DESIGNING A LOW-COST DIGITAL SHADOW DASHBOARD TO MAP PART LOCATIONS IN MANUFACTURING

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Abstract

As an ever-increasing volume of data gets collected within industrial companies, existing data visualization methods become inadequate, and much of this data ends up just filling storage inside databases. This is particularly the case when interpreting data on the location of different resources, such as parts or machines, as it is difficult to represent intuitively with common options like tables or graphs. This paper explores how to effectively visualize this data and provide a solution that facilitates gaining visibility into lost items, production routes, and congestion. Specifically, a digital shadow dashboard is developed that maps production and resource data onto manufacturing companies' floorplans. In addition, dynamic value stream mapping is also explored. Testing is done with industrial small-to-medium enterprises (SMEs), prioritizing low-cost software to ensure viability for them. A research through design approach is used to investigate the information needs of the SMEs, and to develop dashboard designs to address them. As a result, this project sits at a nexus between industrial engineering, UI/UX design, user research within industrial SMEs, and software prototyping on a low development budget. The contribution of the paper is the structured development of a digital shadow of factories' floorplans, with a dashboard to convey part location data to users. The approach and steps taken also serve as a guide for the development of future digital shadow dashboards for industrial SMEs or research.

1 INTRODUCTION

It has been more than a decade since the term Industry 4.0 was coined, and yet, rather than proposed *smart factories* being ubiquitous, most industrial companies are still in the early stages of digitalization. There have been numerous technological advancements that promise greater efficiency in manufacturing, such as automation, IoT, and data science. Unfortunately, for the most part, these remain expensive solutions that require extensive infrastructure in place, with high barriers to entry in terms of capabilities, namely technological readiness and digital maturity, and resources available [1]. This poses a large problem for small to medium enterprises (SMEs) in manufacturing, which typically have less of each [1], [2].

There is a risk of an ever-growing gap developing between larger manufacturers, who can afford the high cost to entry of using Industry 4.0 technologies, gaining efficiency at an ever-increasing rate, while SMEs are slowly left behind [3]. This would have a significant impact on the economy, with SMEs making up 99.8% of (non-financial) companies in the EU and employing 67% of its workforce (89.7 million people) [4], [5]. Based on this, a transition to Industry 4.0 cannot be complete without SMEs being involved. It is our experience that SMEs within manufacturing understand this situation, and constantly explore options for integrating new technologies, but that they require support in overcoming the hurdles required to achieve Industry 4.0.

1.1 Data visualization

The hurdle that this paper focuses on addressing is the problem of how to visualize the vast quantities of data that a *smart factory* can generate. This turns what could be a powerful asset for an SME adopting new technologies into something that just fills storage inside databases. Many papers discuss this disparity, especially that despite the availability of manufacturing data, it is difficult to analyze, understand, and use it in industrial enterprises. However, how to use this data to provide "business intelligence" and improve decision making capabilities, stands out as a neglected area within Industry 4.0 technology development and research [6], [7], [8].

The major obstacles in using this data to support decision making are that the data is "complex, abstract, and variable". [9]. Displaying this data via data visualization rather than as text/structured text formats like tables, allows the human brain to process it and identify patterns more easily. [10] In addition, data visualization methods are an area of Industry 4.0 that can be researched and developed on a relatively cheap budget (when compared to hardware), with plenty of free, open-source options that can be used. This is demonstrated in research papers like [2] and [3]. This means that it is an excellent avenue for low-cost improvements to SMEs capabilities, provided they already have data to visualize in the first place.

1.2 Location visualization

In particular, through discussion sessions and preliminary interviews, location information was highlighted by users within industrial companies as well as fellow SSM researchers, as an area that needed attention. Location information was described as being currently displayed using just timestamps within tables, with associated resource and location ID. This is a problem as the additional time taken to retrieve this data in an emergency, like finding a lost part, causes additional delay and difficulty, especially because the name given to a location is not always clear with just text (e.g. Which assembly bay out of 12 that are spread around the factory is assembly bay 4?). In addition, gaining long-term information about patterns, like analyzing the routes taken is

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difficult when just looking at a table. Common visualization methods like bar charts or graphs can provide basic summaries, such as at which station products wait the longest, or how long different parts waited, but seeing a 'bigger picture' and understanding patterns like which geographic area of a factory sees the most delay, or what in a part's route causes a bottleneck are less clear and require more work done to analyze it. If this data could be viewed in context of the floorplan, it would be more intuitive and faster to interpret the data and understand patterns within it.

