

A Concept of a Digital and Traceable Manufacturing Documentation Based on Formalized Process Description Applied on Composite Aircraft Moveable

Björn Denker,* Dominik Delisle, Christian Krombholz, Martin Rädels, and Frank Dressel

The documentation of component manufacturing has become an essential element of modern production, not only to meet customer requirements but also to support the analysis and optimization of production processes and component designs with respect to structural performance, economic efficiency, and sustainability. To enable effective interaction between different disciplines, standardized process descriptions as well as consistent information and data structures are required. Digital manufacturing instructions and process documentation based on standardized, formalized process descriptions and the automated acquisition of process data offer significant potential for robust and efficient manufacturing. In this context, a semantic data model ensures data consistency and enhances opportunities for process analysis and optimization. This contribution presents a method for the standardized digital documentation of a composite manufacturing process using a formalized process description. A digital life data sheet (LDS), combining manufacturing instructions and documentation, is implemented using Atlassian Confluence and applied to the production of a composite multispar movable of a long-range reference aircraft configuration. The usability of the developed LDS is evaluated, potential improvements are identified, and the underlying semantic data model is described.

1. Motivation

Manufacturing instructions and documentation, which in the aviation industry are summarized in the so-called life data sheet (LDS), are nowadays often still paper-based. The structure and information content of these documents are often not standardized and dependent on the people who create them. A limited information content, ambiguously formulated instructions, the manual recording, and logging of process data offer an increased potential for errors in component production. However, especially in the quality-driven manufacturing of the aerospace industry, data consistency as well as unambiguous traceability is of utmost importance. In connection with digital transformation initiatives, the digitalization of manufacturing instructions is therefore one of the logical steps. Here, however, it is important not simply to display previous instructions on a mobile device, but rather to use the possibilities of digitalization to generate and make additional functionalities and more knowledge

available. One possibility here, for example, is to link the manufacturing instructions with other media, CAD models of the product, or other technical documents with the aim of increasing the understanding and clarity of the instructions. By means of digital process documentation, the progress of the process can also be made available to everyone at any time. If this is coupled with the automatic recording of real process and component data, not only the process progress can be viewed at any time, but it is also possible to react quickly and flexibly to any deviations from the target process.

In addition, pictures taken of the component state during manufacturing, directly embedded into the LDS, can be used to generate important information for subsequent process steps or online analyses, thereby increasing both the quality and the efficiency of the manufacturing process. Another possibility is the coupling of the digital LDS with a semantic data model for the general description of a fiber composite manufacturing process, e.g., to make different manufacturing processes comparable. In terms of transferability, the data model should be structured in a standardized manner.

With the help of such a model in combination with the collected information from digital manufacturing instructions

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semantic model, a detailed analysis of the manufacturing process as well as of different equipment available on the market was performed.

Manufacturing processes, especially of components made of composite materials, can include a large number of individual process steps whose individual parameters can influence the component properties. When designing or planning manufacturing processes for components made of composite materials, it is therefore important to be able to describe the entire process chain with the individual process steps in detail to achieve the desired component properties. The formalized process description (FPD) according to VDI/VDE 3682^[13] is a universal methodology to describe technical processes. With the FPD, it is possible to describe a plant project from a functional point of view in a technology-neutral way in the early planning phases to achieve a common understanding of the process for all the disciplines involved. A resulting process model can be further used as a basis in the individual phases (planning, realization, commissioning, operation, etc.) and successively enriched with new information.^[14] The method according to VDI/VDE 3682 addresses the description of technical processes, whereby a turnover of energy, information, or materials takes place within a process.^[15] Nabizada et al. provide an overview of the contributions and developments with regard to VDI/VDE 3682 and the FPD.^[16] Nabizada et al. also describe an initial approach to the XML representation of the FPD according to VDI/VDE 3682.

Hoang et al.^[17] use the guidelines of FPD as a basis for modeling resource capabilities, which are defined in VDI/VDE 3682. In contrast to the previously mentioned approaches, the modeling is not process oriented. Instead, the elements of the FPD are used to describe the products that can be produced by the respective resource and the associated boundary conditions. Thus, a desired change of the product does not have to be translated into a process step first to identify a possible technical resource. Rather, the desired change can be directly compared to the input and output elements that describe the technical resource.

Although numerous approaches for digital process and resource representation exist, a consistent, domain-specific methodology for the structured description of complex fiber-reinforced composite manufacturing processes is still lacking. The VDI/VDE 3682 provides a generic metamodel for FPDs, but it does not sufficiently capture the specific interdependencies, state transitions, and data requirements characteristic of composite manufacturing technologies. At the same time, existing ontological or OPC UA-based models remain highly fragmented and are typically limited to individual subprocesses or resources. An integrated semantic framework for complete process chains, as well as its user-friendly application in practice, is currently unavailable, despite being essential for consistent digital documentation, increased transparency, and the effective utilization of process and quality data.

Against this background, there is a clear need to extend the VDI 3682 with composite-specific structures, to develop an accompanying semantic model that enables the detailed description of individual process steps, and to implement these developments within a user-oriented software platform. This approach aims to enhance the acceptance of digital manufacturing documentation while establishing the foundation for further advances in the digitalization of composite production processes.

3. Methodologies

As mentioned in Section 2, the FPD defined in VDI/VDE 3682 enables a standardized description of manufacturing processes. The underlying structure of this standard is a solid basis for the general description of composite manufacturing processes. In this section, the VDI/VDE 3682 standard is described and applied to the digital manufacturing documentation.

3.1. Formalized Process Description (FPD)

According to VDI/VDE 3682, **Figure 2** shows the graphical representation of a FPD, consisting of an operator (O), which requires products (P), energies (E), and information (I) as input elements to transform them into the required output elements.

Resources (R) in the sense of technical resources can be used to perform the operation. Flows of energy, products, and information to or from an operator are represented by arrows with a solid line, utilized resources by arrows with a dashed line, and the system boundary (S) by a bold dashed line.

However, when applying the FPD according to VDI/VDE 3682 in the context of the production of composite components,^[18] it becomes apparent that not only technical resources, but also human resources, e.g., machine operator, and environmental resources, e.g., air-conditioned shop floor, are required to describe a process holistically. For this reason, the VDI/VDE 3682 has been adapted, so that the resources are now subdivided into technical resources (R-T), human resources (R-H), and environmental resources (R-E). In addition, the used resources are no longer outside of the system boundaries, as they have a significant influence and contribution on the process and their current status can be modified by processing the operator. For example, the operator “Take product *Vacuum Bag* from product warehouse” changes the stock of the technical resource “Product Warehouse @ German aerospace center (DLR).” This extension of the FPD enables the representation of the system boundary as the accounting boundary for such processes, thereby allowing its application in internal calculations. **Figure 3a** represents the FPD based on VDI/VDE 3682 and its adaptation.

