A Model-Based Approach for Evaluating and Validating the Sustainability of Production Systems

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As an important contributor to the global transportation system, the aeronautics industry has an important role to play in promoting sustainability and accelerating the development of sustainable products. This paper aims to investigate how innovative technologies, engineering methods, and digitalization can support the achievement of sustainability goals in the aeronautics industry. This work argues that the adoption of Model-Based Systems Engineering (MBSE) improves the definition and validation of sustainability key performance indicators (KPIs) and stakeholder requirements while designing and planning both products and production systems. By using modeling languages such as SysML, the production of customizable aircraft becomes more flexible and modular, enabling the industry to adapt to changing product configurations and resource availability. Moreover, this paper demonstrates how MBSE can depict relationships within the production system and can ensure KPIs traceability for both product components and industrial processes. The data and relationships captured through MBSE can be used to plan and optimize production processes, and to simulate them to analyze sustainability aspects and identify energy-saving opportunities. By employing a comprehensive and systematic approach, MBSE enables the aeronautics industry to address sustainability concerns across all stages of the lifecycle from design to production, considering different fidelity levels. This paper presents a methodology for linking model-based production system architectures to real production systems. It highlights how sustainability data obtained from executed processes and resources can be utilized for model-based requirements validation and support the optimization of sustainable conceptual designs

Keywords: Sustainable Production; MBSE; SysML; Process Validation; Co-Simulation

I. Introduction

The European Green Deal was concluded in order to cope with existential threats to the world and humanity such as climate change and environmental degradation. Within this agreement, the objective of eliminating net greenhouse gas emissions by 2050 has been set and strategic plans for the industrial sector have been put in place in order to facilitate the transition to a modern, resource-efficient, and competitive economy [1]. These targets have introduced a paradigm shift in the global economic landscape by emphasizing the importance of sustainable development and eco-friendliness alongside traditional indicators of efficiency and productivity. In this context, the aviation industry has a role to play and must develop sustainable strategies to deal with these global challenges. Yet factors like consumption of energy and natural resources, water supply, manufacturing emissions and waste call for the introduction of new technology as well as changes to sustainable policies, measures, and assessment methods [2].

The emergence of digital technology is playing an important role in guiding and catalyzing change toward the achievement of sustainable development goals. Digital methods are increasingly essential for improving green manufacturing through their ability to analyze and optimize the entire product lifecycle with greater efficiency [3]. Thus, digital technologies provide access to an integrated network of previously unexploited data that can be used to assess and optimize the sustainability of production systems. Furthermore, by connecting artifacts and assets from different life-cycle phases, an understanding of aviation as a system and its impact on the environment and society is enabled.

For these reasons, researchers at the German Aerospace Center (DLR) are developing digital methods to promote sustainability and accelerate the development of sustainable aviation. These methods seek to link conceptual aircraft

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design to production planning and shop floor systems to assess and analyze the production feasibility and sustainability of new or customized aircraft and cabin configurations. By doing so, they provide feedback from production to design, enabling cost-efficient design optimization at early stages. Moreover, optimal use of available resources, such as robots and workers, for required assembly or installation processes can be planned, simulated, and tested in a flexible manner by leveraging production models.

In this context, this work presents an approach that leverages different digital methods and technologies to support the sustainability assessment and optimization during the production phase. The approach provides an overview of these methods and technologies as well as established standards for modeling and assessing sustainability in the industry. Model-based Systems Engineering (MBSE) is used to model and analyze production systems from a sustainability perspective, support the conformity to sustainability standards, and connect production to design models. Digital technologies such as the Internet (IoT) of Things and Cyber-Physical Systems (CPS) are utilized to gather and link real data from the shop floor to production planning and analysis models. The methodology is applied to a use case in the aircraft assembly domain to demonstrate its practical implementation and integration with real industrial data. The results highlight the potential of the methodology to facilitate automated analysis and validation of sustainability targets. Overall, this approach provides a solid foundation for assessing and optimizing products and production processes based on sustainability indicators, thereby contributing to the ongoing efforts at DLR to promote digital and sustainable aviation.

