Development of a Digital Thread Tool for Extending the Useful Life of Capital Items in Manufacturing Companies - an Example Applied for the Refurbishment Protocol

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***Abstract*—With the growth of the world's population and depletion of limited resources, economic development is shifting from 'take-make-waste' linear model to a sustainable Circular Economic (CE) model. It is becoming essential to extend the useful life of products to avoid throwaway. In the manufacturing industry, this is especially relevant for long-life expensive capital items. Literature has presented many approaches to extend product life, such as refurbishment, upgrade, repair, and recycling. Depending on a capital item's condition, manufacturers perform a series of activities to extend its useful life, such as refurbishment activities followed by upgrade activities. These life extension activities may involve various stakeholders and systems and significantly impact the capital item's life cycle. It is a challenge to enable cross-collaboration between these different stakeholders and systems, and provide manufacturers a holistic view of the activities performed along the entire life cycle of a capital item. The Digital Thread (DT) concept, which has been applied in product lifecycle management and manufacturing, provides an opportunity to tackle these challenges. However, there is little research about developing and applying DT for extending the useful life of capital items in manufacturing companies. This paper presents ongoing research to develop a DT design tool for product life extension. We take the development of a DT sample for the Refurbishment protocol deployment as an example to illustrate the approach. This tool will pave the way to support manufacturers to extend their large capital items' useful life.**

***Keywords*—circular economy, product life extension, digital thread, information flow, refurbishment**

I. Introduction

With the growth of the world's population and depletion of limited resources, economic development is shifting from 'take-make-waste' linear model to more sustainable Circular Economy (CE) model. To reach the goal of CE, it is becoming essential to extend the useful life of products to avoid throwaway. In the manufacturing industry, this is especially relevant for long-lasting, expensive capital items, e.g. press machines. The usage phase of the capital items typically covers years or decades. Their performance degrades and eventually cannot meet the increasing market demands. Since they are costly, manufacturers have intentions to keep them at a state-of-the-art status and extend their useful life. Literature has presented many approaches to extend product life, such as life extension design strategies, refurbishment, repair, upgrade, and remanufacturing [1, 2].

Depending on the condition of a capital item, the manufacturer chooses and performs a series of activities to extend its useful life. For example, when a machine malfunctions, the manufacturer may first carry out inspection activities, and then decide whether it needs to be refurbished, repaired, remanufactured, or upgraded, according to the inspection result. This process involves various stakeholders and systems and has a significant impact on the capital item's lifecycle. It is a challenge to enable cross-collaboration between these different stakeholders and systems, and provide the manufacturer a holistic view of the activities carried out along the entire life cycle of a capital item.

The Digital Thread (DT) is "an integrated information flow that connects all the phases of the product lifecycle using accepted authoritative data sources (e.g., requirements, system architecture, technical data package (TDP), three-dimension (3D) CAD models) "[3]. Digital Threads complement digital twins for better data management to improve the production process and performance and ensure continuity and traceability of information [4]. It offers an opportunity to handle the discussed challenges, with the capability of weaving together all activities carried on a capital item along its life cycle. Transparent information flow in a DT allows stakeholders to have a clear view on, for example, which life extension activities have been performed, why an activity is required, and which data is necessary for the execution of that activity.

However, there is little research about developing and applying a DT approach for extending the useful life of capital items in manufacturing companies. This paper presents ongoing research to digitalise and integrate the CE approaches into the DT design tool for managing product life extension activities applied on capital items. We take the development of a DT sample based on the Refurbishment protocol to illustrate the approach. This tool can help pave the way to support manufacturers to extend their capital items' useful life.

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The rest of the paper is organised as follows. Section 2 describes the background and motivation for the DT development for product life extension. Section 3 outlines the methodology used for the development of the DT design tool. Afterwards, section 4 describes the development of a DT sample for the Refurbishment protocol deployment. Finally, the last section draws conclusions and states future steps.