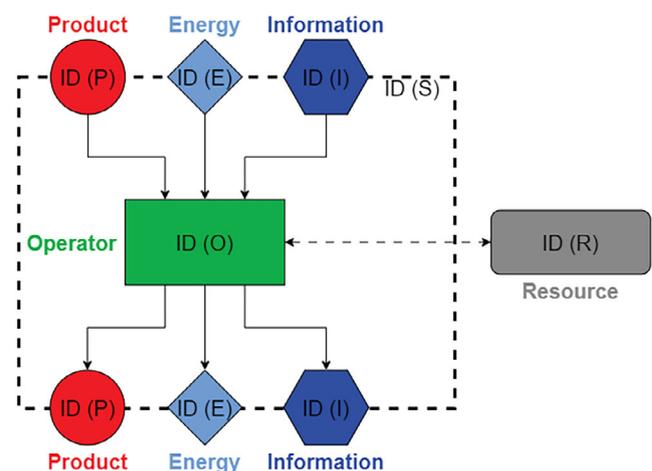


Figure 2. Graphical representation of a FPD based on VDI/VDE 3682.^[13]

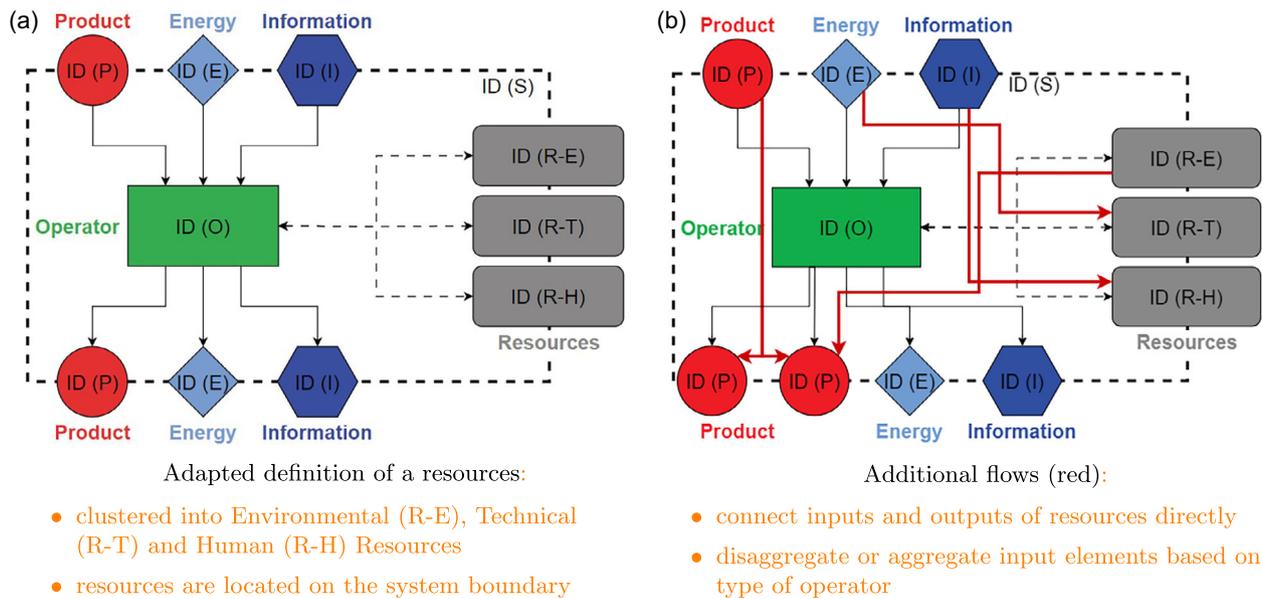


Figure 3. Graphical representation of a FPD.

Another area where the FPD requires adaptation has been identified in the lack of specification regarding the recipients or targets of the flows, see Figure 3b. Through the proposed extension, it becomes possible to:

1. Model input requirements depending on specific resources, This means, for example, that electrical energy can be automatically added or allocated to the flow for electrical consumers such as machines.
2. Model outputs in a resource-specific manner, This enables a more precise description of processes in which, for example, products from warehouses or resources such as machines are used for the process.
3. Disaggregate or aggregate flows, for example in terms of materials and energy.

This allows the flows to be detailed in such a way that input products can be linked to output products and waste or dust.

These adjustments represent only a potential extension of the standard, intended to provide process designers with enhanced capabilities for verification and validation especially for more complex processes.

3.2. Digital LDS—Design and Functionalities

3.2.1. Current LDS

A LDS has to specify and document the whole manufacturing in a way that the manufacturing and all measured data is traceable even after years. For this purpose, the LDS has to fulfill customer specifications and requirements of, e.g., DIN EN 9100 or DIN EN ISO/IEC 17025.^[19,20] Therefore, a LDS design varies to specific industry and component manufacture, but mainly the following contents are included:

1. Cover sheet (project name, part ID, company, LDS version, ...).
2. Index.

3. General information to project, manufacturing process and part.

4. General documents (process specifications, part specification, ...).

5. Used resources (measuring instrument, tools, jigs, ...).
6. Used materials (structural material, auxiliary material, ...).
7. Detailed description of manufacturing process (check boxes of working steps, process parameter, verification, ...).

Especially the needed resources and materials are often summarized in a list and then referred in chapter 7 “detailed description of manufacturing process.” A cross-reference in a paper-based version of a LDS is often not user-friendly due to turning pages. In LDS creation process, a production planner creates the LDS by editing the specific part manufacturing in a LDS template or by adapting an existing LDS of a similar part manufacturing. Then, the LDS is released by a quality manager, printed for the worker in the shop floor, scanned after finished manufacturing, and archived for several years.

3.2.2. Design of a Digital LDS

As mentioned in Section 1, the purpose of a digital LDS is to use digital functions, e.g., to improve usability and process progress tracking. Linked to a semantic data model, all manufacturing-related information could be directly used for an efficient subsequent analysis. Nevertheless, the digital LDS should satisfy all properties of the existing and proven structure of paper-based LDS as well as to consider the structure of the FPD. Therefore, a software is needed which is based on a knowledge management system to has the ability to link information and files. Additionally, the digital LDS should be first realized and evaluated on an available software to generate requirements for a needs-oriented LDS software. This procedure is chosen due to the high complexity of functions, which are cumulated during the continuous development process of the digital LDS

Due to these requirements and needs as well as a high internal acceptance and usage, the software Atlassian Confluence is chosen for the realization of the digital LDS.^[21] The software has also a large number of preimplemented features that are useful for designing a digital LDS, for example, direct links to web pages of instances, file attachments, page tags, metadata for selecting and assigning FPD elements from a global search to operator pages as well as automated extraction and aggregation of information boxes of operator sides to enable a holistic analysis. More information about the used features is followed in the paragraph “LDS functions.”

Figure 4 shows the architecture of the digital LDS in Atlassian Confluence. It consists of a main page and subpages for operators. On the main page, general information about the project is described, see points 1–6 from 3.2 section “current LDS.” The detailed description of the manufacturing process is described on subpages of the operators which are comparable with point 7 from 3.2 section “current LDS.”

The operator sites (in the middle of **Figure 4**) link to databases of instance of the used FPD elements, in which FPD element-specific metadata is provided, such as manufacturer, article number, production site, batch number, or expiration date. Additionally, the quantities of products and resources required for the production are also entered. This quantity information for each instance is then aggregated to the main page of the LDS and displayed in tabular form under the sections “database product: structural and auxiliary material” and “database resource: technical, human and environmental,” see **Figure 5**.

This tabular summary provides all the information required for efficient procurement and resource planning. In addition, the products and systems used are already available for a life cycle

assessment (LCA) analysis. Further analyses based on the main pages or operator pages can be, for example, time analyses, semantic analyses of FPD elements, and measured value analyses, see **Figure 4**.

In detail the major page contains all manufacturing metadata of a “cover sheet” (e.g., project name, cost unit, project manager, LDS version) and links several subpages or tabular summary, which could be expanded if desired, see **Figure 5**. The expandable subpages are project information, part information, manufacturing process (e.g., in the form of a flowchart), database resource (technical, human, and environmental), database information, database energy, database product (structural & auxiliary material), and the operator sides.