II. Literature Review: Leveraging Digital Technologies for a Sustainable Production

A. Impact of Industry 4.0 technologies on Sustainability

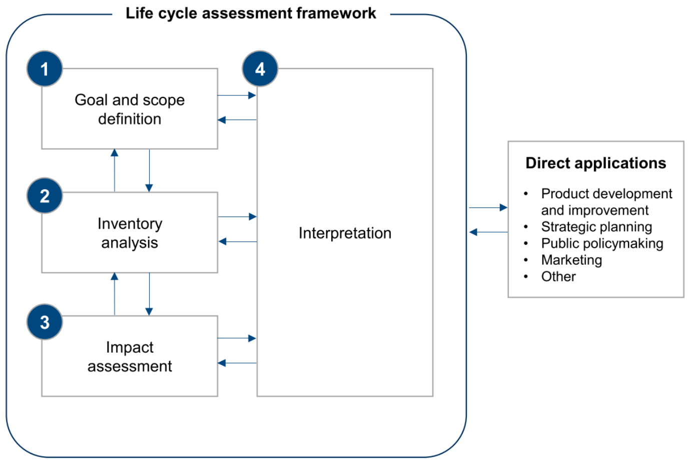
According to a report from the International Energy Agency, the manufacturing industry contributes to more than 35% of CO2 emissions and consumes nearly one third of energy on a global scale [4]. As digitalization and intelligent manufacturing continue to develop, industrialization is moving towards its fourth generation, known as Industry 4.0. The goal of Industry 4.0 is to attain greater levels of efficiency and productivity while reducing costs and using fewer resources [5]. This endorses the transition towards environmentally sustainable and energy-efficient production methods that are conducive to maintaining a stable climate. At the core of Industry 4.0's sustainability support is the exploitation of existing optimization potentials. This is to be achieved through the collection of previous separate data streams [6]. As part of these efforts, new ways of manufacturing are being explored. In particular in the field of robotics, a paradigm shift is happening, wherein instead of conceiving robots as a replacement for human labor, they are instead envisioned as a support to a human worker. Furthermore, autonomous transport systems play a major role and may be combined with traditional robots to enable both the manipulation and transport of products [7]. Moreover, infrastructural technologies such as the IoT support the connection of manufacturing assets with each other to allow interaction and cooperation. For the industrial field, the term Industrial Internet of Things (IIoT) is often used. Production machines that have sensors and actuators can be connected to the internet through the IIoT, allowing them to collect, analyze, and transmit data instantly to either other machines or humans [5]. To enable the communication within this network, important standard have been introduced. OPC UA is a widely accepted standard for communication between machines. It provides access to data from real-world objects through a server. Clients may connect to the server to subscribe to specific information. The OPC UA standard is also further developed by the OPC Foundation to provide more Industry 4.0 related features [8]. Besides OPC UA other communication protocols like HTTP, WebSockets or MQTT may also be used in IIoT applications [9]. For the transmission of real time data, services such as Kafka are very beneficial and can be used as distributed streaming platforms to store and process data streams [10]. To gather the data required for the successful application of Industry 4.0 smart sensors are used. A smart sensor refers to a sensor that possesses communication capability and provides information to a monitoring system to increase operational efficiency. Applications of smart sensors may include, tracking of processes, energy management and machine health tracking [11].

However, some studies demonstrate that, despite of the many benefits of Industry 4.0 technologies, these can have a harmful impact on the environment [12]. The use of rapidly-updated electrical and electronic equipment and devices in IIoT leads to a significant generation of e-waste and consumes an increasing amount of resources, which hastens the depletion of natural reserves. The expanding demand for energy to support digitalization and data centers produces considerable emissions [5]. Thus, it is crucial to consider both the positive and negative effects of digitalization on environmental sustainability in manufacturing. Therefore, analyzing and evaluating the impact of digital production is of paramount importance.

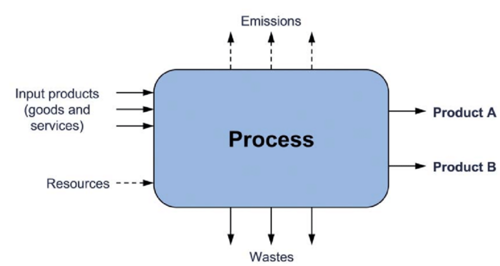
B. Sustainability Assessment in Aircraft Production

Due to increasing societal pressure as well as industry-wide goals to reduce emissions, it is of great importance for manufacturers as well as airlines to be able to quickly and transparently calculate the environmental impacts of their aircraft during its different life-cycle phases. Consequently, there is a growing demand for a systematic and transparent approach to evaluate the environmental impacts of products, processes, and services [13]. To ensure consistency among different approaches to assess the environmental impact of products and services, including emissions and resource consumption throughout their entire life cycle, the Life Cycle Assessment (LCA) standard has been developed and outlined in ISO 14040 and ISO 14044 among others [14].

The standard includes four main stages as depicted in Figure 1a: goal and scope definition, inventory analysis, impact assessment, and interpretation. In the first stage, the study's objective and scope are defined, including the product system under investigation and the system boundaries. Additionally, the functional unit, which describes the product's function being assessed, is established. The second stage involves collecting data necessary for preparing a life-cycle inventory using the defined system boundaries. Therefore a unit process is used to create an input-output model, where inputs describe resource withdrawals, and outputs are emissions into the environment as shown in Figure 1b . In the third stage, the impact assessment is performed by applying different impact categories. Finally, in the fourth stage, the findings are summarized, and conclusions and recommendations are made, depending on the study's objective [14][15].