1.3 Related Literature

A wealth of literature exists on data visualization for the manufacturing industry, however, with a seeming lack of exploration into visualizing part locations. Instead, a greater focus is placed on using visualizing data for other specific applications that are case-study dependent. This can be seen across [11], [12], [13], [14], [15], [16], [17]. Using a Digital Twin/Digital Shadow (DT/DS), was mentioned numerous times throughout these and seemed like a promising option for location visualization (DTs/DSs further explained in section *1.5 Proposed Digital Shadow)*.

Homing in on papers [18], [19], [20], [21] that explored using DTs/DSs for tracking part location, these were theoretical, and without development or testing with use cases. This indicates a gap in academic literature when it comes to developing digital shadowing/twinning of entire factory floors and being able to view the locations of parts using them, especially for real world case studies.

1.4 Problem analysis

Therefore, the problem this research paper seeks to address is that of a lack of suitable location visualization solutions within industrial SMEs, which leads to an underutilization of location data, and in turn hinders process optimization, and causes downtime when looking for parts. While there is a gap in academia, there are commercial solutions that exist for tracking resources. SME partners identified the following problem areas with these:

- Risk of 'vendor lock-in', where the SME becomes increasingly dependent on the software provider.
- Expensive without a clear return on investment (ROI).
- Difficult to integrate with existing ERP systems used by SMEs.

This was in line with previous findings of barriers to entry [4]. In addition, while researching these commercial tools, there was no publicly available information for specifics like the cost, look and feel, and ease of integration. This complicates objective analysis and reveals lack of transparency as an additional problem. To address these problems, this research focuses on creating an open source, low-cost proof of concept to investigate how these needs can be met. Emphasis is placed on having an open, exploratory process that other researchers and developers can build on.

1.5 Proposed Digital Shadow

The proposed solution to the aforementioned problems is the development of a digital shadow dashboard. In other words, this would be an app that mirrors the real state of the factory floorplan, tracking the locations of parts and machines on the production floor. To allow for real-time monitoring with vast volumes of data, a digital shadow (DS) architecture is chosen.

A digital shadow is a copy of a physical object, in this case the factory floor. This makes it easier to interpret and allows for tracking of resources. It is important for the data to be placed in context, like a map that the user can consult as it is immediately clear what location is which, speeding up analysis. Digital shadows are differentiated from the more common concept of digital twins, by the direction data flows between them and the physical object/system they represent. DSs only receive data from the physical entity, whereas Digital Twins (DT) have a "two-way" [22] flow of information, and send data to, and affect the physical object. A DT could, for example, be used to shut down a machine from a distance, if it seems like there is any risk. Developing a DS rather than a DT is chosen, as it requires less development time, and less advanced hardware. These are crucial since SMEs mentioned expensive existing solutions, and an unclear return on investment, as barriers to visualizing collected manufacturing data. A digital twin would take more resources to implement for a given SME than a DS, and the research results from this project do not show SMEs having needs that would justify this. [22]

A DS is chosen as the solution for contextual data visualization, that will enable SMEs to track the location of resources in production, gain visibility into the routes taken by their parts, view congestion, and locate missing products. Should this be achieved, it could reduce time spent looking for parts, and support process optimization, leading to reduced time and cost in manufacturing [23]. In order for the user to interface with the digital shadow it will also need to act as a dashboard that can be used to analyze data. As such the tool being developed is dubbed the Digital Shadow Dashboard (DSD). The tool's target users are management and supervisors in discrete manufacturing SMEs, which produce in subsequent steps. The focus was especially on small series and large variety manufacturers.

1.6 Tagging/Tracking hardware

Experimentation with the hardware used for location tracking of parts is out of the scope of this paper. This is because existing research already covers it (e.g. [24], [2]), and because completely different research methods are required compared to data visualization. Multiple technologies can be used for resource localization in manufacturing, but the main options are RFID tagging, QR or Barcode scanning at a workstation, or manual input of events. SME partners involved in the project already use either QR/Barcode scanning or manual event input to record manufacturing steps for parts in the factory. These recorded events include the production cell where they took place and thus provide the location of parts. RFID tagging methods can track location without adding additional time for tagging, but are often very expensive, particularly for complete Real Time Localization Systems (RTLS). An innovative low-cost approach is having passive RFID tags, and a tag-mapping robot that drives around the factory floor detecting tags [25].