The main difference to the original “paper-based” LDS is the linked databases as well as the well-structured metadata and working steps information on the operator side, which receives all information of the FPD elements, explained in Section 3.1.

The Atlassian Confluence software consists of a front end and a back end. A template of the front end of an operator subpage and the FPD relations is shown in **Figure 6**.

On the left side, FPD elements (product, information, energy, resource) in addition to operator metadata (green area), such as description, predecessor and successor, start and end dates, and focal point, are named. Also the reference flow, which is necessary for a LCA, is integrated. Below these attributes, FPD elements are linked to databases which consist of the individuals and their detailed description. The description of the individuals is standardized depending on the FPD element. Due to these database links worker can provide itself with all operator relevant information (e.g., NC-code, stacking, specifications). Additionally, the structure of the FPD with their linked FPD elements as well as the

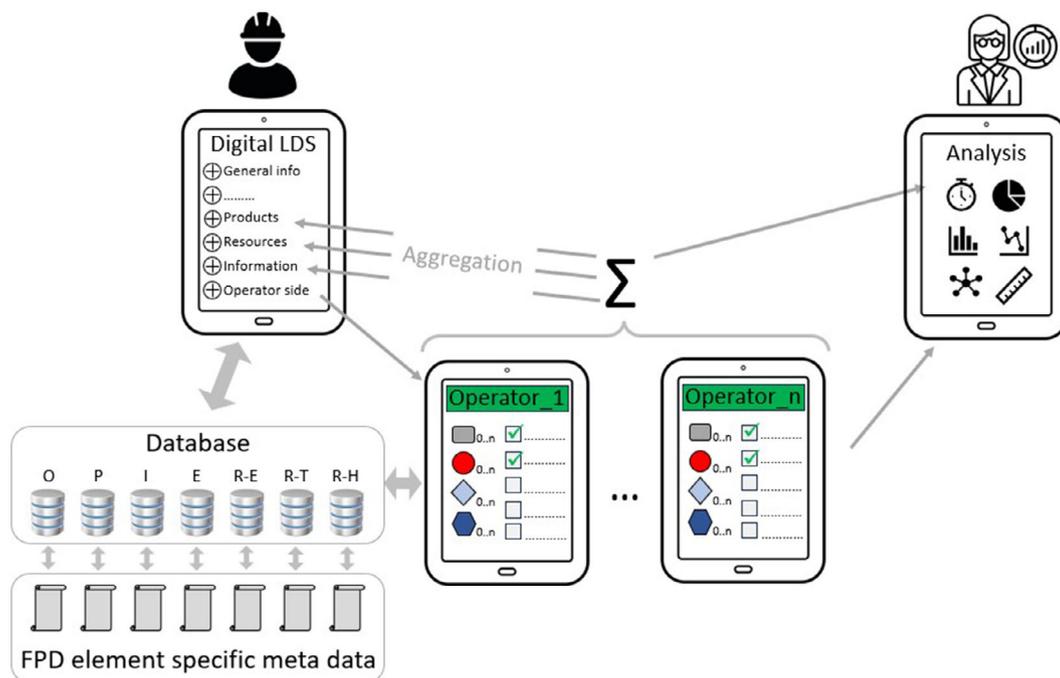


Figure 4. Architecture of digital LDS with front end of main page and operator subpages, linked databases, and analysis options (realized in the software Atlassian Confluence).

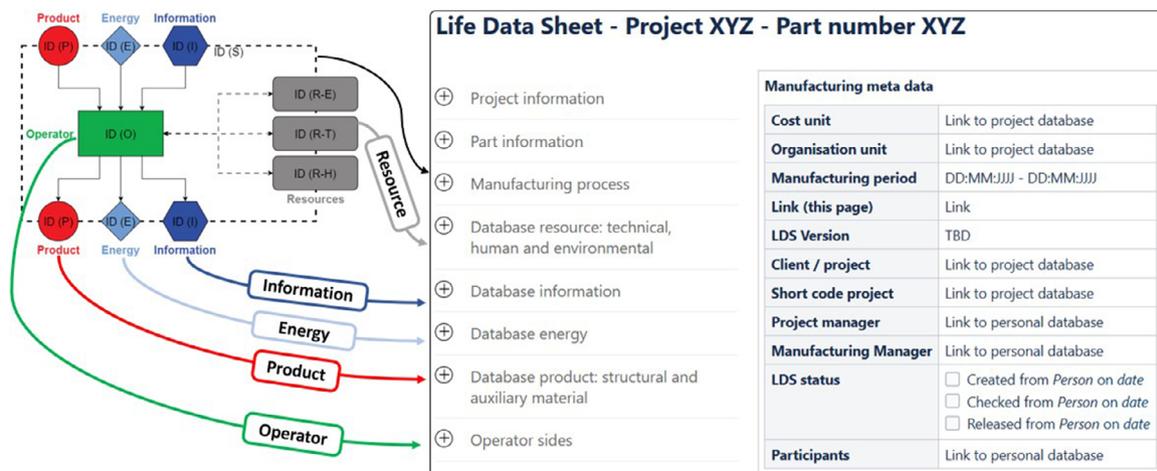


Figure 5. Overview of LDS template and its relations to FPD elements.