(a) LCA framework according to ISO14040 and ISO14044 [15][16]



(b) Unit process within life-cycle inventory analysis [17]

Fig. 1 LCA framework and unit process

The majority of sustainability assessment efforts in the manufacturing sector have concentrated on the product level, with less attention given to the process level, despite the fact that manufacturing processes have a substantial impact on energy resource consumption and the generation of hazardous emissions. Furthermore, sustainability considerations are frequently not integrated into a company's strategies, resulting in challenges in accurately measuring sustainable manufacturing and production using appropriate Key Performance Indicators (KPIs) [18]. Thus, it is crucial to identify quantifiable sustainability indicators that impact sustainable performance considering its three essential dimensions: environmental, social and economic. Generally, these are measurable criteria that can identify all aspects and dimensions of sustainability and can be utilized to assess the performance of various manufacturing processes [19]. These indicators can be categorized into quantitative indicators that can be measured and calculated using standard techniques and formulas, such as energy consumption and CO2 emissions, and qualitative indicators that need to be assessed using surveys or expert judgment, such as product satisfaction and health risks. Indicators are assigned weights based on experience or specific methods and then quantified using methods such as total amount (absolute), relative amount (per unit of product), or both. The quantification process involves identifying suitable measurement techniques and gathering the required measurement data [20]. On this basis, sensitivity analyses can be implemented to ensure reliability of obtained results and provide a basis to make value-based trade-off decisions.

C. Leveraging MBSE in a Sustainability Context

Sustainable manufacturing is a multifaceted and challenging issue that involves various stakeholders and interconnected research areas. Given its complex nature, Model-Based Systems Engineering (MBSE) can offer a suitable framework for decomposing and analyzing sub-system interactions, thereby enabling a systemic and holistic approach to fulfill the numerous requirements. The Systems Engineering community provides a wealth of tools, methods, and guidelines that can support the specification, analysis, and development of complex systems, while ensuring the consistency and traceability of modeling artifacts within the MBSE context [21][22]. The System Modelling Language (SysML) [23] is the main modelling language incorporating MBSE methods. By identifying stakeholder needs and contributions, integrating system constraints, and defining various system architectures, these methods can facilitate the validation and verification process [24]. Despite its potential advantages, MBSE remains underutilized in improving the sustainability of manufacturing systems. However, the integration of specific representations, previously identified to address local interactions between elements of MBSE models, can be used to address this issue and enhance the development of sustainable manufacturing practices [25].

The V-Model is a widely accepted guideline in systems engineering for the development of complex systems [26]. It outlines a systematic approach to product development that includes system analysis, development, and integration. In [27], Steimer et al. proposed modifications to the V-Model that enable a model-based design process for early-stage manufacturing system planning. The modified V-Model comprises two parts: cross-disciplinary early system design and discipline-specific design, which allow for iterations within and between the two parts. By representing four levels - context, manufacturing technique, structure and control, and technical solution - the proposed approach supports Manufacturing System Planning (MSP). The use of MBSE enables data exchange between design disciplines and facilitates the development of manufacturing systems from various perspectives in the early stages.

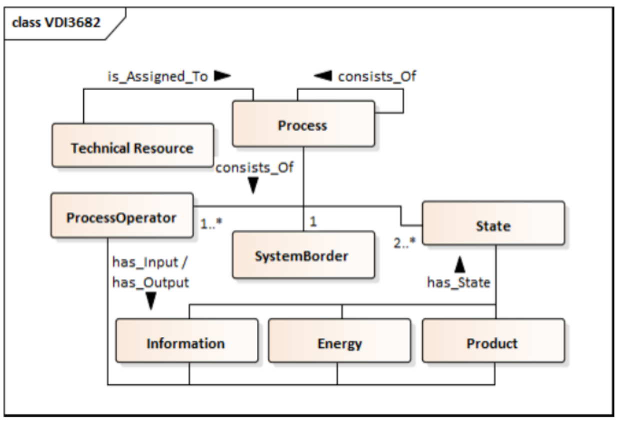
Model-Based Systems Engineering (MBSE) solutions can be highly beneficial to meet current sustainability requirements. It supports the identification of relevant metrics, which could include carbon emissions, material sourcing, or other traceable data points from the initial concept design to the end-of-life stage of the product. However, given the many interconnected pieces between engineering domains (e.g., mechanical, electrical, electronic, and software) and the extensive supplier networks many businesses employ, these decisions must be validated to ensure they are correct. While physical testing or simulation environments may be sufficient for simple systems, sustainability is too complex to represent accurately using these methods. Instead, a combination of physical data and comprehensive simulations in a digital twin is necessary to create models associated with MBSE. These models act as a substitute for the actual product to enable faster iteration and validation of changes to the system, without compromising the requirements. Therefore, the MBSE methodology and digital twin technology are highly intertwined and their combined use is valuable for developing increasingly complex products and enterprise networks [28].

Moreover, it is crucial to consider the potential unintended sustainability consequences that may arise at various levels. Although efforts to enhance sustainability may yield positive results at the product level, they may also result in negative outcomes at a higher level. To address this issue, SysML can be employed to develop multi-scale models that aid in the design and analysis of large-scale systems. The elements and concepts of this modeling language are useful in mitigating LCA boundary selection issues. By incorporating multiple perspectives into the model that formally define the modeling domain, objectives, assumptions, and constraints, it is possible to reduce uncertainties that arise when defining the boundaries and scope of the analysis [29].