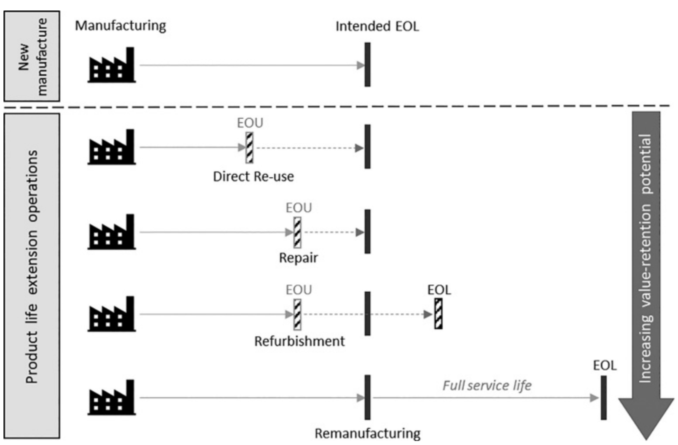
II. BACKGROUND AND MOTIVATION

This section describes the background and motivation of applying a DT approach for extending the useful life of capital items in manufacturing companies. The first part summarises the CE and approaches for extending product life. Afterwards, it introduces the DT approach, which is helpful for connected information flow and cross-domain collaboration. These two parts motivate this last part, about integrating the product life extension approaches from CE into DT design tool for product useful life extension.

A. *Circular Economy and approaches for extending product useful life*

As an approach to gain sustainability, the CE concept has received increased attention in academics and industry in recent years. Literature provides various contributions to the definition of the CE. One of the most renowned definitions is given by the Ellen MacArthur Foundation. They defined CE as "An industrial economy that is restorative or regenerative by intention and design" [5]. It would close loops in the industrial economy and minimise waste, with two groups of business models [6]:

- foster re-use and extend service life through repair, remanufacture, upgrades and retrofits
- turn old goods into as-new resources by recycling the materials



Note: EOL = end of life; EOU = end of use

Figure 1 Graphic representation of product life extension operations [1, 8]

These two business models are appliable for extending the useful life of capital items, their parts, and materials. "Foster re-use and extend service life" mainly protects the value of products and their parts. "Turn old goods into as-new resources" is the way to preserve the value of materials. Companies can achieve product life extension through various approaches, such as long-lasting design, maintenance, repair, re-use, remanufacturing, refurbishing, and recycling [7]. Each approach has its applicable situation. The IRP defined four common operations to extend product life: direct re-use, repair, refurbishment, and remanufacturing (Fig. 1) [1]. For instance, when a product reaches its end-of-use due to technical failure, the direct re-use and repair operation helps the product reach its intended end-of-life (EoL). The operations refurbishment and remanufacturing allow a product to extend its intended end-of-life.

From a material efficiency perspective, products go through alternative routes with different approaches in the context of a product life cycle (Fig. 2) [9]. These approaches give companies a rough idea about extending the life of products, their parts or components, and materials. Several studies further describe more details about these approaches to provide companies with more guidelines. For example, Andrew and Ibrahim presented the key steps in the remanufacturing process [10]. However, these guidelines about specific EoL activities are still limited. To support companies extending product life in practice, a systematic guideline and respective supportive tool are required. They should help companies decide and stepwise perform the suitable approaches for their machines.

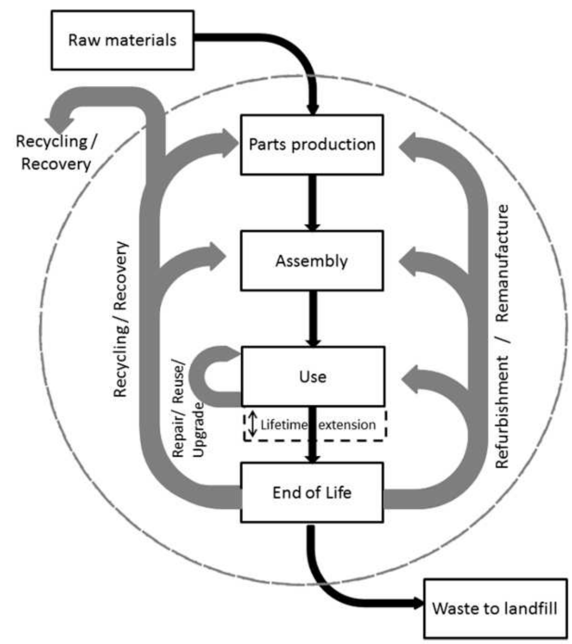


Figure 2 Material efficiency aspects in the context of a product life cycle [9]

B. *Digital Threads*

The DT refers to "the communication framework that allows a connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed functional perspectives "[11]. It aims to link heterogeneous information systems and data sets across the various domains of the product lifecycle (e.g., design, manufacturing, quality) in dynamic ways, and enables the holistic view and traceability of an asset along its entire lifecycle [3] [12]. The DT includes any data, behaviours, models, protocols, security, and standards related to the asset and the context where it is expected to operate [12].