The remainder of the paper is organized as follows: Section *2 Methodology* presents the research and design methods followed, Section *3 Results* presents the architecture and visual representation of the DSD, Section *4 Discussion* discusses the adoption by SMEs and discusses further development and Section *5 Conclusions* concludes the paper.

2 METHODOLOGY

The objective of the research is to demonstrate the potential of using a digital shadow to visualize location information, in a way that it can be replicated for use in other industrial SMEs. This leads to the research question:

How can the location information of products and machines on the factory floor, at SME manufacturing companies, be displayed using a digital shadow, to meet the information needs of their management-level employees?

2.1 Interviews with management level employees

In person interviews (N=8) were held with production and IT management employees within industrial SMEs. They focused on understanding information needs, and the existing data visualization methods within the SME. The interviews took the form of unstructured, open-ended conversational interviews, but with an outline of questions to answer that the researcher had with them to steer the conversation as needed. These interviews were recorded and transcribed with the consent of the participants.

2.2 Online survey/questionnaire with open questions

In addition to interviews, an online survey was used to further reach participants about the information needs within their SMEs. This was done to validate the interviews, and get responses from a broader set of participants, where interviews were more difficult or not possible. Participants (N=10) were contacted among regional SMEs via email, and through a LinkedIn post. The questionnaire was aimed at taking less than 10 minutes for each participant to complete, to not be disruptive for the industrial companies involved

2.3 Dashboard design

Once the needs of the users (see Section 3.1 below) had been established using interviews and surveys, a solution could be designed to meet them. Design followed an iterative, double diamond process, where focus was first placed on diverging and generating as many ideas as possible, before converging and selecting those that were best suited to the project requirements. Dashboard design principles highlighted in [26] were followed. A function analysis was used to categorize what functions needed to be figured out and create ideas accordingly. This separated the core functions which had to be developed from 'extras' that were beneficial but could be added over time based on how much interest there was. The core functions were: receive data, display a graphic of the production floor, display part data over this graphic, and, update to reflect changes in real-time. Extra functions were: analyzing long term data, adjusting the level of details (e.g. zooming in/out), creating dynamic value stream maps, as discussed in [27], and, displaying workstation statuses. Solutions were generated first through hand draw sketches, with proposed combinations created as wireframe drawings of the dashboard interface. Following this, a first prototype could be created.

2.4 Prototype development

Digital prototyping has been carried out in tandem with the design process, where prototyping is used to refine and iterate upon the current design. Using this approach, a number of subsequent prototypes were developed, improving elements with each iteration. This allowed for the concept of the digital shadow dashboard to be in line with what is realistic and what users expressed when testing the prototypes.

2.5 Prototyping tool selection

In order to develop prototypes in the first place, suitable tools had to be chosen. This was done by ranking options using important criteria to the project, both for the feasibility of development, and from discussion with SME stakeholders. These criteria were that it had to be developer friendly, low-cost, open-source, web-based, and have a good look & feel for users. As part of being developer friendly, the tool using Python, or being low code, was another factor, as broadly, most researchers and students consulted with were very familiar with Python and using the Pandas Python package for modifying the data.

Criteria	Weight	Streamlit	Grafana	Dash	Voila	Jupyter	Node-RED	Flask	Firebase
1. Developer Friendly	12								
1A. Python based	4	10	8	10	10	10	8	10	1
1B. Documentation	4	8	7	8	6	4	5	6	7
1C. Low code option	1	5	10	8	7	7	8	7	7
1D. Easy to get started	3	7	7	8	7	9	8	6	8
2. Cost	2	10	10	10	10	10	10	10	10
3. Look & Feel	1	7	6	8	4	2	4	7	7
4. Adaptable	5	7	6	9	7	6	8	8	7
Totals	20	160	147	177	151	142	148	156	125

Figure 1: A ranking of possible prototyping tools following the most relevant criteria. The ranking shown emphasized developer friendliness.