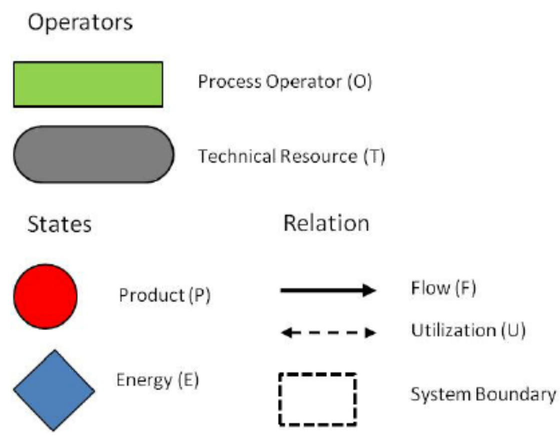
D. Ontology building of production context

While using MBSE to support the productions assessment, sustainability aspects should be incorporated in all modeling processes, not just at the assessment level. The first step to achieving this is creating an appropriate ontology that can model, assess, and trace sustainability concepts and data. This is especially important in the context of Industry 4.0, where highly flexible networks of Cyber Physical Systems are integrated into the manufacturing domain to provide real-time information for process improvement and automation, as well as to support shop floor management with live key performance indicators, energy consumption management, and manufacturing process planning [30–32]. To achieve semantic homogeneity and ensure interoperability and consistency within the production domain, the use of an adequate ontology is essential. Ontologies have been shown to be effective in serving both conceptual and technological purposes. They can provide a lightweight representation of domain terms and relations that can be used to engineer a CPS and can be implemented in a machine-interpretable format with tools for querying, rule-based inference, and efficient large-scale data storage [33].

When creating ontologies, it is critical to refer to existing standards and guidelines that support the depiction of essential concepts and relationships in a particular domain. The ontology established in this work is partially conform to the Formalized Process Description (FPD) for Product-Process-Resource (PPR) as specified in the VDI guideline 3682 [34]. The latter provides visual representations to enable a comprehensive model of the functional view of the Cyber-Physical Production System (CPPS) in the initial planning phase [35]. For this purpose, the guideline defines a procedural model that aims to provide process-specific data and information for both individual trades and the life cycle, in addition to general process understanding. For example, a light weight ontology representation of concepts and relations defined in the VDI 3682 guideline is shown in Figure 2a. This knowledge representation can be used to describe how products, processes, and resources interact to achieve the specified production functions and aims. In order to achieve process understanding, a small number of symbols and rules for modeling are defined as shown in Fig. 2b [36].



(a) Light weight ontology according to vdi 3682 [30]



(b) Graphical symbol in vdi 3682 [36]

Fig. 2 Ontology representation and symbols according to vdi 3682

Although much research has been conducted on this and other standards (see survey in [37]) that provide detailed PPR specifications for products, these tend to focus solely on the product being produced. As a result, there is a lack of connection between the detailed PPR specifications and analysis models supporting all lifecycle phases of the production system itself. To address this issue, stakeholders who are interested in both the product system and the production system need to increase communication and collaboration. Furthermore, many existing standards are domain-specific, primarily targeting smart manufacturing. However, modern enterprises often integrate functionally heterogeneous systems that are geographically distributed, making it necessary to have a more comprehensive specification. Therefore, the National Institute of Standards and Technology (NIST) has provided a specification for Discrete Event Logistics Systems (DELS) that can serve as a foundation for integrating or coordinating decision-making and execution across diverse systems. This specification can also help to integrate the Industry 4.0 research and development efforts that are spread out across the supply chain, transportation, production, and warehousing domains [38].

III. Methodology for Sustainability Modeling and Analysis of Aircraft Production

In this work, a methodology has been developed that leverages MBSE to support the sustainability evaluation of aircraft production systems according to the LCA standard presented in Section II.B. The focus of this methodology is on conducting goal and scope definition and inventory analysis by applying MBSE concepts and using SysML language elements. The Cameo Systems Modeler tool is employed to facilitate the language for both conceptual and technological purposes. The ability to execute the SysML model within the tool environment enables interoperability with information generated from external tools and CPS-networks. The methodology also demonstrates how external tools and IIoT infrastructure can be integrated into the SysML model to assess production sustainability. Figure 3 depicts the main aspects of the presented methodology, with the SysML model at its core, incorporating an ontology conforming to VDI 3682 and following NIST standards in SysML ontology modeling. The introduction and description of the ontology is given in Section III.A.

The ontology is then used to define the goals and scope of the sustainability assessment study. Starting from a context diagram, stakeholders and their impacts on sustainability are modeled, and requirements to meet their needs as well as sustainability indicators are specified in the SysML model. In a further step, scope analysis is conducted by modeling the functional production use cases and refining the identified processes with a functional architecture that provides contextual production turnover and interconnected unit processes. Subsequently, the unit processes are allocated to the physical resources available in the production system. The identified sustainability indicators are then linked to the resource parameters to enable the validation and traceability of measured data in the model.

