Digital Dataspace and Business Ecosystem Growth for Industrial Roll-to-Roll Label Printing Manufacturing: A Case Study

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***Abstract*—Manufacturing industries across the globe are adopting modern technologies rapidly and are now moving towards Industry 5.0. However, many manufacturing units still need to yield their Industry 4.0 level amid reasons including heavy investments in upgrading existing infrastructure and scrapping existing machinery in the name of modern digitalization. These Small and Medium-sized Enterprises (SMEs) need help finding the best-fit technology to meet their business requirement and impact along with the capital to support digitization. In this study, we present one such case of a Danish manufacturing industry, a label printing SME, stranded between conventional technology and a race towards modern digitization. On the one hand, it has old machinery with a large volume of heavy printing and lamination operations with an established customer base. On the other hand, it is willing to digitalize its manufacturing processes (with minimal upgradation in its existing mechanical infrastructure) to enhance its efficiency and sustainability and catch up with the pace of digitalization for further expansion. This can be achieved by nurturing the benefits of digitalization through the latest technologies, such as Enterprise Resource Planning (ERP), Internet of Things (IoT), Edge, Blockchain, Cloud computing, etc. We studied and analyzed the case of the SME in consideration to understand the core requirement and anticipated bottleneck in the process. This paper has presented our findings through related business process flow mappings, challenges, vision, and possible digital architectural solutions using modern-day technologies, scientific approaches and realization tools. These findings and methods will also be value-added and applicable to other SMEs in similar situations. Thus, it enables them to save their Return on Investment (ROI) while adapting to modern technologies with minimal risk, impact and investments.**

***Index Terms*—Architecture, Blockchain, Business Process Mapping, Digitalization, Edge, IoT, Label Printing, Manufacturing, Semantics**

I. INTRODUCTION

The manufacturing industry has been the backbone of any economy across the globe for decades. With the advent of Industry 4.0 [1], the manufacturing industry has focused towards adaptation, automation and data-driven manufacturing operations leveraging modern technologies such as the Internet of Things (IoT) [2], Big Data [3], Enterprise Resource Planning (ERP), Platform Solutions, etc. [4]. The industry is slowly moving towards Industry 5.0, wherein human and machine interaction is a prime focus. However, the Industry 5.0 evolution can only be achieved once Industry 4.0 is adopted, as it addresses the socio-economic impacts of Industry 4.0 on humans [5]. Thus, the manufacturing industry must first achieve the Industry 4.0 goals, which seems way easier for large manufacturing companies because of the available workforce, resources and investments than SMEs. Adopting Industry 4.0 seems strenuous for SMEs as they have limitations with finances, knowledge resources, workforce, and trending technical advances [6].

To deal with similar challenges of SMEs in Denmark, the Danish government has started a growth technology project called Manufactory to boost collaborations between industry and knowledge institutions at a regional level under the supervision of the Danish Industry Foundation [7]. This project has several consortium partners from academia and industry to develop a common platform where both can collaborate and co-create solutions, leveraging modern cutting-edge technologies, to real-world industrial problems (particularly for SMEs). This study results from one such initiative among several taken under this Manufactory project at our Department of Business Development and Technology (BTECH), Aarhus University, - a key academic partner in this project. We collaborated with a Roll-to-Roll (R2R) Label Printing SME with a worldwide clientele base in the Midtjylland area of Denmark. The company got its latest machinery and other infrastructure installed in 2007; thus, the upgradation to modern mechanical infrastructure is not straightforward. However, the SME still has a desire to nurture benefits and cope with modern digitalization to create efficient and value-added expansions, such as data sharing with their customers in real-time, making the production environment smarter and augmenting digitalization slowly and steadily to come up with a differentiator and transformed business model in the Label Printing domain. In this context, for example, IoT technology and related edge network sensing capabilities, such as environmental, print quality, ink toning, bar-code, energy efficiency, predictive maintenance, production line sensing, etc., can streamline operations, improve quality control, enhance supply chain visibility, and reduce costs for the SME. Thus ultimately benefiting both the SME and its customers.