Weights were assigned to each criterion based on its relevance to the project, with 4 different rankings (with an example in *Figure 1*, seen above) being done with different weights based on considering how different priorities changed weights. The scores of all of these were averaged to arrive at the final scores. The prototyping tools Grafana and Dash scored the highest, and an initial prototype was created for each to compare. Grafana (by Google) seemed excellent as a low-code tool for creating prototypes, but after experiencing the development process using it, the researchers found it difficult to create custom graphs, with precise coordinates, as needed for the floorplan map. The outcome was the selection of Dash as a tool to create the web app, and Pandas used for data processing tasks. Dash is a python package that utilizes Plotly.js, React and Flask, and is tailored to quickly creating interactive web apps to display data. Only python code is required to create the apps, and pre-built components exist. This allowed for flexibility in developing custom functions as needed, while being user friendly.

2.6 User testing & validation with management of industrial SMEs

User testing was used to test and validate prototypes, allowing for insights to be gained for iterative improvement of the design and prototypes. This was crucial to check back at how well the information needs identified were being met. Participants (N=11) were the target users of production and IT management at SMEs, as they had provided the needs. Testing was carried out through a combination of tasks given to complete and open-ended interview style questions. Room was given for users to freely discuss their thoughts in a conversational manner. User testing was carried out via a 7-step process that ranged from briefing the user, inquiring about their daily tasks, asking about how they perceive the interface of the DSD, and feedback, comments and reflection is prompted on how they found using the DSD. Results are summarized in Section 4.1. below.

3 Results

3.1 User needs

The interviews and surveys confirmed that users were dissatisfied with current data visualization, especially regarding location. Mentioned as needs not met by existing commercial solutions were being able to: find lost parts and tools on the production floor, analyze and review production lines and the routes taken by parts, spot bottlenecks on the dashboard, respond quickly to crises that may appear, based on more intuitive monitoring of the shop floor.

3.2 Prototyping insights & User testing

Initial prototypes revealed that the Digital Shadow Dashboard was feasible using Dash and was used for initial user testing. Test use cases were diverse and included: a miniature simulation factory (Training Factory Industry 4.0 24 V by Fishertechnik GmbH) in a university lab, an SME working in precision metal manufacturing, an industrial SME working in prefabricated housing, and an SME working in metal pipe manufacturing. These test cases were selected based on availability and interest in the project, as well as ensuring variety in type of manufacturer. Subsequent user testing in adapting to different case studies revealed that adaptability of the DSD was crucial in navigating the different use cases and their needs. The biggest example of this was the different data input methods required between test use cases. Three different methods for data input would be developed: CSV event data uploaded to the DSD's directory, an InfluxDB time series database from which data can be uploaded and queried, and API calls being made directly to the SMEs ERP/MES system. A flexible architecture was used to accommodate these different data formats, a simplified version of which can be seen below.

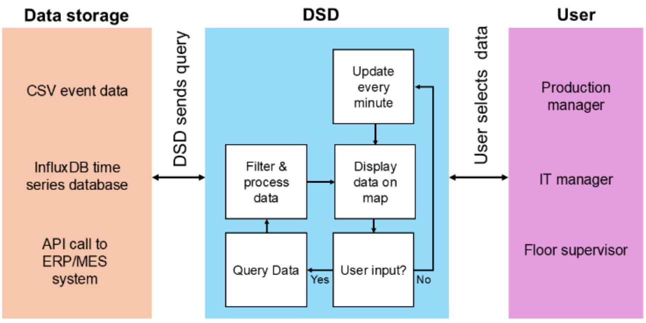

Figure 2: A simplified system architecture of the DSD, showing how it interacts with users and external data storage.

An additional factor that underscores the need for flexibility in the architecture of the DSD is the lack of uniformity across terms, formats and headers in databases. While one company will have columns and values like: "ResourceID: C-00231", another will have "Part: 0245". This is the case for every type of field encountered with SME data, including terms such as Timestamps, which as an example were called: "Timestamp", "start/stop", or "happened".

This lack of standardization was a real problem in ensuring the code of the digital shadow dashboard is transferable. The current solution is to convey the terms required by the DSD to the user through a manual, with existing code that can be used to match names between the provided data and expected format.