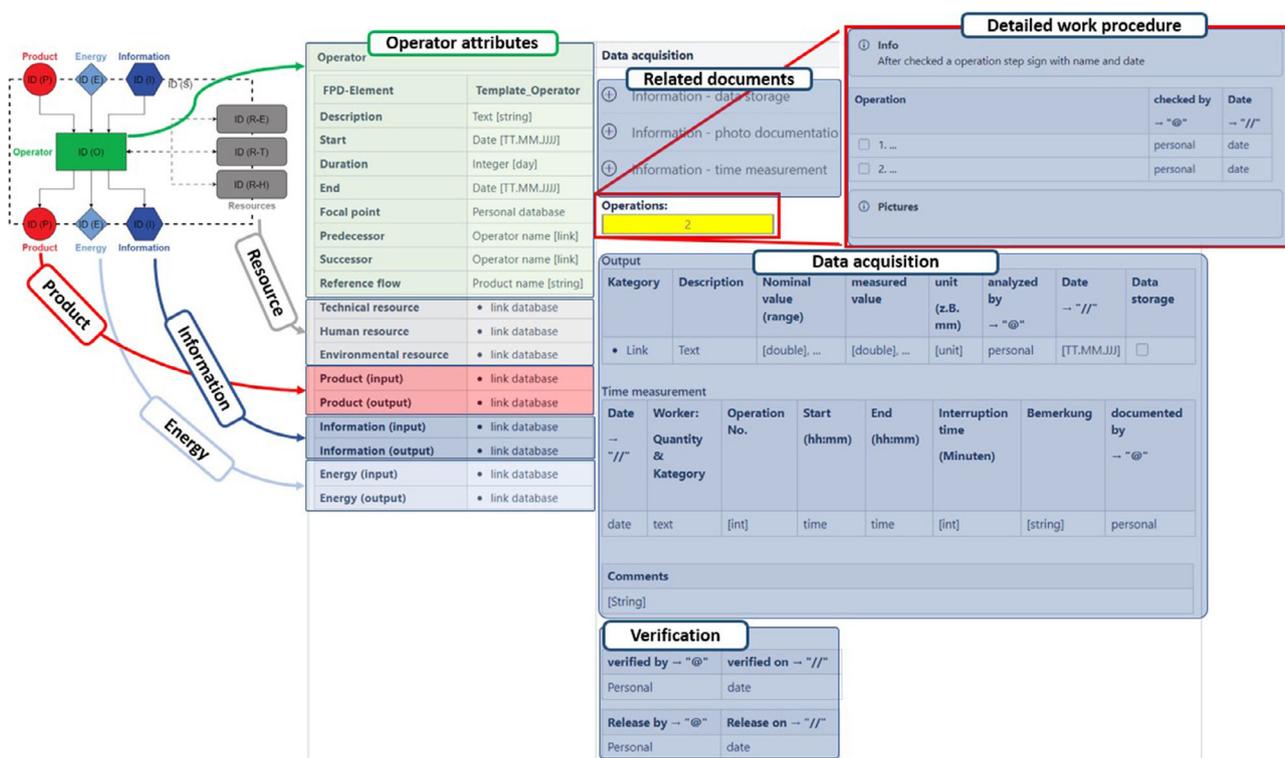


Figure 6. Layout of the operator side of the digital LDS and its relations to FPD elements.

linkage between operators enables a semantic description of the whole manufacturing process. The right side of the operator side has boxes with relative documents for the working procedure, a process progress visualization as well as the detailed working procedure, data acquisition, and verification of the operator after finishing all working steps. Working steps relative documents can be expanded if desired and consists, e.g., of information to data storage, photo documentation, and time measurement. The detailed working procedure is expandable by click on the process progress

bar. After finished a working step, the check box is checked and signed with name and date. If data, like measured sensor values, material consumption, or duration of a working step, is generated, this information output can be directly documented in the box "data acquisition." In addition to the documentation of measured values, measurement files can also be easily added on instance pages of the related FPD information element, which is linked on the left side of the operator side. Also part of "data acquisition" is a comment box to edit characteristics, which are particularly

important for subsequent analysis. At the bottom of the operator side, the verification of the documented manufacturing by quality manager and/or project manager can be done.

3.2.3. LDS Functions

The main advantages of the developed digital LDS comparing with a paper-based LDS become apparent by explaining functions that are programmed in the back end, especially of the operator side. First of all, the database links of FPD instances cause a direct access to detailed FPD element-specific metadata or referenced files. Additionally, these FPD instances can be easily linked in the back end during LDS creation using a search field. Tags on FPD instance pages enable an efficient search and LDS editing of the operator linked FPD instances. In the back end of the operator side, the topic clustering, e.g., detailed work procedure or data acquisition, can be subdivided into the objects of investigation (e.g., LCA) which make pre- or postprocesses more efficient. Some functions of the operator side are mentioned in the following.

1. The cell information of start and end dates of the operator is used for manufacturing and resource planning and can be visualized for process progress in a Gantt chart. A time lag or resulted resource (technical & human) shortage can be directly derived.

2. A personal management system is linked to the LDS, so that a focal point can be defined. This person or group of persons are responsible for the operation. If edits are made or persons are tagged on the operator side, an email is sent automatically.

3. Several persons can work simultaneously in the back or front end to improve LDS creation and editing process.

4. The software provides all sides (major page, databases, operator side) with a version management system which allows the comparison of different versions.

5. Fade in and fade out of information to keep focus.

6. The process progress bar on operator and process level was observed (ratio of complete to open working steps).

7. FPD elements of every operator and the relations between operators in a machine-readable manner to enable semantic analyses are summarized.

8. All outputs like measured data, material consumption, and comments of all operators in an exportable list to derive sustainable analyses, process improvements, trends, dependencies, and target/actual comparison are summarized.

3.2.4. Workflow of LDS Creation for a New Manufacturing

If a digital LDS for a manufacturing documentation is needed for the first time, the following steps have to be done:

1. Manufacturing modeling by using FPD elements.
2. Design a major side of the LDS.
3. Create databases for each FPD element.
4. Define templates for each FPD database with detailed information and the database tag.
5. Create the FPD element instances for the databases based on the templates and edit the detailed information.
6. Create operator sides based on the operator template.
7. Create all FPD element links from databases to the operator side by using the search field.

8. Define working steps and if necessary create visualizations.

If a digital LDS of a part manufacturing process is already existing, then it can be duplicated, the measured values have to be deleted, and some individual information like part number can be adapted. If some operators or database elements are missing, they can be easily added by using the operator and database templates. Hereby, the databases are still growing, which leads to standardization of manufacturing processes, which is the base for comparable and optimized manufacturing processes (e.g., optimized for sustainable processes).

4. Application of FPD and LDS

The developed digital LDS based on FPD structure is applied to a manufacturing of a composite multispar aircraft moveable, see **Figure 7**.

4.1. Manufacturing Process of an Aircraft Moveable

The manufacturing process of the moveable is divided into the subprocesses like skin manufacturing (process A), spar manufacturing (process B), and assembly, curing & postprocesses (process C), see **Figure 8**.

In process A, automated fiber placement of dry fibers was carried out.^[22] After that, the flat subpreforms were draped over a preforming tool. The spars of process B are manufactured manually on tools and consolidated by diaphragm membrane in an oven. In process C, the skin and spars are assembled and positioned into a curing tool. After equipping the tool into the autoclave^[23] and to the injection unit, the injection and curing process is carried out. As last step, quality assurance (QA) and fine trimming were done. The whole manufacturing process as well as the acquisition of manufacturing data to validate simulations for certification is described in detail in ref. [24]. In this contribution, the focus is on the FPD and digital documentation of the manufacturing and measured data. Some expressions of the manufacturing are shown in **Figure 9**.

4.2. Digital LDS Applied to the Use Case

The first application for the described workflow of FPD (see Section 3.1) and LDS (see Section 3.2) is the demonstrator manufacturing. According to the described workflow of LDS creation from chapter Section 3.2, the first step of the process description is to define the manufacturing process by using FPD elements “operator” and the product life cycle steps to create a better overview of the high amount of operators by clustering. The product life cycle steps for process A, B, and C are design & process definition, preparation (production unit), software &

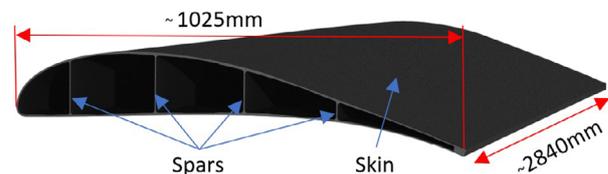


Figure 7. Aircraft moveable.