This study summarizes the insights and knowledge acquired while collaborating with the R2R label printing SME through workshops and one-on-one interactions with the company's

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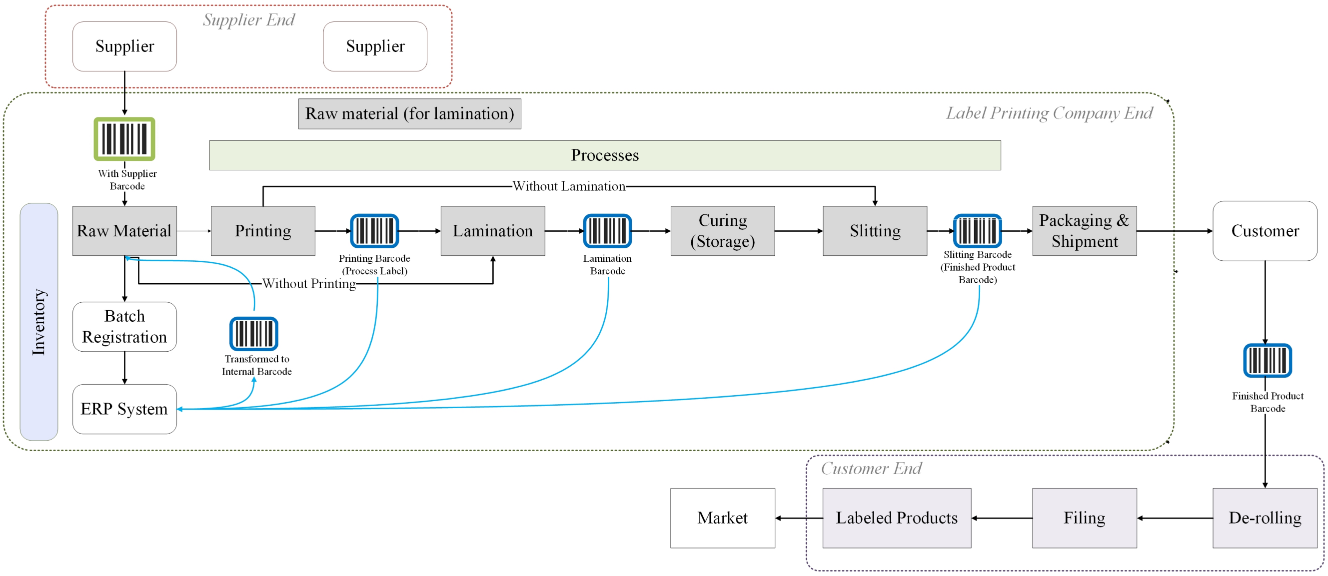

Fig. 1. Business Process Model for the SME workflow

top-level management to understand their business process, perspectives, associated challenges and vision. The study contributes with both business and technical standpoints wherein a business of SME is investigated, which leads to the identification of challenges and process level understanding and results in a system architecture that supports the vision and mission towards digitalization and sustainability.

The rest of the paper is organised as follows: Section II will highlight the background of the label printing industries with associated challenges and our approach to the investigation and analysis. Section III will elaborate on our findings and business propositions, and highlight BPM. Section IV will present the proposed architecture to mitigate and digitize the concern challenge. Finally, Section V will conclude the paper with future opportunities and research scope.

II. Background and Methodologies

The label printing industry is essential in manufacturing for creating labels for varied purposes such as brand promotion, product packaging, information leaflets, etc. These industries are further classified based on the print type, material, and adopted technology. For instance, the labels can be of various types with materials ranging from paper to specialized films, such as pressure-sensitive, shrink sleeves, cut-and-stack, in-mould, etc., employing different print technologies like flexographic, digital, and offset printing [8]. With such exhaustive and complex processes, it is evident that errors in label print manufacturing can disrupt production and affect label quality. Common errors in the print industry include misalignment, colour variations, ink smudging/fading, inconsistent print quality, registration, paper jams, spooling, tearing, adhesive problems, barcode errors, missing labels, material compatibility, poor winding quality, etc. These errors can cascade on SMEs, impacting their operations, customer relationships, costs, and overall business performance [9]. To address these challenges, manufacturers employ quality control, equipment maintenance, and staff training to ensure labels consistently meet quality and accuracy standards. In this realm, the convergence of technologies (e.g., IoT, AI, and Blockchain) and dedicated sensors orchestrates precision and efficiency, from monitoring temperature, humidity and pressure to tracking motion, light and colour functions of label printing. The application of sensors in line with the manufacturing process enables real-time data generation, monitoring and collection to provide efficient label printing and quality control in industrial automation settings.