3.3 Final Interface Design

For the user interface of the DSD (*see Figure 3 on the next page)*, the outcome of the iterations is a comprehensive multi-age app, with a minimalist UI and parameter bars that can be used to filter data and configure each page. The digital shadow dashboard interface developed consists of a map of the factory floor in the center of the page, over which information can be overlayed. At the top of the page is a navigation bar that can be used by the user to switch between 'tabs' that offer different features. Below this is a 'parameter bar' used to configure visualization type, time range, and look for specific resources using their IDs. The tabs are characterized as follows:

1. Operational map: This tab is created for real time awareness, including viewing recent events in the factory, spotting bottlenecks or problems as they occur. It contains a map of the floorplan that updates live following a recent time range that the user can select in the past from the current time (e.g. The past 1 minute).

2. Analysis map: Displaying the same map with overlayed data as the previous tab but is instead intended for long term analysis. It is a separate tab as different (asynchronous) code is used to retrieve this long-term data, which is far larger, and the map does not update live. A calendar selector is used for the start and stop of the time range the user wants to view.

3. Locations: A static map that shows the locations the DSD was able to retrieve via and any associated data. It is a separate tab since it does not retrieve events, and as such uses different code. This can be used by users to see what locations are currently being used in the other tabs, clarify details (like which welding station counts as 'Welding 3'), and double check that they are at the right coordinates on the floorplan.

4. Tag mapping: A map that updates live and shows what the last tagged resource in the factory was. Intended to supply a live view on the shop floor and be used for intended, it is its own tab as it handles raw location testing and verifying that the tagging hardware works as events, without additional data analysis features.

5. Value Stream Map: This tab is a tool where part IDs can be input, and value stream maps are dynamically created. These are diagrams that show which 'value adding' processes each part went through, and what the waiting time was. Multiple parts can be added, with a table at the top of the page allowing for a comparison of their total processing time, and how much of it was 'value adding'.

6. Data table: A tab that shows the raw data retrieved for a given time range or resource ID. This can be used to consult specific information or verify whether the data shown in the maps is accurate.

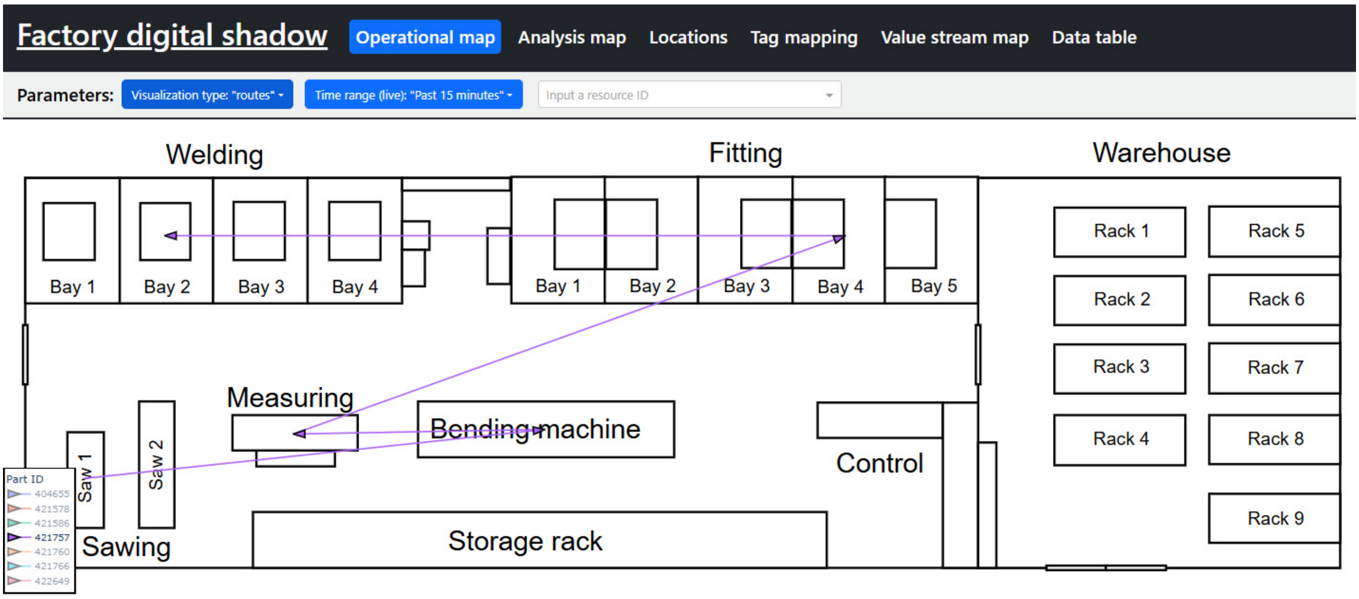

Figure 3: A screenshot of the current prototype Digital shadow dashboard interface, an example factory floorplan is used to preserve SME partner data privacy