Literature and commercial vendors describe the application of DT in many areas, such as product design, manufacturing, and product lifecycle management [13] [3] [14]. The DT offers the opportunity to connect activities with data, stakeholders and applications in the process of product life extension. It would foster interoperability and close collaboration between them and enable traceability of activities.

C. Motivation of applying DT approach in product usefule life extension

The extension of product useful life in CE involves the collaboration between many stakeholders (e.g., technology providers, industrial manufacturers, industrial equipment OEMs, engineering and maintenance companies…) and systems. This is due to the fact that each stakeholder has expertise only on certain technologies and activities. For example, the company in charge of the recycling activities may have no expertise in upgrade or inspection, but a sustainable approach relies on close collaboration between each other. The recycling company recycles the old components discarded from the upgrade activities. The decision to perform upgrade activities depends on the inspection results. In basic terms, it can be viewed as the exchange of information, models, parts and materials between multiple stakeholders and systems along the life cycle of products. To support this kind of exchange, integrate information flow besides physical material flows is helpful.

Meanwhile, it is necessary to monitor and track the activities performed on a capital item. This is important for product owners because it provides a clear view of their products' historical and current status. For technical partners and engineering and maintenance companies, it is meaningful for decision-making, for example, to understand why a repair activity is performed and when is the best time for the next maintenance action.

This study intends to investigate the integration of CE and DT approach for product life extension. Various approaches in CE supports product life extension, and the DT approach can support the management of connected information flow and cross-collaboration between stakeholders. It seems promising to digitalise the product life extension approaches from CE and manage them in DT design tools for guiding and supporting manufacturing companies extending the useful life of capital items.

III. Approach to develop a digital thread Tool for product useful life extension

This section describes the authors' approach to integrating the CE approaches into DT design tool for product life extension.

We adopted the top-down approach to develope a systematic guideline in the form of organised Circularity Protocols. It started at Protocol Z-Modernise, and going through Protocols-Functional diagnosis, Inspection, Refurbishment, Disassembly, Repair, Remanufacturing, Upgrade, Recycling, to finally reach Protocol Ω - Re-assembly and Testing (Fig. 3). We described the synergies and interactions between these protocols. The systematic guideline provides a holistic view about different approaches that can be applied for product life extension. It would guide companies to choose and perform suitable actions for product life extension in the physical world.

Afterwards, we defined interfaces and and digitalised all actions/activities in the systematic guideline to support interoperability and close-collaboration between stakeholders in a digital world. For all life extension activities, we defined a clear interface about their expected input and output. This is to ensure that participants on the activities to be aware, for example, of which information is required, in which formats, and according to which standards. So that, the right information can be delivered to stakeholders and systems in other activities. This kind of interface definition is important to achieve interoperability and close collaboration between stakeholders.

Figure 3 LEVEL-UP Circularity Protocols (Source: http://www.levelup-project.eu/project/circularity_protocols)

Finally, the Circularity Protocols were realised and integrated into a DT design tool. We developed a DT design tool with a digital representation of all protocol actions, i.e. product life extension approaches and actions. It allows companies to stepwise plan, apply, and track various life extension actions applied on their capital items. The DT design tool helps manage the digitalised product life extension activities, their connected information flow and the collaboration between stakeholders. It provides companies in the digital world a holistic view of all performed product life extension activities.

In detail, the whole process of the Digital Thread development for product life extension involves the following five main steps. The first three steps are mainly about the development of the systematic guideline. We intended to keep the guideline generic enough to accelerate the adoption in industries. The specification of interfaces and digitalisation of all actions/activities are in steps 2 and 4. The last two steps are about the development and deployment of the DT design tool.

Step 1: Define the protocol. This step provides a definition and description for each protocol. It describes the protocol scope, protocol purposes, applicable conditions, triggers, input, and output. Within this step, protocol developers work together with manufacturing companies to understand the problems or questions that the industrial companies currently have and want to solve. This kind of problem understanding helps define protocol clearly for problem-solving in industrial companies.

Step 2: Provide a list of actions for the protocols. This step specifies the action schema for protocols, i.e. a list of actions/activities to be performed in the protocols. Within this step, protocol developers add, update and improve the action schema for each protocol and describe the relationships and interactions between these protocol actions. It defines clear interfaces for each protocol action, and describes, for instance, the required supportive systems/tools and detailed steps.