We adopted Business Process Modeling and Notation (BPMN) models and tools [10] to realize efficiently the SME's process flow. It helped us to identify bottlenecks, challenges, gaps and opportunities to enable digital technologies in SME's environment. In addition, a mix of case study and action research methodologies have been used to conduct our research for this study. We also conducted onsite and offsite workshops with the company's top-level management and researchers from the university as a method of qualitative research to understand, observe, collect, map and analyse the information about the relevant processes, operational flows, challenges and future perspectives. The workshops were conducted openly, focusing on transparent communication, setting clear agenda and objectives, practical use cases and scenarios of the SME, and the participant's presentation, followed by in-person visits to the SME facility, discussions, feedback loop and lots of brainstorming sessions.

III. Business Analysis

The Danish Label Printing SME for our study is a pioneer in flexible packaging employing the Flexo printing technique followed by solvent-free and water-based laminations. The SME also provide customer-ready foils for customers to use on their packaging machines after cutting and adding customized functionalities to the foil, such as micro-perforation, embossing, etc., if requested. Based on the data gathered through the workshops, the process flow was developed to map all the operations and inter-departmental process flows as illustrated in Figure 1. It represents the entities in the supply chain, from raw materials to market-ready finished products, primarily categorized into three clusters: Supplier End, Label Printing Company (i.e., SME) End, and Customer End, as explained below:

- **Supplier End**: Once the raw materials are delivered from the suppliers, the supplier barcode placed on each item is uploaded to the ERP system and then transferred to an internal barcode.
- **Label Printing Company End**: Label manufacturing consists of four main processes: printing, lamination, curing, and slitting. After each process, the new barcode is created, printed and attached to the printed/laminated/slitted reel, except for the curing operation, which needs to be processed separately. Then, the reels, a.k.a bundles, are slitted into smaller reels labelled with the finished product barcode, packaged, and shipped to customers.
- **Customer End**: The received reels of labels are de-rolled and applied to the customer products in distinct techniques concerning the type of the products that must be packaged, i.e., labels can be attached, wrapped, laminated on the product, or filled with the product.

A. Identified Challenges

Flexography, used by the SME, is a well-known printing technique for producing high-quality images and graphics at high printing speed in a versatile and cost-effective way [11]. Although flexography is based on a simple concept of ink transfer, multiple variables affect the final quality of the production, including properties of the plates, anilox rollers, printing pressure, and printing substrates [12]. As a result, the investigated SME faces several challenges related to print defects requiring frequent process stoppages for quality control. The following challenges have been identified as outcomes of our workshops and visits to the SME's facility.

- **Error Management**: The main challenge for the SME, which it wants to address immediately, is error management. During the printing or lamination operation, errors occur and need to be communicated internally and to the customer. For internal communication, two (green and red) labels are used manually to mark the start and end of the material to be scrapped during the slitting processes, shown in Figure 2. Similarly, the external error marking allows SME's customers to manually adjust their filling and packaging operations based on the position of the red label, thus acting as passive markers of errors.
- **Automation of Processes**: The processes at the production line are primarily manual. For instance, the real-time information flow between different production stages and waste management is logged manually. The company's ERP system does not cover all the operational aspects, as upgrading and integrating old machinery infrastructure is challenging, impacting overall productivity efficiency.

Fig. 2. Error in Bundle (Red/Green Label indicators)

- **Reduction in Waste Material**: During printing and lamination operations, the occurred errors result in waste. But no data or logs are maintained for the errors' cause, occurrence or frequency. Therefore, a semantic context awareness-driven digital method enablement must be there to enhance productivity and reduce scraps.
- **Data-driven Compliances and Decision Enablement**: Abiding the Climate Act, Denmark, like other EU countries, aims to significantly reduce greenhouse gas emissions by 50-54% in 2025 and 70% in 2030 compared to 1990 levels [13]. Thus, this necessitates stringent compliance from manufacturing industries, demanding comprehensive data on their operations. The SME is found to be struggling to comply with these requirements due to a lack of data-driven operations.