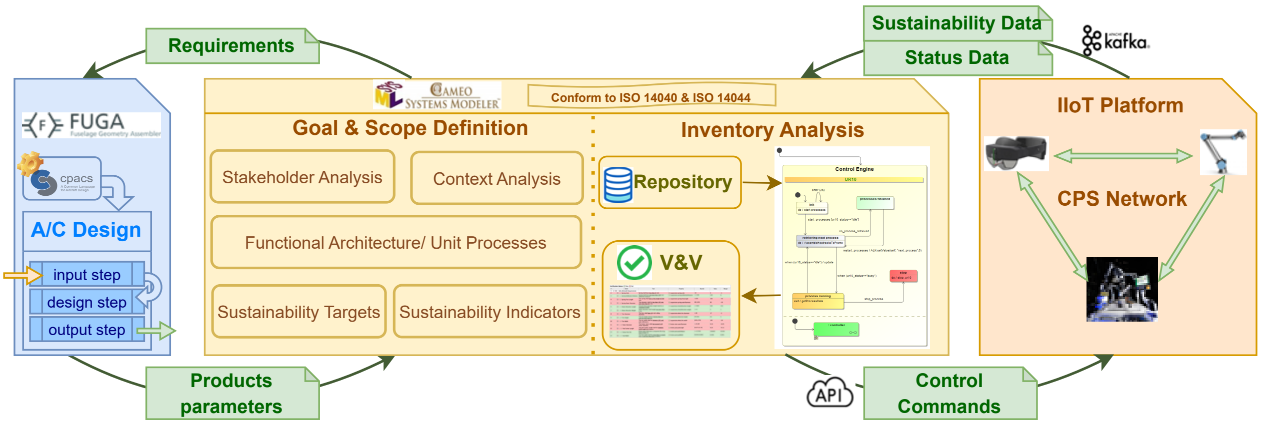


Fig. 3 Model-based methodology for sustainability analysis of aircraft production

In order to conduct inventory analysis within the SysML model, information regarding the products to be assembled or produced, as well as measured data from the resources, must be integrated into the model. Specifically, product structure and geometric information are imported from the Fuselage Geometry Assembler (FUGA), a tool developed by DLR. A detailed description of FUGA can be found in Section III.B. SysML objects and their corresponding value properties are instantiated based on the configuration generated in FUGA. The SysML model communicates with FUGA via an integrated REST API over a TCP/IP interface.

Furthermore, communication between the SysML model and the CPS in the IIoT is facilitated through a REST API and Kafka data pipeline. A detailed architecture description can be found in Section III.C. An integrated SysML state machine is employed to read process data from the model repository and send commands to the CPS via API. Meanwhile, the Kafka pipeline is utilized to read resource and sensor data for linkage to the model. The status parameters derived from these sources are also used to control the process behavior, which is integrated into the state machine.

A. Adapting Model Ontology to Sustainability Targets

As stated above, the ontology developed in this work considers the concepts defined in the VDI3682 standard. These concepts are modeled using block definition diagrams (bdd) and SysML relationships as shown in Figure 4. Using the decomposition relationship, the concept of a process consisting of *ProcessOperator*, *Product*, *Energy* and *Information* blocks can be depicted. Each of these elements is represented by a block, with specific attributes. To model the relationship between these blocks, reference properties typed by the related elements are used, e.g. to represent that a resource is assigned to a process operator. Attributes that are relevant for inventory analysis are specified as block value properties. Inputs and outputs are modeled using proxy ports that are typed by the corresponding directed flow elements. Further specifications such as the differentiation between automated and manual processes is modeled using "*generalization*" relationships.

To define an adequate vocabulary and terminology to sustainability concepts regarding stakeholders, requirements, use cases, and functional elements, a sustainability profile is defined. SysML elements can be expanded with stereotypes that include new attributes such as sustainability indicator or impact, as well as their corresponding relationships. During modeling activities, these stereotypes are then applied to the model elements and attributes can be specified with required information.