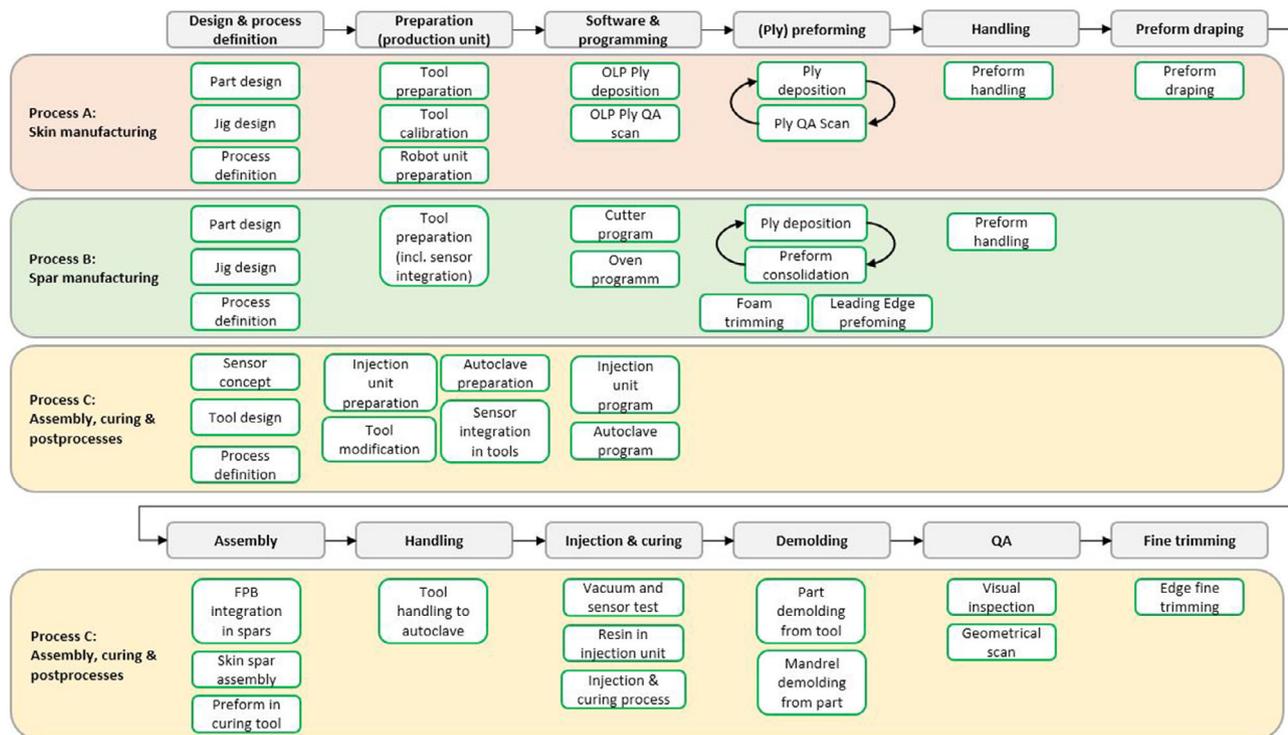


Figure 8. Moveable-manufacturing process.

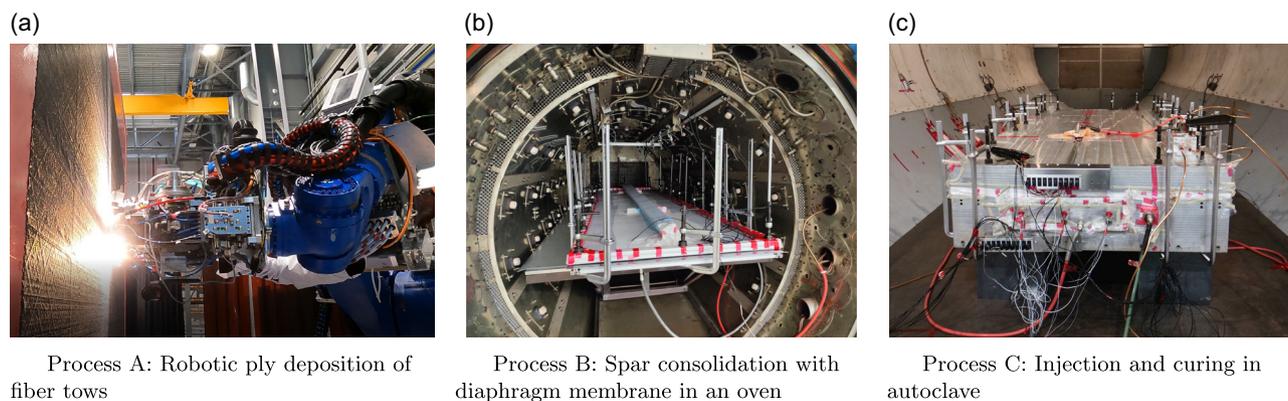


Figure 9. Process chain of moveable manufacturing.

programming, (ply) preforming, (preform) handling, preform draping, assembly, (tool) handling, injection & curing, demolding, QA, and fine trimming, see Figure 8.

Then, all process operators of skin and spar manufacturing as well as assembly, curing, & postprocesses are defined according to the definition of Figure 3a. The operator definition consists of the related FPD elements, such as energy, information, product, and resources. In Figure 8, some of the main operators added to process groups are visualized. In a detailed point of view, the whole manufacturing consists of 316 operators. This high amount of operators results from the approach to define operators that can be reused in other composite manufacturing processes. The operator name consists of the process [A, B, C],

number of product life cycle [010, 020, ...], number of operator [010, 020, ...], and described name [name]. For example, "A-040-010-Deposition_Preform1_Seq1" is part of process A, product life cycle 40 = preforming, operator number 10, and has the name "Deposition-Preform1-Seq1." After specifying all process operators, the related FPD elements are defined and saved in respective databases. Exemplary, the FPD structure and its links for "A-040-010-Deposition_Preform1_Seq1" of process A are shown in Figure 10. The operator is about the ply deposition of dry fibers of the first sequence of the preform 1 with a production unit on a tool, see Figure 9a. In detail the operator has products (e.g., fiber material on bobbin), information (e.g., NC-program-AFP), and energy (e.g., electrical energy) as

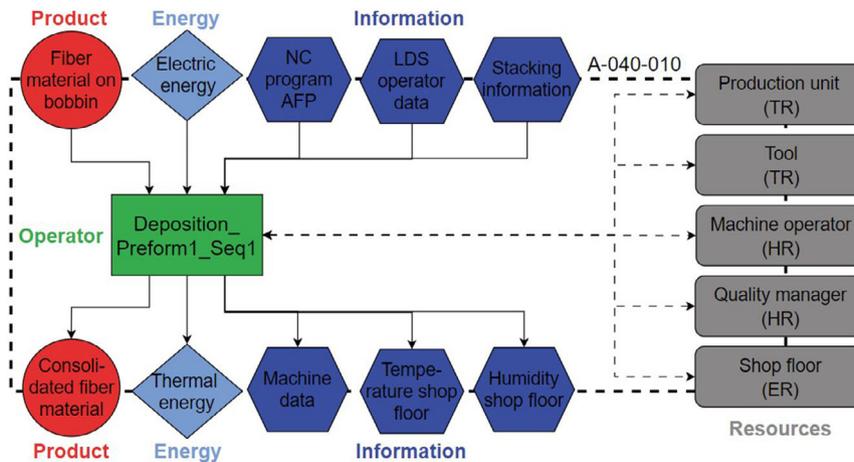


Figure 10. Links of operator “Deposition_Preform1_Seq1” to his FPD elements.

input and products (e.g., consolidated fiber material), information (e.g., machine data), and energy (e.g., thermal energy) as output. In addition, the operator uses technical resources (e.g., production unit), human resources (e.g., machine operator), and environmental resources (e.g., shop floor). All FPD elements are shown in Figure 10.

In a next step of LDS creation, operator sides based on the structure previously described in Section 3.2 are created. The operator attributes (e.g., description, start date, focal point) as well as the links to FPD elements of databases are edited, see **Figure 11**. The detailed working steps descriptions, predefined by the FPD, can be complemented with additional visualizations. If a target/actual comparison of measured values should be done, the target values and permissible deviations have to be edited.