User testing revealed room for improvement with multiple existing UI elements, desiring greater feedback being provided to know what they can interact with, and when they have interacted with an element. This led to several improvements such as new improved calendar date selection, ability to hover over data points, and a loading animation while data is being retrieved. There were also many user requests for new features that could be integrated. Some notable examples include: The search bar to retrieve data for specific products, the ability to view routes taken by parts through the factory and the option to zoom in and out of the map to specific areas. A requested features document was made where features could be placed in a queue by order of importance and difficulty. This way feedback from user testing was never forgotten and would in time be added, but there was prioritization as not every feature is as realistic or necessary, and trying to implement all at once would have been overwhelming. A GitHub repository containing a shareable version of the code, and media showing the UI can be found at this link.

3.4 Final DSD Prototype

The most recent outcome of the iterative cycles of prototyping and development is a fully functional web application that retrieves data directly (via API calls) from the partner SMEs Manufacturing Execution System (MES) to be a digital shadow of the production floor that updates in real time. The SME used for testing found the finds the DSD useful for monitoring the routes taken by parts, analyzing where bottlenecks usually occur, and aiding logistics in locating parts for deliveries. Currently, they have machine operators, welders, and logistic employees scan barcodes to report when jobs are done, and this is used by the DSD to track where pipes are and have been. To set up and configure the DSD, the SME had to provide an SVG image of their floorplan, coordinates for where different locations are on the floorplan (In a JSON format), and to connect their event data (through API calls for this SME). The existing data from the user, in this case in their MES system, acts as a Single Source of Truth, and ensures that their data cannot be harmed by the DSD.

4 Discussion

The goal of this research paper was the development of a low-cost digital shadow dashboard that would be suitable for industrial SMEs and would help solve their information needs without having the same drawbacks as existing commercial solutions. In this respect the designed DSD has been successful, which will be substantiated in the following sections. This research paper, through the final prototype and the design of the DSD provides an answer to the initial research question (written in 2 Methodology).

4.1 Reception with SMEs

Reception with all the involved SMEs has been very positive. When asked if they would use such a system, a metal working SMEs IT systems manager said that they would "Want this system right now". A logistics manager working in a pipe manufacturing company said that they were impressed with the tool and were interested in receiving what could be shared in the code to see if they could begin integrating it in production. Finally, a manager working in an SME that makes prefabricated wooden buildings was very interested in the tool but was interested in creating a version that used JavaScript for their companies. This was an interesting example of how the DSD could spark development of similar tools just by showing the concept to SMEs. SMEs were interested in the low-cost aspect and lack of vendor lock in.

4.2 Low-cost development

When it comes to the cost of developing the DSD, the technology used was all free and open-source to use, with only the development time needed as a cost. This means that the extent to which it is low-cost is entirely dependent on how much work is needed to adapt it to different test cases. The digital prototyping tools of Python using Dash, and other Packages for handling data and retrieving data were all completely free to use for development, although Dash does also have a paid version that could be used for hosting the web app (though not used during this project). Dash uses the MIT license, and Python has its own PSFL license, both of which are open-source and permissive. Inkscape was used for cleaning up floorplans but is also free. The Microsoft Office was used for editing CSVs and creating documents, though this could easily be replaced with a free alternative. All things considered, the researchers do not find any room for making the tools used more 'low-cost'. In terms of development time, it was considerable, but greatly lengthened because of the exploratory, iterative approach, which was trying to figure out what to develop, as well as how to at the same time. It should be noted that none of the researchers involved have experience as professional developers, and that a senior developer, or for example, a team of computer science students, could likely follow the design process taken and develop a DSD in a much shorter time. This was validated by a team of students from FONTYS Eindhoven, who managed to re-create the DSD, having code and assets shared with them, using completely different tools (JavaScript, Rest API) within a few months. This showed the transferability potential of the DSD