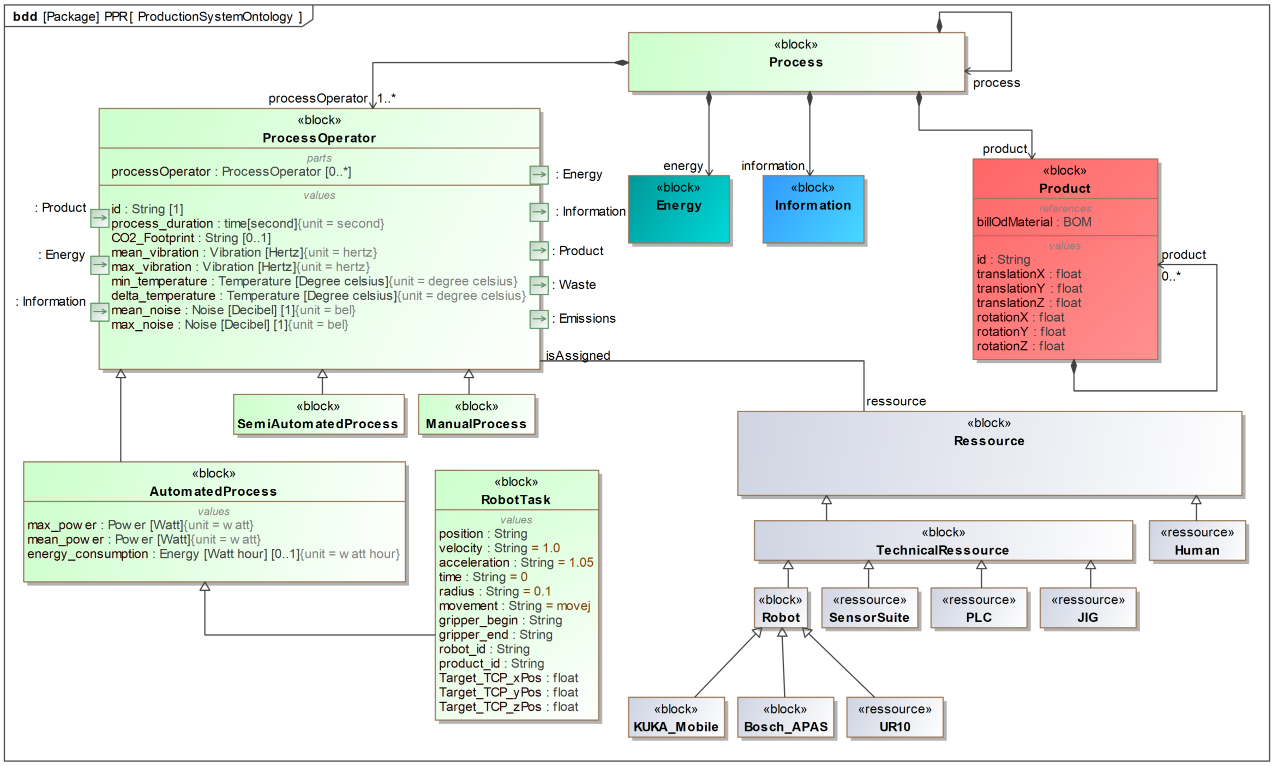


Fig. 4 Block definition diagram for ontology modeling under consideration of vdi3682

B. Integrating Aircraft Design in Production Models

It is widely believed that around 80% of the environmental impact of a product is determined during its design stage [39–41]. This is especially relevant when investigating innovative, sustainable aircraft designs. To be able to track design impacts throughout all design stages while allowing for a quick implementation of last minute changes would be an insurmountable task if done by hand. Thus, it is necessary to utilize flexible and intelligent tools when designing aircraft. To accomplish this, FUGA has been developed to solve this task utilizing a parametric, knowledge-based methodology. Originally, FUGA was created to allow for a consistent and parametric fuselage and cabin design. It has since then been extended to parametrically compute production parameters, such as mounting points. This way FUGA is incorporated into the overarching workflow, linking preliminary design and process planning A brief overview of the methodology behind FUGA is given here, a more detailed description can be found in [42].

The general FUGA workflow can be divided into three steps. For a given design problem, the data repository is first filled using the data given in the input step. In the design step, FUGA uses a Knowledge-Based Engineering (KBE) approach to generate a finished design from a consistent parametric basis, incorporating extra data (e.g. the cabin interior). The Maximal Connectivity Graph (MCG) (see Figure 5) for this problem is constructed using the rules implemented in the knowledge repository and visualises all known relationships in a given design system. In the output step, the MCG - or a subset of it (e.g for production), depending on what result is requested - is then solved, yielding the requested outputs.

The input step utilizes CPACS as a central model that contains the product data [42–44]. The CPACS data set contains a preliminary aircraft design based on Top Level Aircraft Requirements. This creates the initial boundaries for the subsequent design performed using FUGA. Essentially, FUGA is used in the next step to extend the given design. For example, the CPACS data set does not contain any information regarding the cabin interior. To allow for an individual cabin layout, some additional design parameters can be input to FUGA (e.g. for specific monument placement) [42]. This set of inputs is then used as a basis for the subsequent design step.

Within the design step, FUGA designs the remaining aircraft based on the inputs given. As outlined previously, FUGA uses a knowledge-based methodology to accomplish its design task. This KBE approach is based on descriptions given in [42, 45]. Specifically, three fundamental KBE-elements, which are the data repository,the knowledge repository and the inference engine are implemented in FUGA.

This parametric KBE approach implemented in FUGA supports efforts towards the sustainability of production systems both indirectly and directly. The indirect support is realized through the generation of output data for a given design. This output data can then be passed to a SysML tool to plan, optimize and validate the production system. The interface between FUGA and SysML also allows for a link between requirements and design rules using FUGA. This enables immediate feedback on how specific requirement values affect the final design. The direct support of sustainability requirements is planned to be realized through the incorporation of new sustainability rule sets. These new rule sets would take the influence of materials on sustainability into account. This would extend the KBE system by weighing a components mass against their respective carbon footprint.