B. Vision

Our workshops and brainstorming sessions with the SME management highlighted their vision behind the initiative to incorporate and facilitate the convergence of technologies into their existing manufacturing and production lines. The SME expects to digitalize the operations to make their products smarter. For example, the printed bundles have associated a lot of operational data during their printing journey, but it is not captured and thus adds no value. The SME's immediate focus is on error management, a low-hanging fruit where digital operations can be induced as a starting point and scaled incrementally for other challenges. Additionally, they want to develop a data-driven servicing model in future, which can sustain and expand the current business horizon for the SME. Therefore, we proposed a platform model based on which the servitization business model [14] will provide value-chain enablement across customers and also enable them to make their production environment smarter.

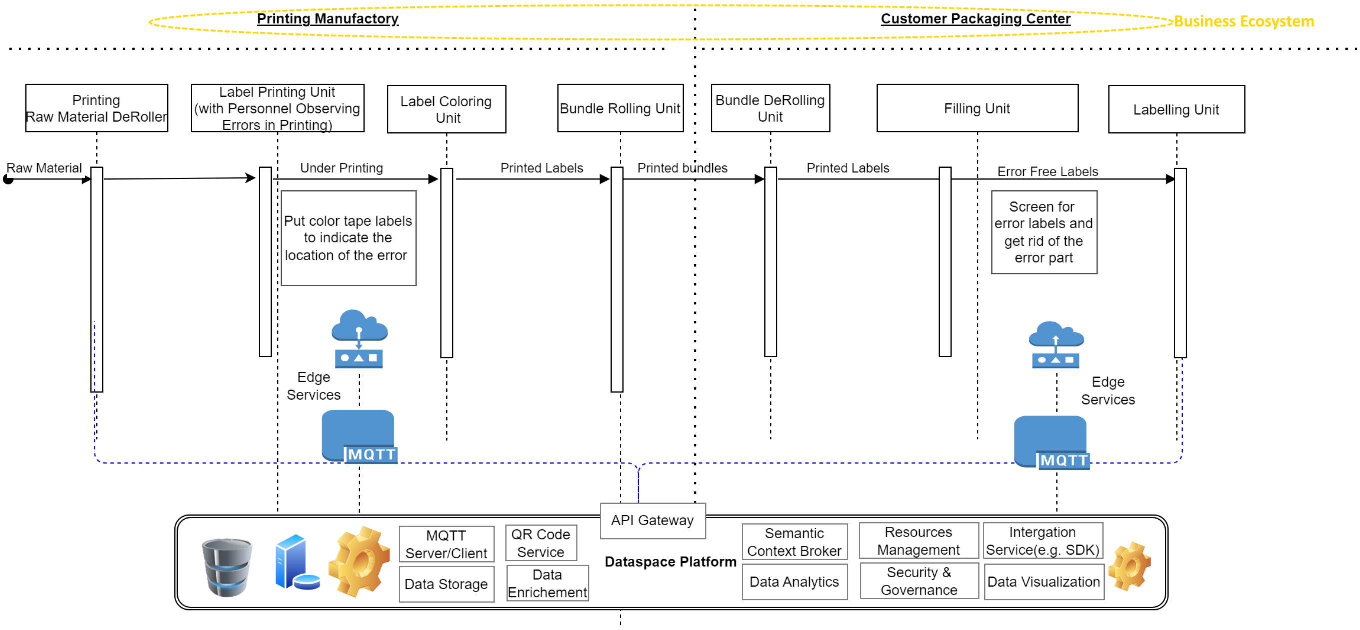

Fig. 3. Digital Intervention Architecture

IV. ARCHITECTURE

This section will primarily provide potential solutions and an architecture to address the identified challenges, focusing on Error Management as the starting point for inducting digital tools in the SME environment. In the present scenario, the entire error identification at its occurrence and relevant communication/action process is handled manually without any digital intervention, giving rise to our problem statement: *"How can we make error management and dependent operations smarter to enhance the overall productivity?"*

Based on our interactions and analysis, we proposed a solution to tackle the challenge of managing errors through the entire workflow and having a log of occurrences. A digital intervention architecture is shown in Figure 3 to address this question. This consists of digital enablement of services at SME and relevant customer on-premises environments, and finally, the Dataspace platform-enabled services provide real-time distributed data services to all the stakeholders. The high-level operational flow of the label printing process is given in the following three steps:

- **Step A**: The Manufacturing Unit receives raw material in huge bundles, each of which goes on the de-rolled roller.
- **Step B**: The de-rolled material goes through the design printing operation, where errors are manually observed during the printing operation and marked with tapes for identification, which is removed later. The error could occur for many reasons, as explained earlier. For instance, when one bundle is finished, it is spliced into a new bundle, and the point of occurrence is notified using tapes. Apart from splicing, errors occur due to printing operations, such as misalignment, colour variations, ink smudging, inconsistent print quality, machine malfunction, etc. To address such errors, we proposed a digital intervention to detect and record the error (explained in the next section).
- **Step C**: At the customer end, the reverse process is repeated to de-roll the bundle and make adjustments on a machine for the error flag in the bundle, and then the error-free labels are split from the bundle and pasted onto the final product.

The above steps have associated data labels as barcodes or manual receipts, but they lack real-time linkage as they flow through the printing operations. Thus, to automate this stage, we propose IoT edge-enabled Quick Response (QR) code-based data labels at all stages of printing operations. We also propose to generate a *"Context-Aware Operational Environment"* and link the information in different functional flows in future during the entire "Order and Error Management" process for the relevant customer. The semantic model can easily capture the business level flow relevant operational context and provides technical implementation grounding at the system level, such as using semantic RDF [15], NGSI-LD [16] or JSON-LD [17] standards. In the following subsections, we have described the applicable process and system model using the semantics ontology approach that can be implemented by the supporting digital platform to induce digitization in the processes.

A. *Digital Processing Model for Printings Operations*

Figure 4 illustrates the semantic data model for managing printing errors. The *Customer* places an *Order*, which has to be processed with delivery target *Date* by assigning an order identification - *ID*. Similarly, the *ID* property can be used for every operational entity in printing processing. To process this order, there is a need for *Bundle* that contains the raw material for printing with a certain *Length* in meters provided by the customer in his order to print the labels. During the printing operation, there might be *Error* associated, which is identified by an *ID*, defined by its *Metadata*, occurred due to a *Reason* that in turn belongs to a specific *Type* of an *Error*. The printing bundle is finally prepared on specific *Date* for delivery to the customer that receives the final bundle on relevant *Date*.