4.3 As an example for future development

The DSD and the process of developing it serves as an open-source guide for future development of digital shadows to visualize the locations of parts in manufacturing. Following meetings with SME partners and within the researchers, it has been agreed to create a GitHub with code developed for the project, as well as a *readme* document will be created for the project. Ideally, an interested party would only need to read the readme instructions, provide their floorplan and data in the correct location/format, and then could run the DSD. Options for implementation within industrial SMEs are: the SME requesting a similar tool from their ERP/MES system provider, developing it themselves, or implementing it with support from the university. Diagrams and flowcharts of how the DSD works, and the development process have also been created as visual aids for development guides (e.g. *Figure 4*, below).

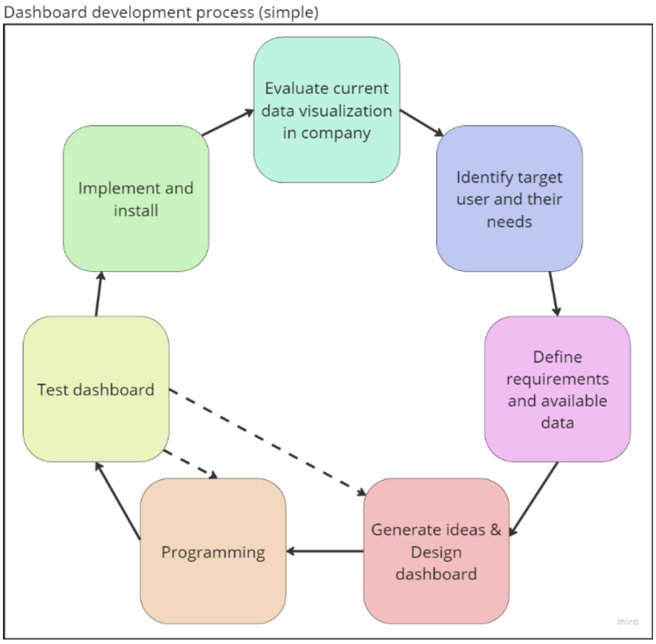

Figure 4 - A diagram of the Dashboard design process followed. It is iterative and cyclical, with dotted arrows to represent re-designs following testing. It has been greatly simplified to be readable.

4.4 Recommendations

While the results of the study are promising and demonstrate the possibility and usefulness of developing the DSD to meet information needs, there is room for improvement. The following recommendations are proposed to be researched:

- Validating user testing and interviews with a greater number of participants. The current sample size is rather small and could be inaccurate for users at large.
- Testing with a greater range of SME case studies, operating in different types of manufacturing, and with varying levels of IT infrastructure. The SME case studies used may not accurately represent the range of industrial SMEs.
- Development through other software development tools (JavaScript, directly in HTML, C++). While Dash and Python code proved adapted to the needs of this research, other tools could be better suited and this should be explored.
- Analyzing the information needs of other stakeholders (machine operators, welders, assemblers). This research focused on management as it was the easiest to reach and the most engaged with data visualization, but other users would bring valuable new input and opportunities.
- Experimenting with new features, such as different accounts for types of users, or a configurability/settings menu. There were several requested features that were not possible to develop within the timeframe of research but have great potential and should be explored.

5 CONCLUSION

This research paper investigated how a digital shadow could be used to communicate the location of parts within industrial SMEs to human users, in a way that met their information needs. Initial findings from management in industrial SMEs revealed a dissatisfaction with commercial solutions for viewing location, and a list of unmet information needs. From these, a Digital Shadow Dashboard was designed, and iterative cycles of prototyping, user testing, and further designing were used to refine the DSD. The first prototypes revealed that it was technically feasible to create the proposed DSD with the chosen methods, and its current iteration is complete proof of concept that has been validated across varied test cases with industrial SMEs. This research paper has met all of its goals, with reception of the DSD being positive with manufacturing SMEs and having been developed at a low cost. The design process taken, as well as code and overall design aim to serve as a foundation that others, whether in industry or research, can build on, developing their own DSDs, which would hopefully improve efficiency within industrial SMEs, by reducing time searching for lost parts, along with supporting process optimization and decision-making capabilities. Should this happen, it would be a small, but meaningful step in ensuring that these SMEs don't fall behind and are able to thrive and benefit from Industry 4.0.

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