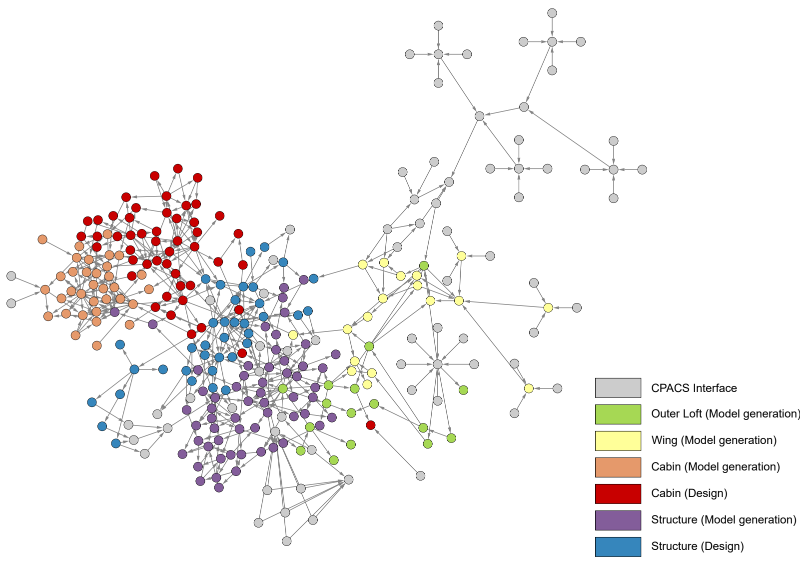


Fig. 5 Example maximal connectivity graph of the FUGA rules, grouped into their respective rule sets [42]

C. Integrating the Production Model into IIoT Platform

The architecture used in this work takes advantage of multiple communication technologies and methods. It is adapted for the available resources at the DLR pre-assembly station, which is used in this study's use case (see section IV). The architecture consists of connecting available robots (UR10 and APAS in this case) to a PLC, which possesses itself a standard OPC UA Server. External access is provided over an Ethernet connection, which in turn is connected to a router to provide wireless access over WiFi. For the transmission of real time data, the service Kafka is used as a central data pipeline. Data is written to the data pipeline by two microservices. First, the digital twin of the robot which provides live position data as well as the current status of the robot. The status of the robot may be either busy or idle depending on whether the robot is currently executing a command or not. Second, a small service which subscribes to relevant data found on the PLC and sends them to the data pipeline. Commands intended for the robot are sent through an HTTP connection to the digital twin, which then sends them to the robot itself. Furthermore, architecture has access to multiple sensors which are directly connected to the PLC. These include: power consumption, vibration, noise, temperature and atmospheric pressure. The data may be visualized through a HoloLens, which also receives the data from the central data pipeline. Human data, such as position or control signal are transmissed in real-time to the central data pipeline. From there, the SysML model can access all data and use it for data acquisition and process control. A simplified overview of the architecture can be found in Figure 6.

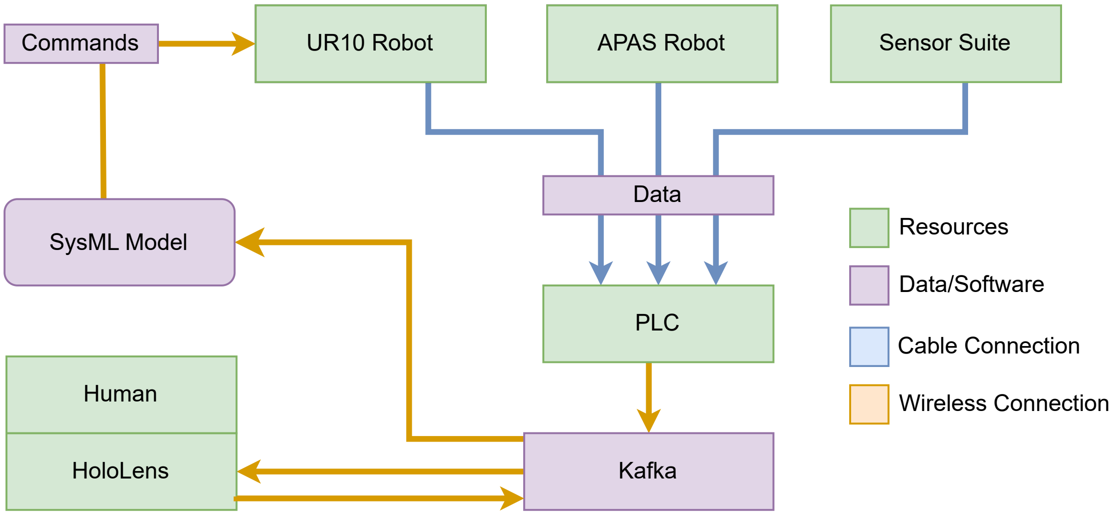


Fig. 6 Architecture Overview of IIoT platform used in the study's use case

IV. Use-case: Model-based Sustainability Analysis of Crown-Module's Pre-Assembly

This section presents a use case to provide a comprehensive illustration of the methodology introduced earlier and its practical applications. The methodology is employed to model and analyze the sustainability of the pre-assembly process of the so called crown module (see figure 7b), which is currently a focus of research in the installation of aircraft cabins for the purpose of decoupling the cabin and the airframe. The crown module comprises the aircraft's ceiling area, hat-rack, and a variety of customized components, including electrical, air conditioning, oxygen supply, and mechanical fixings. Due to the complexity and diversity of these components, the individual positioning and assembly of each component is a time-consuming process, and there are numerous interfaces between them and the primary structures, which increases the complexity further. By developing a pre-assembled module that integrates cabin components and can be installed into the aircraft in a single mounting step, the decoupling of the cabin from the airframe is enabled [46]. The demonstration of the use case and the implementation of the IIoT architecture presented in III.C are realized at the DLR pre-assembly station (see figure 7a). Available resources that are included in the use-case are the UR10 robot, HoloLens, the crown-module jig, the sensor suite and the PLC.