Step 3: Visualise the protocol guidelines. After clarifying the protocol's understanding, this step consists of illustrating the protocol guidelines in visual flowcharts. The visual flowcharts help users in industrial companies follow the protocols in an easier manner and solve their problems in reality. This step takes the outcomes from the last two steps as input to provide a flowchart as output. Each protocol has a flowchart with starting point and endpoint. The starting point is the trigger of the current protocol, and this can be, for example, another protocol or some decision-making. The endpoint can be either a trigger of another protocol, or other condition as a decision-making step in the process, or a working performance continuation.

Step 4: Develop a Digital Thread tool for product life extension. This step includes developing a DT design tool to support the plan, execute, and track the protocol actions performed on capital items. For that purpose, the first goal is to develop a Digital Thread ontology based on the protocol guidelines and defined interfaces. The ontology manages all important semantic concepts within the Digital Threads for product life extension. It enables an ontology-driven derivation of needed actions and parameters for a given protocol. Based on the Digital Thread ontology, we will develop a DT design tool. The DT design tool is a web application that provides a model editor for DT. The model editor uses a variant of the PrimeFaces FlowChart [1] whereby the underlying meta-model is not predefined. The available DT related activities, properties and steps are derived dynamically on a DT ontology. The DT ontology is linked to the DT design tool and enables the tool to derivate the meta-model and corresponding UI modelling elements.

Step 5: Deployment of the Digital Thread tool in industrial pilots. This step involves deploying the DT design tool as a service in manufacturing companies. After the service's deployment is ready, manufacturers can stepwise apply and realise protocols activities on their capital items to extend useful life. It allows manufacturers to manage the status of capital items during their life cycle.

IV. APPLICATION SCENARIO – DIGITAL THREAD DESIGN TOOL FOR REFURBISHMENT PROTOCOL

This section describes the development and customisation of a DT design tool for the Refurbishment protocol. This activity covers three main actions, namely: developing Refurbishment protocol guidelines; transforming the Refurbishment protocol into a maintainable DT as ontology; and the provision of a DT design tool for the inclusion of every DT related ontology.

The following presents the detailed steps. It defines and visualises the Refurbishment protocol guidelines in the first three steps. Subsequently, the developed guidelines derivate the DT ontology for the Refurbishment protocol. Finally, the integration and usage of the DT ontology inside the DT design tool are given as an example to illustrate the customisation of the DT design tool. By doing so, it shows the potential usage of the DT design tool in manufacturing companies to extend product useful life.

Step 1: Define the protocol. In industrial process facilities, corrosion is the biggest single cause of plant and equipment breakdown, including machinery, vessels, structures, supports and pipelines. While atmospheric corrosion in the form of air (oxygen), and water (moisture, humidity, vapor, etc.) is the main culprit, environmental factors including high temperatures and pressures as well as harsh substances, chemicals and gasses can also accelerate the corrosion of carbon steel and other metals.

The Refurbishment protocol is about the light repair and cleaning of the system to bring it to its original status and integrity (as-new status). Old grimy machines, with corroded or rusted surfaces, will be cleaned and treated to enhance their superficial appearance (painting) and improve their durability, easy cleaning or chemical resistance in harsh working environments (coating application). Furthermore, safety regulations will be upgraded to meet all appropriate health and safety requirements considering the necessary protective measures to mitigate or reduce those risks that cannot be totally eliminated.

The Refurbishment protocol might trigger the Repair protocol in case a component is damaged. In case of non-repairable parts, they will be removed and replaced by new ones. In case there are no available substitutes, then the upgrade or the Remanufacturing protocol are triggered. Within each of these protocols, the simulation of the different repair or remanufacturing processes and the virtual commissioning of the upgraded machine will also guide the decisions of the best actions to be taken based on the performance, quality, cost, and minimisation of future risks.

Step 2: Provide a list of actions for protocols. Three main actions are organised to support the Refurbishment protocol application:

Figure 4 Cleaning surfaces of a sample machine

- **Clean component/machine surfaces**. Remove rust and old paint using polished, laser and/or blast cleaning to

[1] https://www.primefaces.org/showcase/ui/data/diagram/flowchart.xhtml?jfwid=af024

avoid future problems like corrosion and prepare the surfaces for the new painting and/or coating application (Fig. 4).