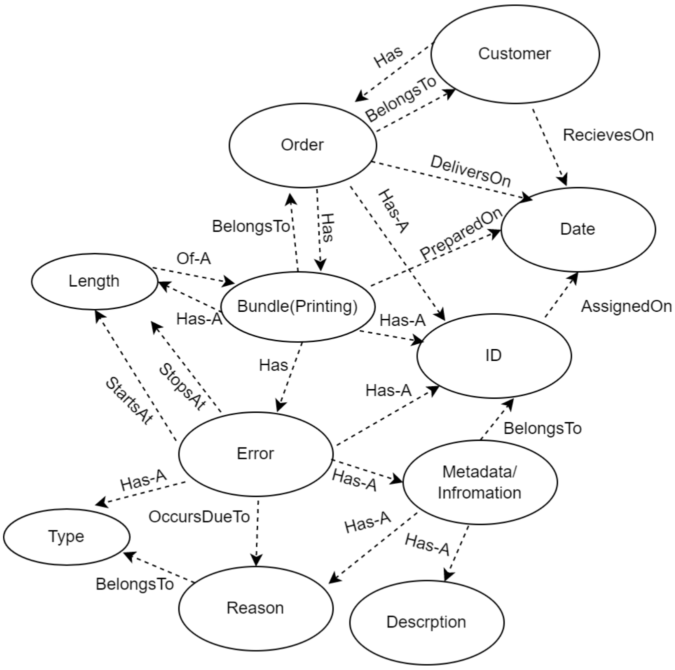

Fig. 4. Semantic Processing Model for Label Printing Operations

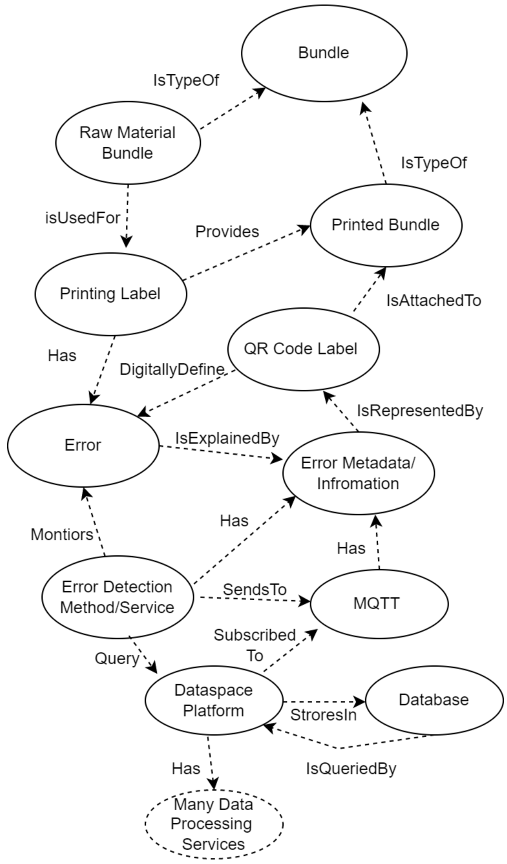

Fig. 5. Semantic System Model

B. Semantic System Model

To initiate digitization, we mapped the SME processes against the digital processes. The system is perceived as a semantic system that provides operational and linked data context awareness [18]. Figure 5 shows the semantic system model that captures the system's relevant operational entity level information. The system focuses on the activities inside a label printing manufacturing unit, that starts with the *Raw Material Bundle*, a type of *Bundle* used for *Printing Label*. During the printing operation, there can be an occurrence of *Error*, which is explained by its metadata that is digitally captured in a *QR Code Label* by the error detection method that also sends the related error information to the *Dataspace* via *MQTT* protocol. In addition, the error method can also query the information from *Dataspace* for various purposes, such as to generate a QR code for encountered errors. At present, the error is monitored manually by personnel of the SME, but in the future, we propose to automate and replace it through edge-enabled (on-premises) IoT sensing and computer vision capabilities. The data received by *Dataspace* platform is persisted in the *Database*, which can be queried later.

C. Dataspace Platform

We propose a platform with Dataspace capabilities [**?**], currently implemented at the university facility, for the SME to prototype and validate its expectations towards initializing digitalization for its error management challenge. The platform is implemented with dataspace capabilities for many reasons: first, the SME management wants to enable digitalization for its processes to augment data-driven decisions over cross-organizational boundaries and thus exploit it as a value addition in their products, i.e., printing bundles, for their business value-chain. For example, the transition of dummy bundles into smart bundles having associated data at the customer end in real-time that can explain the bundle digitally and enable customers to fine-tune their operations and planning accordingly, thus enhancing operational productivity at the customer end. Second, it allows the SME to bring innovation in their business value chain that spans and has an impact at the customer end. This will enable the expansion of SME's portfolio using the platform services model based on smart printing products. Finally, the significant objective for any business is to create monetary opportunities provided by this Dataspace platform, based on the data associated with printing operations. As shown in Figure 3, the Dataspace platform consists of a wide range of data processing services, as explained below.

- **MQTT**: This is an industrial protocol standard [19] that provides standardized push, pull, subscribe or notify data operations. It is widely deployed in the IoT domain that needs lower resources and power to transmit data over the internet. Though the data model is not standardized at the application level, the communication protocol is standardised. Therefore, context-aware semantic models such as NGSI-LD can be used at the application level.