After the completion of operator sides, the information on the LDS topic side part number, author, project manager, or LDS

version is edited. An aggregation of the linked FPD instances in databases (e.g., resource, product) is automatically generated and visualized in the main page of the LDS, see Figure 4. After verification of the LDS, the manufacturing with the needed resources is planned due to the start and end dates of the operators’ sides. The manufacturing starts if the named focal point of the first operator gets digitally informed by the software, see Figure 11.

The worker gets all information of the LDS visualized on a mobile device or computer, see **Figure 12**. In operation, the worker checks the complete working steps by name and date. The process progress can be directly traced by the progress bar, as shown in Figure 11. Green numbers stand for checked and yellow numbers for open working steps. Using the LDS on a mobile device, pictures of, e.g., defect detection processes can be easily taken. Comments can be added immediately, which

Operator		Data acquisition													
FPD-element	A-040-010-Deposition_Preform1_Seq1	⊕ Information - data storage and photo documentation ⊕ Information - time measurement ⊕ Information - defect detection													
Description	In this operator sequenz 1 of the preform 1 will be layed by the fiber placement robot.	Operations: 2 ██████████ 11													
Start	📅 14.12.2022	Info After checked an operation step sign with name and date													
Duration (day)	1	<table border="1"> <thead> <tr> <th>Operation</th> <th>checked by</th> <th>Date</th> </tr> </thead> <tbody> <tr> <td>1. Start and document time measurement above</td> <td>@ Denker, Björn</td> <td>📅 14.12.2022</td> </tr> <tr> <td>2. Controll data acquisition of production unit</td> <td>@ Denker, Björn</td> <td>📅 14.12.2022</td> </tr> <tr> <td>3. Load NC-Program "Preform1_Seq1" in folder of the robot unit and adjust the program "AllCourses"</td> <td></td> <td></td> </tr> </tbody> </table>		Operation	checked by	Date	1. Start and document time measurement above	@ Denker, Björn	📅 14.12.2022	2. Controll data acquisition of production unit	@ Denker, Björn	📅 14.12.2022	3. Load NC-Program "Preform1_Seq1" in folder of the robot unit and adjust the program "AllCourses"		
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End	📅 14.12.2022														
Focal point	@ Denker, Björn														
Predecessor	A-040-007-Preparation_data_acquisition														
Successor	A-040-020-QS_Preform1_Seq1														
Reference flow	Consolidated_fiber_preform1_seq1														
Technical resource	• Production_unit														

Figure 11. LDS front end of operator “A-040-010-Deposition_Preform1_Seq1.”

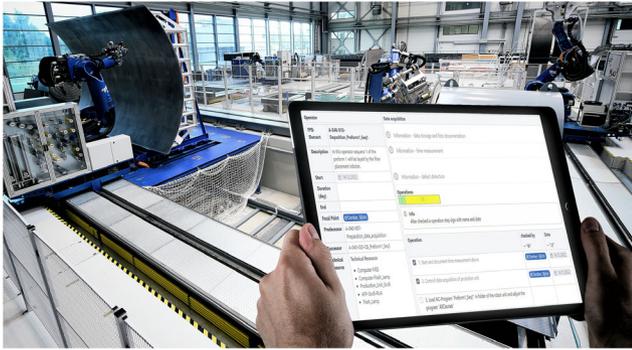


Figure 12. Digital documentation of the operation “A-040-010-Deposition_Preform1_Seq1” via mobile device in the DLR shop floor in Stade.

also improves the quality of the comment itself due to the description of what is seen and not what is remembered. Additionally, the operator side combines the two sides of information acquisition: manually generated information and automatically generated information. All manually generated information (check boxes, comments, and measured values), as well as the linkage of manufacturing date, enables the correlation of different information via date and time from the version management of the software. While the traceability of manually edited information is given by the signature of the worker, the automatically generated data needs a further information, here provenance data, to ensure traceability.

Provenance is the information about the origin of things. In the case of the described approach, it is the history of the process data. While the descriptive information about the process is represented in the LDS together with its data history, the manufacturing data is generated independently and exported as file, see **Figure 13a**. To achieve traceability of the data generated during the manufacturing process by the machine, provenance metadata for each dataset is generated. This metadata contains information about the start and end dates as well as the used configuration of the manufacturing system. Provenance according to the W3C prov model^[25] is used, which allows for each activity (data generation process) the definition of used entities (other data). For the manufacturing of the moveable, machine configuration and specification (down to

single modifications) as documents along with the documents’ provenance are generated. With this approach, a continuous traceability in the combination of LDS, machine, machine configuration, and machine operator could be achieved.

Provenance container (see **Figure 13b** and ref. [26]) as a technology-independent data format is used, which plays well with including the data and provenance both in the LDS but also for further analyses in a data warehouse.

5. Evaluation of FPD-Based LDS for Moveable Manufacturing

After a successful manufacturing of the aircraft moveable (see **Figure 14**) and a digital documentation with the digital LDS, the main achievements will be summarized and discussed in this chapter.

The method of FPD outlined in Section 3.1 was used and transferred into the structure of a digital LDS, which was evaluated on the basis of a manufacturing process for a moveable made of composite materials. The focus was on capturing the core elements of the FPD used in the selected manufacturing process—operators, products, energies, information, technical resources, human resources, and environmental resources—as holistically and formally as possible. In addition, the generated information was used to support parallel activities in the areas of data structuring and semantic modeling.

In the first step, the structure of the FPD was modeled at the operator level, so that the linkage of products, information, and

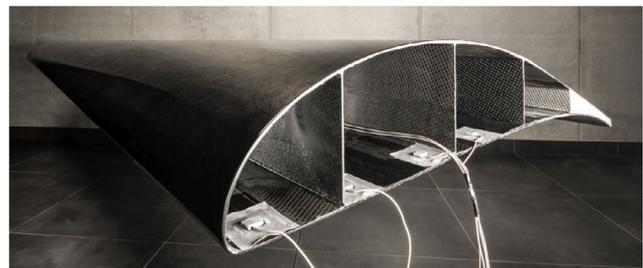
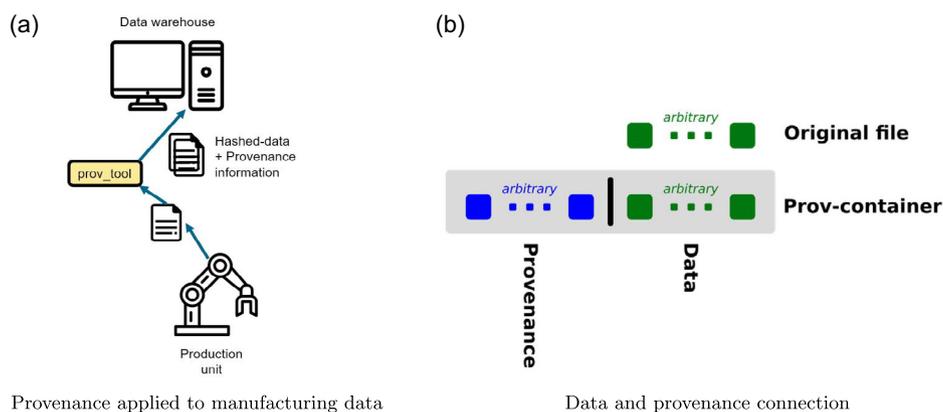


Figure 14. Manufactured moveable.



Provenance applied to manufacturing data

Figure 13. Provenance data.