- **New painting or coating application.** To improve the machine/component superficial appearance, new painting will be applied. The application of a protective coating on safety-critical components to extend process equipment durability, enhance easy cleaning or chemical resistance in harsh working environments (e.g., high temperature, CO2 and H2S environments, corrosion and wear resistant coatings, coatings for oil sands and other oil and gas exploration and production environments...) will be evaluated and applied if required.
- **Safety regulations upgrade.** Upgrade of the machine to meet all appropriate health and safety requirements. It will take the necessary protective measures to eliminate risks, or reduce as far as possible those risks that cannot be eliminated. The protective measures include, for instance, the implementation of additional cover parts of the machinery used specifically to provide protection by means of a physical barrier, and the inclusion of information for machinery users with the residual risks, the protective measures adopted, and the indications about the necessity of particular training or requirements of personal protective equipment (PPE) considering the Machinery Directive 2006/42/EC regulation. If the machine requires the addition of an upgraded mechatronic component, the Protocol Upgrade will be called (Fig. 5).

Figure 5 Safety regulation update of a sample machine.

This step also defines the information exchange interfaces for each protocol action. Table 1 shows sample interfaces for the action "Clean component/machine surfaces" about its' expected input and output.

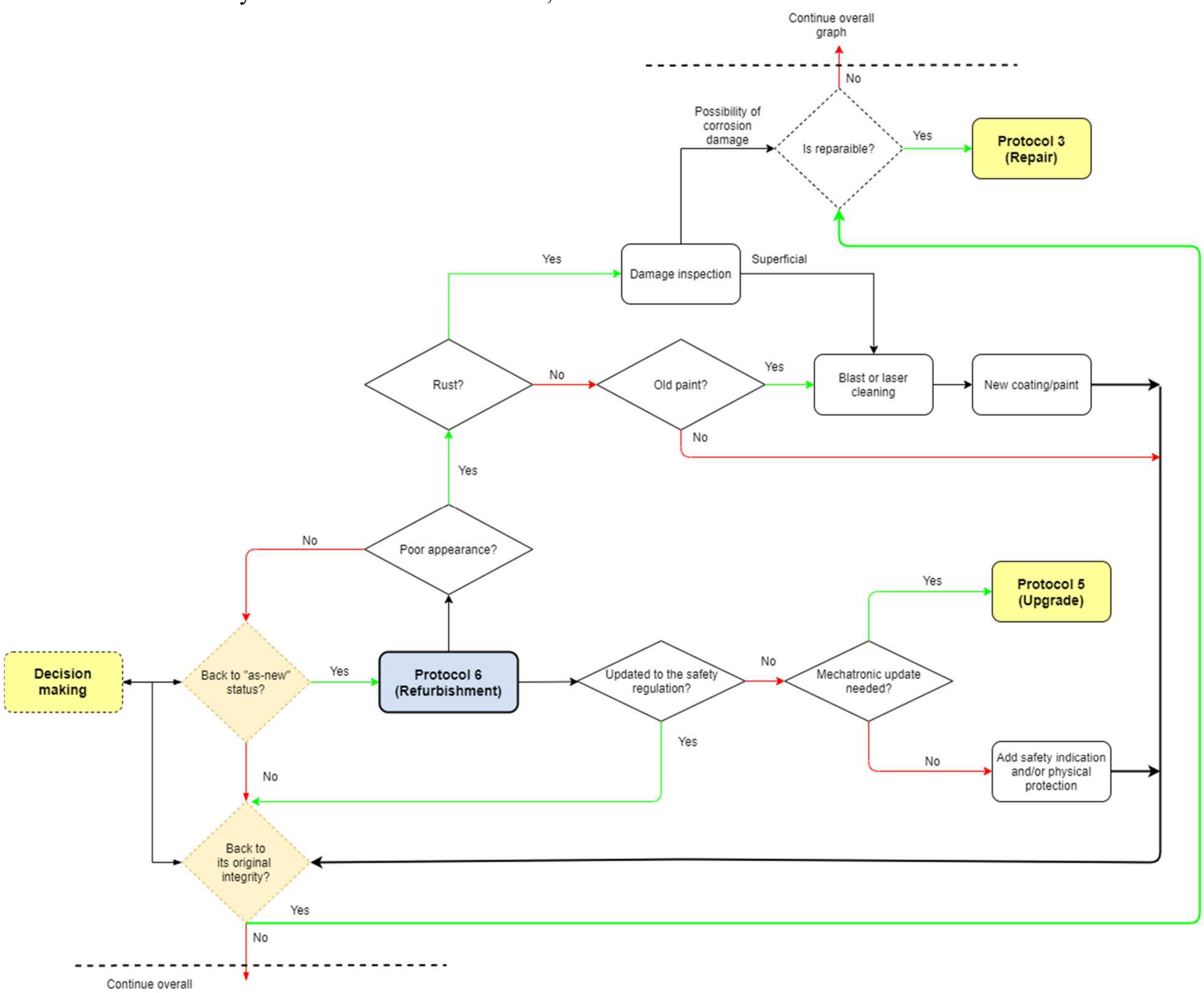


Figure 6 Protocol Refurbishment workflow

TABLE 1 INTEFACES OF ACTION "CLEAN COMPONENT/MACHINE SURFACES"

Expected input (information content)	Expected Input (Characteristics of Information)	Expected output (information content)	Expected output (Characteristics of Information)
(1) Refurbishment protocol selection and Machine inspection checklist from Protocol 2-Inspection. (2)Summary of Refurbishment actions performed before.	PDF/.docx/.xlsx. Ideally, web questionnaire.	(1) List of cleaning actions performed/ date/ personnel /pictures of the machine before and after/other important information. (2) Other protocols trigger	PDF/.docx/.xlsx. Ideally, web questionnaire.

