, Submodel Template of the Asset Administration Shell. [Online]. Available: https://industrialdigitaltwin.org/wp-content/uploads/2024/06/IDTA-02011-1-1_Submodel_HierarchicalStructuresEnablingBoM.pdf

[26] ——, "Carbon Footprint Specification," Frankfurt a.M., 11 2023, Submodel Template of the Asset Administration Shell. [Online]. Available: https://industrialdigitaltwin.org/wp-content/uploads/2024/01/IDTA-2023-0-9-_Submodel_CarbonFootprint.pdf

[27] B. Shneiderman, "The eyes have it: A task by data type taxonomy for information visualizations," in *VL '96: Proceedings of the 1996 IEEE Symposium on Visual Languages*. IEEE Computer Society, 1996, p. 336.

[28] D. Burkhardt, K. Nazemi, P. Sonntagbauer, S. Sonntagbauer, and J. Kohlhammer, "Interactive visualizations in the process of policy modelling," in *Electronic Government and Electronic Participation - Joint Proceedings of Ongoing Research of IFIP EGOV and IFIP ePart 2013*, ser. LNI 221, vol. 221. Bonn, Germany: Gesellschaft für Informatik e.V.., 2013, pp. 104–115, iSBN: 978-3-88579-615-2. [Online]. Available: https://dl.gi.de/handle/20.500.12116/17255

[29] D. Keim, G. Andrienko, J.-D. Fekete, C. Görg, J. Kohlhammer, and G. Melançon, *Visual Analytics: Definition, Process, and Challenges*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 154–175. [Online]. Available: https://doi.org/10.1007/978-3-540-70956-5_7

[30] Industrial Digital Twin Association, "Specification of the asset administration shell - part 2: Application programming interface," 06 2023. [Online]. Available: https://www.industrialdigitaltwin.org/wp-content/uploads/2023/06/IDTA-01002-3-0_SpecificationAssetAdministrationShell_Part2_API_.pdf

[31] R. Gürbüz, "Assessing vue as a tool forcreating prototypes ofsystems for expert users," Master's thesis, Uppsala University, 2023.

[32] M. Bostock, V. Ogievetsky, and J. Heer, "D^3 data-driven documents," *IEEE transactions on visualization and computer graphics*, vol. 17, no. 12, pp. 2301–2309, 2011. [Online]. Available: https://doi.org/10.1109/TVCG.2011.185

[33] A. Lavanya, S. Sindhuja, L. Gaurav, and W. Ali, "A comprehensive review of data visualization tools: features, strengths, and weaknesses," *Int. J. Comput. Eng. Res. Trends*, vol. 10, no. 01, pp. 10–20, 2023. [Online]. Available: https://doi.org/10.22362/ijcert/2023/v10/i01/v10i0102

[34] D. Burkhardt, T. Ruppert, and K. Nazemi, "Towards process-oriented information visualization for supporting users," in *Proceedings of 15th International Conference on Interactive Collaborative Learning (ICL 2012)*, ser. 15. Piscataway, NJ, USA: IEEE, 2012, pp. 1–8. [Online]. Available: https://doi.org/10.1109/ICL.2012.6402080

[35] D. Burkhardt, J. Harbarth, and A. Görmer, "Process mining for production optimization in smart manufacturing," in *2025 29th International Conference Information Visualisation (IV)*. IEEE, 2025.