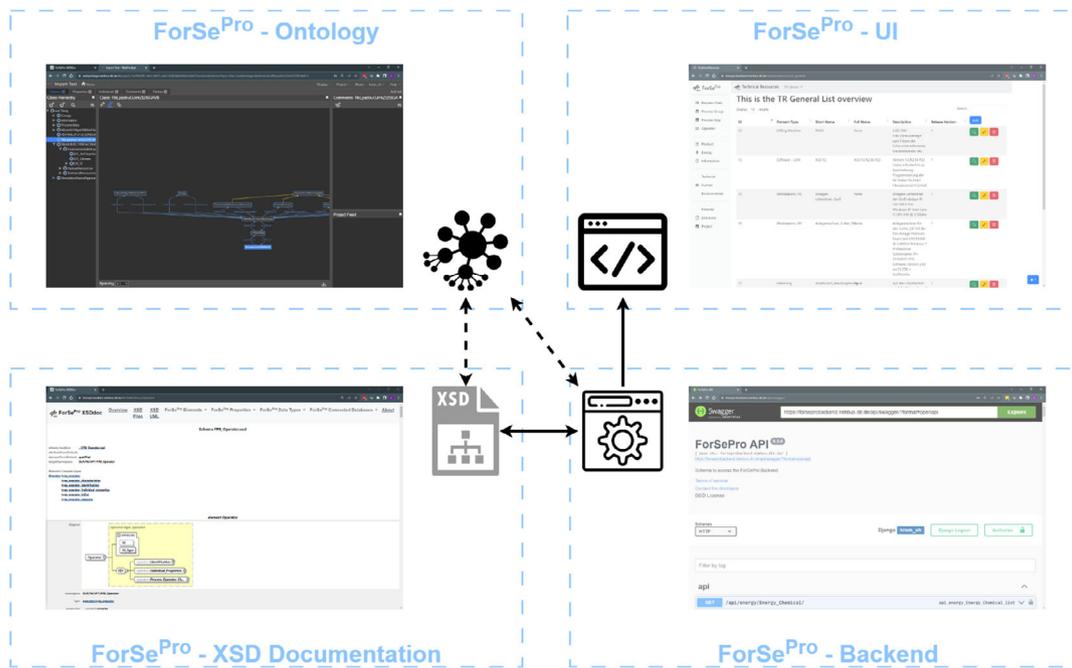


Figure 15. Core elements of the *ForSe^{Pro}* framework.

energies as well as resources are mapped. In the second step, the data required or obtained in the context of process planning and LDS was described.

The generated XML schema definition (XSD) files of the FPD and referencing data were then transferred to a developed web application *ForSe^{Pro}*. *ForSe^{Pro}* is an acronym for “formalized and semantic process description” and represents a software framework. **Figure 15** shows the four core elements of the web application:

1. *ForSe^{Pro}*-XSD Documentation: For the documentation of terms and structures.
2. *ForSe^{Pro}*-Ontology: Based on XSD files and data to create ontology class diagrams.
3. *ForSe^{Pro}*-Backend: Transfer of XSD data into class models, incl. DB management, API management, etc.
4. *ForSe^{Pro}*-UI: User interface from single-container applications over process designing up to the use in the shop floor.

ForSe^{Pro} has shown that the basic approach of a standardized description of FPD terms and the FPD structure, as well as the transfer and utilization in a web application, is successful. However, a detailed description of the *ForSe^{Pro}* framework is not covered in this article, but will be published separately at a later date.

For the moveable manufacturing, the realized digital LDS consists of 316 process operators and 2488 working steps, using 274 technical resources, links 70 information and 104 products, and creates 60 comments and 1796 photos, see **Table 1**.

Some of the 70 information that are used or generated are input for operators of the processes A, B, and C, so that the sum is more than 70. An information is, for example, a measured data object which consists of several sensors. In the operator

“Injection & curing,” only six information outputs, one data log per sensor type, is generated, although 36x thermocouples, 24x ultrasonic sensors, 1x Gelnorm sensor, 1x pressure sensor, four dielectric sensors, and 8 × 4 fiber Bragg gratings are involved. A lot of data space is used for the digital documentation, especially for photos (11 GB) and the 20 laser triangulation scans of the operator “Ply QA” (70 GB). The data is stored in a data management system and linked to the operator side of the LDS. The LDS operator structure with input (product, energy, information), output (product, energy, information), and resources (human, technical, environmental) is

Table 1. Amount of technical resources, products, and information at the moveable manufacturing.

FPD element	Process A: Skin manufacturing	Process B: Spar manufacturing	Process C: Assembly, curing, and postprocesses	Sum: (A + B + C)
Process operator	226	33	56	316
Working steps	1695	281	512	2488
Technical resource	56	53	165	274
Information (input & output)	49	7	26	70 (doubling)
Product (input & output)	36	49	19	104

complementary to the folder structure of the data management system, so that the standardized structure can be used for a semantic analysis of the manufacturing. manufacturing. In summary, the manufacturing processes consisted of many working steps, grouped in a lot of operators which were linked to each other and to their FPD elements, which all together causes a high data complexity which need to be handled and analyzed.

To visualize the data complexity, the information network and interactions for the processes from part design to ply deposition are shown in **Figure 16**. For example, the LDS is an output of the process operator “A-10-020-Process_definition” which has the input part design, Composite part design/stacking, manufacturing specification, and related documents. This LDS compared with the robot NC-code and alignment data is input for the operator “ply deposition” which generated manufacturing data inclusive provenance as an output. They can be linked in a digital LDS to provide the human resource an overview and a better understanding of the interactions which can lead to less inquiries. Primarily, the semantic links can be used for analyzing the whole manufacturing process.

After the evaluation of the manufacturing process and a detailed example of the information interactions, the workflow of FPD and digital LDS should be analyzed in detail. In **Table 2** and **3**, some of the main pros and cons are visualized.

One of the main advantages of the digital LDS is the utilization of data and information due to the linkage and aggregation

of all process relevant data on one LDS side and the machine-readable export of the data for postprocesses. The search of data at different locations (e.g., documents or folders) is no longer required. Therefore, the access and analysis of data get more efficient. For example, the operator “Ply deposition” (see **Figure 10**) provides information to NC-program, process parameters, stacking information which can be compared to the measured manufacturing data, and the defect detection. Additionally, the used energy or waste products can be analyzed in reference to sustainable aspects. Through the provenance information, the manufacturing process can be also analyzed even after several years.

The main disadvantage is the missing automatic transfer of FPD elements and their attributes to the LDS, so that many manual steps are necessary. Additionally, a semantic modeling of the whole manufacturing requires a description between all FPD elements. Dependencies between FPD elements could be, for example:

1. Part design effects material.
2. Material effects process parameter.
3. Material or process parameter effects technical resource.
4. Technical resource effects human resource.