Step 3: Visualise the protocol guidelines. The previous step identified the needed actions to be performed for a protocol. This step visualised the protocol guidelines as a flowchart (Fig. 6). To be aware of all possible paths and the one to be followed, these actions are illustrated in the protocol flowchart.The specific sequence depends on different criteria, whereby the criteria's values differ between the production lines.

Step 4 & 5: Develop & deploy Digital Thread tool for product life extension. In these two steps, we describe how to realise the Circularity Protocols into the DT design tool with the example of refurbishment protocol. It first presents the building of the Digital Thread ontology based on Circularity Protocols (i.e. refurbishment protocol), and then introduces the subsequent integration of the ontology into the DT design tool. The definition and development of a Digital Thread ontology is presented with the example Refurbishment protocol, but the approach is applicable for all 10 protocols (see Figure 3).

The definition of a Digital Thread ontology for a specific protocol is based on OWL-DL. The ontology aims to define the protocols, their activities, the steps, the meta-information, and the corresponding instantiation as the DT. The following paragraphs describe the ontological representation of the DT in detail.

The protocol actions such as *Clean component/machine surfaces* for the refurbishment protocol are defined as protocol activities and belongs to the concept Protocol_REFURBISHMENT_ACTIONS. Each specific protocol action is an individual of the type Protocol_REFURBISHMENT_ACTIONS. The example of the individual P_Ref_Clean which represents the action *Clean component/machine surfaces* is shown in Fig. 7.

Each protocol activity, such as the individual P_REF_Clean, has meta-information to add information for the instantiation. The current ontology version covers meta-information such as, the defined interfaces (e.g. input and output), and the potential support of hardware or software. The definition of mappable hardware, software and data sources are also added as concepts and corresponding individuals inside the ontology.

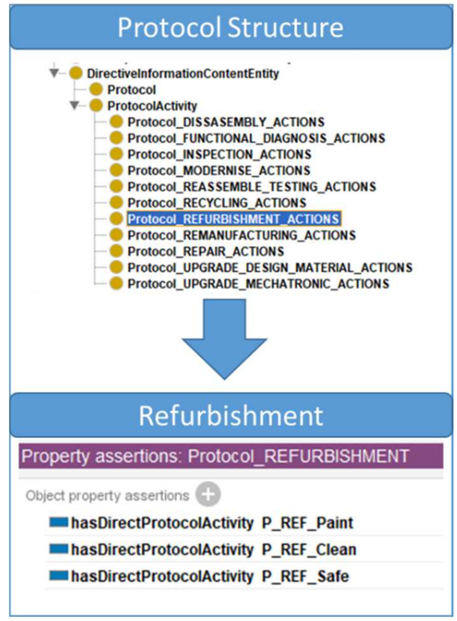


Figure 7 Digital Thread Ontology.

A DT is an individual of the Digital Thread's concept and supports the definition of a sequence of DT activities. Each Digital Thread's individual defines a sequence of activities whereby each activity can contain a couple of meta-information. The example of a DT and linked DT activity is shown as individuals in Fig. 8.