- **QR Code Service**: This service creates, generates and manages QR codes compatible with various programming languages such as python-qrcode, js-QR in javascript, etc. through open-source libraries. QR codes can be generated from JSON data models, derived from the earlier semantic process model, improving error tagging in manufacturing. This will digitalize the printing operations at each step we explained earlier. In addition, these QR tags can be pushed to the blockchain network to make them digitally traceable and transparent for all stakeholders [20].
- **Data Enrichment**: Inside the platform, this service will allow the modification of received data from the manufacturing unit, e.g., to add a timestamp when the bundle gets its error or when it gets delivered to the customer or error reference modifications or semantic adaptation.
- **Data Storage**: This service allows the data to persist for history and real-time operations among different stakeholders within or across customers of the SME.
- **Semantic Context Broker**: This provides context awareness over the data defined as per the semantic model—for example, the error, length, bundle, customer and delivery relationship. The stakeholder can query the data with a specific context. For example, a customer can ask - *How many and where the errors were when the ordered bundle was printed?*. Under such a scenario, the knowledge base created by a semantic context broker will yield the corresponding query result in a much simplified manner.
- **Data Analytics**: These AI/ML-driven data analytical services can assist SME and customers in their decision-making process. For example, questions like *how many errors have occurred in the last 6 months and how much material has been wasted due to different error types?* can be answered through these services efficiently, and estimated predictive analysis can also be performed.
- **Security and Governance**: This aspect is very important, especially when data and multiple stakeholders are involved. On top of that, GDPR compliances are stringent in Europe for manufacturing units to comply with to avoid hefty fines. This can be implemented using smart contracts among stakeholders, leveraging Blockchain technology such as HyperledgerFabric [21]. This will enable trust through transparency, immutability, digital traceability and tamperproof printing operations. In addition, this service will also provide identity, authentication and authorization management functionality.
- **Resource Management**: This typical ERP-related service manages resources at different operational stages. In addition, this service can also host the responsibility to manage the edge and cloud-level resources consumed by instantiated or orchestrated services. Here, oper-source ERP systems such as Odoo [22] can be very helpful for SMEs to start with.
- **Data Visualization**: This service will provide data visualisation in different formats such as bar charts, line charts, pie charts, heatmaps, 3D charts, Scatter plots, Gantt Charts, etc. Here, open-source tools like Grafana, Elastic Search Logstach Kibana (ELK) stack and industrial tools like Power-BI are heavily used.
- **Integration Service**: This service will provide the required interfaces or Software Development Kit (SDK) to integrate with the Dataspace platform. This will be needed when the SME, under its customer service initiative for its products, say smart bundle, wants to share its operational data with the customer at the customer end so that the customer can align its processing or planning operations accordingly or for other purposes.
- **API Gateway**: This acts as a proxy gateway for the backend microservices running in a distributed environment and thus provides a single point of interaction for the SME or the external world, including customers. This can be implemented using production-grade open-source such as Nginx.

This dataspace platform is recommended to implement following the distributed microservices architectural design approach. This allows the services to be realized at the edge with the IoT sensing capabilities for data generation and processing to optimize bandwidth usage and reduce latency at the edge, i.e., the on-premises environment of the SME. In addition, this can be extended further to integrate the digital twin functionality to achieve operations validation during command and control, higher levels of efficiency, quality, and flexibility. This platform can be deployed on-premises as a private edge cloud and can leverage resources at the cloud level, following the Cloud-Edge continuum hybrid approach [23]. We suggested starting with the edge level deployment to re-use the existing infrastructure to deploy edge cloud leveraging open source Kubernetes-based bare metal microservices oriented containerized approach [24]. Later, as required, it can expand to the public cloud, e.g., AWS, MicrosoftAzure, Google Cloud Platform, etc. This platform enables value-added services across the value chain of the SME by enhancing the label printing process through optimized data-driven real-time operations, ensuring data integrity, and providing powerful analytics and visualization capabilities. This will empower the SME and its customers to make informed decisions, transparency, trust and drive efficiency in label printing operations.

V. CONCLUSIONS AND FUTURE WORK

In this study, we have provided insights on business analysis and digitizing approach for Industrial R2R Label Printing Manufacturing SME in Denmark as part of the Manufactory project. We observed that the SME, operating on a global scale with substantial printing operations and recently installed heavy machinery, faces significant challenges in upgrading its existing infrastructure due to various constraints such as capital investment, resources and affordability. Our approach focused on understanding the intricacies of the SME's operational processes, leading to valuable insights. As a result, we did the business process mapping that provides a better and more precise understanding of enabling data and digitalization points in the existing environment. We identified numerous challenges, including productivity enhancement, error management, communication inefficiencies, waste reduction, compliance requirements, and the potential for smart products through platform-based data augmentation etc. To address these challenges, we narrowed our focus to error management within printing operations and presented a semantic process and system model. We addressed the error management challenge specific to printing operations that can occur for many reasons, e.g., inconsistent material, colour, speed, alignment, etc.) through the induction of digital processes around the same. In addition, we have also proposed a process-mapped architectural solution based on a semantic model that captures the business and technical level aspects concurrently. This proposed solution implementation approach is also explained based on well-defined standards, protocols and an open-source tools ecosystem that requires minimal investments and risks. As an outlook, we would like to measure the impact and value addition of the proposed solution on SME's printing operations to enable digital transformation in business productivity enhancements, reduction in waste material, and expansions through data-driven sustainable growth.

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