Improvements: The acceptance of a digital LDS by the different stakeholder is dependent on the usability and the functions that make the work more efficient. On the one side, the mentioned disadvantages of the actual digital LDS version should be eliminated, but on the other side, there are some more general improvements that can be named:

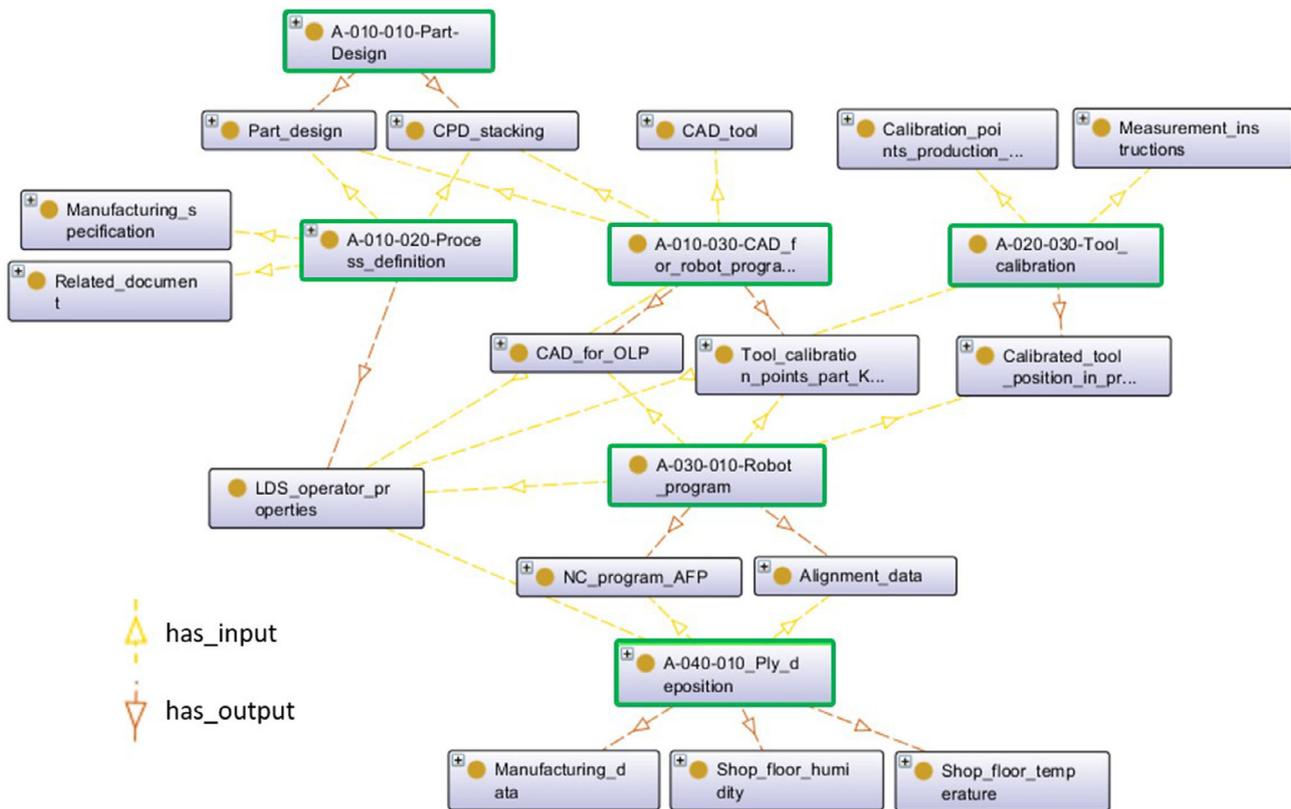


Figure 16. Information flows from part design to manufacturing data.

Table 2. Pro argument of digital LDS.

Topic	Pro argument
Increased data quality and completeness	<ul style="list-style-type: none"> - Version control and visualization of differences of all sides - Selection of FPD elements of the database during process planning ensures data consistency - Measurement data is entered directly on the mobile device (no scrolling in the paper LDS to the table of values is needed) - Legibility of the information (no illegible handwriting) - Data referencing instead of duplication, e.g., in holistic analysis, increased data consistency - User-friendly LDS design increased user motivation (e.g., links to additional information of FPD elements, fade in/fade out of information)
Time saving	<ul style="list-style-type: none"> - Direct access to all required information from the linked databases reduces the search time of information (one platform, personal reference via focal point) - Parallel documentation of operators by several persons is possible - Parallelization of work is possible through visibility via a flowchart (the paper LDS allows only linear processing) - Automatic sequence and time planning enabled by metadata of the operator side, e.g., predecessor–successor relationship, start and end dates - Material procurement is simplified through the material consumption definition at the operator level and aggregation to the main LDS page - Reduced data entry effort by predefined and clustered input fields, e.g., comments, measured value incl. prefilled unit - Assigning people to, e.g., comments (who receive automatic email) increases quality and reduces nonproductive time
Reduced probability of errors	<ul style="list-style-type: none"> - Prefilled input masks - In-text integrated sketches or photos to explain descriptions in more detail - Visual representation of dependencies (predecessor–successor, products used, required information) - Linked instances of FPD elements with FPD element-specific metadata and attached files, e.g., up-to-date processing instructions of a product
Scalability	<ul style="list-style-type: none"> - LDS structure enables holistic analysis, even across multiple component productions
Analyzability	<ul style="list-style-type: none"> - Online process tracking (on operator and working step level) - Online evaluation reduces scrap rate through early analysis of measured and machine data as well as comments - Improved data analysis due to the summarized content of all operators incl. data export, e.g., for LCA - Linkage of FPD elements to operator and between operators enabled semantic analysis - Data traceability of, e.g., information flows and their change history throughout the whole manufacturing process, e.g., for provenance description - Data consistency via time stamps of, e.g., entries of measured data or comments to relate to external data, e.g., machine data or photos - Concept of digital documentation enables interdisciplinary analysis capability and thus reduces errors, especially with small batch sizes

Table 3. Contra argument of digital LDS.

Topic	Contra argument
General	<ul style="list-style-type: none"> - Software for transfer FPD elements in a digital LDS is not available yet - LDS software has no possibility to define cross-dependencies between input and output as well as resource elements of an operator - Edits on the operator side have to be done in the back end - Missing logic on which operator should be prioritized in parallel processes - No creation of photos from the application (an additional app was used)

1. Automated naming of captured photos with operator name and time stamp as well as automated storage in the data management system in the related folder;

2. Inline photo editing for visualization of specifics and comments;

3. Functionalities that provide extended information (like hover in HTML);

4. Troubleshooting by suggested potential solutions;

5. Help button to directly activate an online conference with project manager (use camera for troubleshooting);

6. Changeable LDS design (for process planer or worker (beginner or professional));

7. Changeable language;

8. Part identifier to load digital LDS, e.g., QR code.

6. Conclusion and Outlook

A standardization of manufacturing modeling and LDS creation by using FPDs and templates are carried out. The developed workflow of FPD and LDS is successfully applied and evaluated on a manufacturing of an aircraft moveable. Digital capabilities are being implemented in the LDS to improve usability and automated analysis as well as to use machine-readable information for postprocesses. Additionally, the traceability of manufacturing processes could be demonstrated by the LDS design and especially by adding provenance to manufacturing data. Operator modules and FPD individuals within the databases can be reused for further manufacturing processes which accumulate new modules and individuals by using operator templates. A semantic description of FPD elements and operators was defined to gain further process knowledge.

A lesson learned with all stakeholders (process planer, worker, data scientist, customer) identifies improvements regarding LDS as well as data structuring and semantic modeling, see Section 5. These points will be directly applied in the BMWK-founded project PredictECO, e.g., in a development of a commercial software for digital documentation. Additionally, further standards will be defined, e.g., in terms of definition for sustainability assessments of manufacturing processes or definition of provenance information. In general, digital functionalities and interfaces should be used to improve transfer steps and

to reduce manual working steps, e.g., transferring FPD elements to the LDS or naming and storing photos in databases. This enables rapid implementation and high acceptance of the digital LDS by all stakeholders, which leads directly to an increased analysis capability.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that supports the findings of this study is available from the corresponding author upon reasonable request.

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