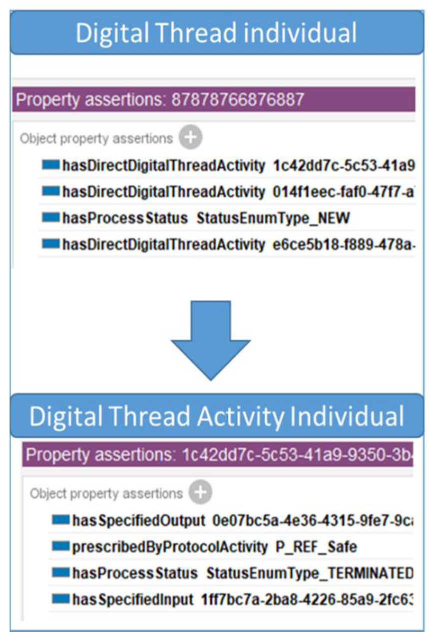


Figure 8 Example of Digital Thread individual

As presented before, the ontology defines the protocol, protocol activities, and Digital Threads. Thus, this ontology enables the interoperable representation of Digital Threads but cannot be applied by Digital Thread's stakeholders because they are more familiar with mechanical engineering or system engineering instead of description logics.

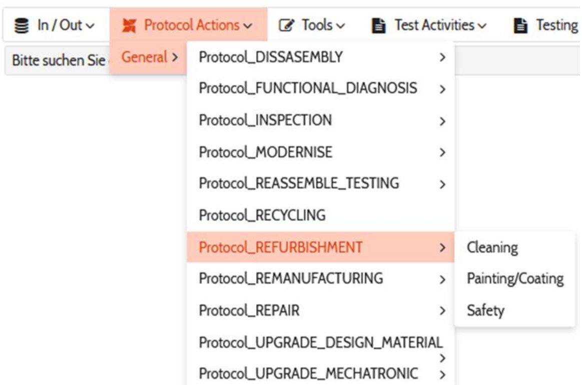


Figure 9 Screenshot of protocol's palette as a menu.

To solve this barrier, the DT is embedded into a web application. This web application focuses on the modelling of flows whereby a flow describes a DT. The primary purpose of the DT design tool, namely *Digital Thread Wizard,* is to:

- Define the Digital Thread as flow
- Update the Digital Thread activities by different stakeholders
- Inform stakeholders by events when the Digital Thread's status has changed.

The ontological content related to protocol activities, data sources, tools is available as a palette inside the tool. A menu above the modeling editor represents the palette. Each menu entry adds the corresponding ontological individual as a flow's node to the DT's flow. Fig. 9 shows the available palette.

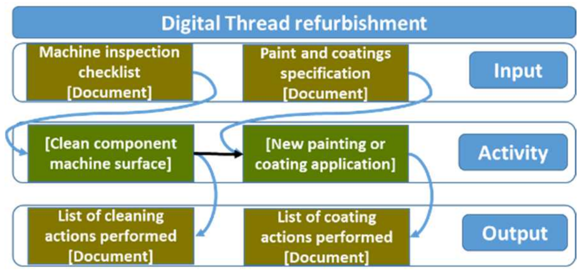


Figure 10 Sample refurbishment Digital Thread

Each selected menu entry appears as a node on the editor. Connections between protocol activities model the overall DT. The role of connections from data sources and tools to the protocol activities is to map the protocol activity's input and output. Fig. 10 demonstrates the DT for the refurbishment as a flow. Besides, each flow's node contains parameters that can be set or updated during the Digital Thread's lifecycle. One of the mandatory parameters is the status of a DT activity.

The comprehensive tool supports the creation and status monitoring of Digital Threads inside a web application and supports the deployment as a service. A screenshot of the Digital Thread modelling view is given in Fig. 11.

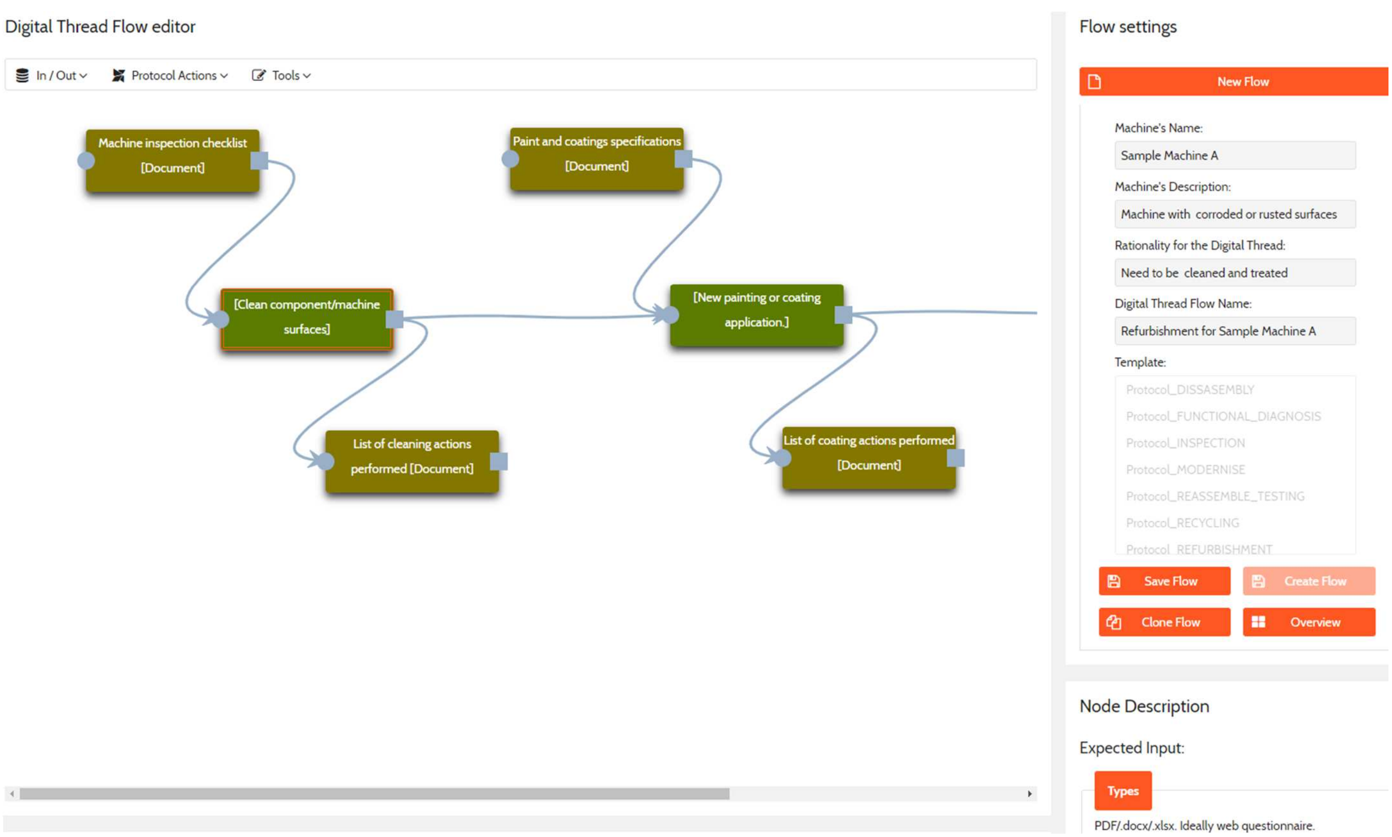


Figure 11 Screenshot of the Digital Thread Wizard

The available protocols, protocols activities, tools, data sources and their parameters are not fixed inside the Digital Thread Wizard. The applied approach reads the information from the Digital Thread ontology and updates the modelling environment accordingly. This approach guarantees the extendibility and adaptability to specific domain-specific regulations.

V. Conclusion

The paper presents the development of a Digital Thread design tool for extending the useful life of capital items in manufacturing companies. To support the development of life extension maintained as DT, the authors introduced the 10 Circularity Protocols. The specific actions, results, and impacts vary between the protocols and the concrete production environment. The paper proposes action-oriented guidelines and a DT to support the sustainable application of protocols. The Circularity Protocols guidelines are modelled as an ontology, and it feeds the DT design tool. The authors propose a web application for the management and execution of the DT, with the example of the Refurbishment protocol deployment. The first prototype already applies the Digital Thread ontology and enables the modelling and status monitoring of Digital Threads. The next step is the evaluation phase based on real industrial use cases, which will execute and validate the protocols and test the Digital Thread design tool. For that purpose, the European project LEVEL-UP delivers 7 applicable industrial use cases, including obsolete large machines from various sectors and with different technical issues and business strategies for their digital uplifting. The digital thread weaves together multiple protocol actions performed by one or more technical partners and systems. It will eventually enable cross-collaboration between these different partners and systems, and provide manufacturers a holistic view of the activities performed along the entire life cycle of their capital items.

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