(a) Pre-assembly station at DLR **(b) Crown module [46]**

Fig. 7 Pre-assembly of crown-module at DLR's pre-assembly station

A. Defining the Goal and Scope of the Sustainability Study

According to the LCA ISO standard, the goal and scope of the study must be defined first. The LCA goals are modeled using specific requirement elements, that can be linked to related stakeholders and traced in further analysis stages. The goals defined in this study can be summarized as follows:

- Understand the sustainability impacts of a pre-assembly station in the production context.
- Model a functional architecture for the intended crown-module's pre-assembly, considering sustainability functions.
- Analyse the pre-assembly context and functional behavior to identify relevant sustainability aspects.
- Link the analysis artifacts with indicators to trace production data to stakeholder needs.
- Enable real-time communication between the functional model and production operation for live tracking, monitoring, analysis and validation of sustainability requirements.

The context analysis starts by treating the pre-assembly process as a black box, with the objective of identifying all elements that are associated with it. These elements comprise of stakeholders, environmental effects, and external or boundary systems. They are modeled using stereotyped actor elements that are linked to the process block, as illustrated in Figure 8. The use of stereotyping allows for the specification of additional attributes that are pertinent for sustainability analysis. Aspects such as sustainability type, impact type, impact description, and indicators can be defined for each of the contextual elements. An extract of specifications for these elements is depicted in Figure 9.

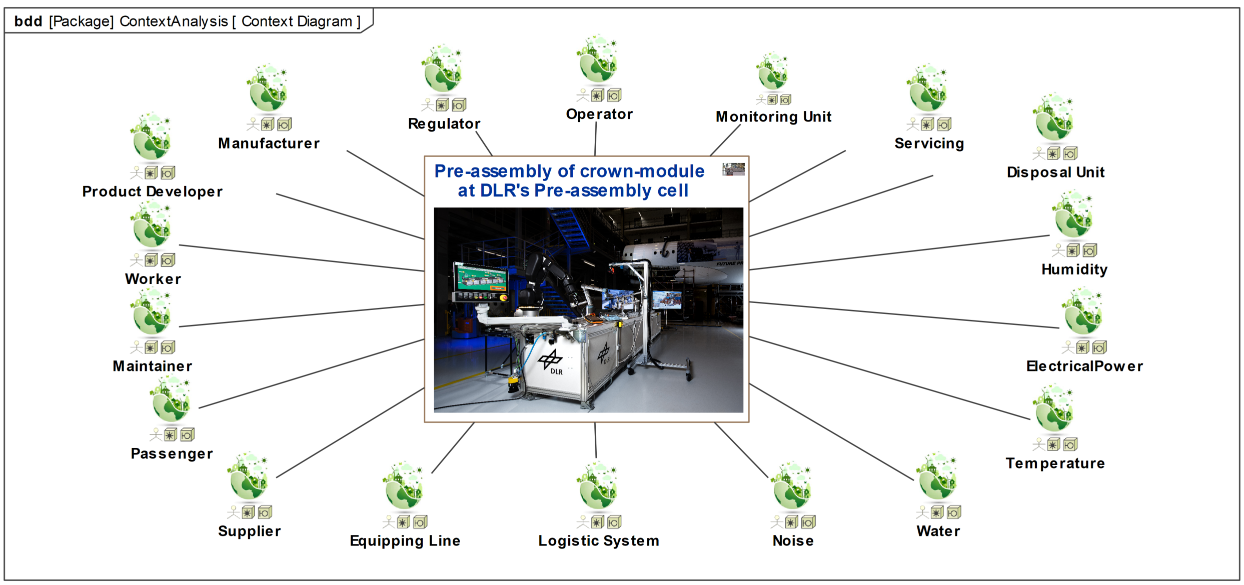


Fig. 8 Context diagram for crown module pre-assembly

Subsequently, the scope analysis is conducted by modeling the functional use cases while taking sustainability aspects into consideration, as depicted in Figure 10. In this step, contextual elements that have a functional interaction with the process are selected. The main use-cases, represented in grey, denote the primary functionalities that the process implements, in accordance with the design and assembly requirements. The use cases are further refined using sub-use cases, which are linked via the "*include*" relationship. Furthermore, sustainability use-cases, shown in green, are modeled to extend the main use-cases with functionalities that are necessary to achieve sustainability targets. This approach ensures that sustainability aspects are integrated into the functional architecture of the assembly processes as part of the production planning.

#	Name	Sustainability Type	Impact Type	Impact	Indicator
1	ElectricalPower	Social Environmental Economic	impacting&impactedBy	Carbon Footprint depending on energy sources Energy efficiency through ressource damage due to high or low voltages Safety and Health conditions of worker at pre-assembly station	CO2 Footprint Electrical energy consumption
2	Temperature	Economic Social Environmental	impacting&impactedBy	Safety and health conditions of worker at Pre-Assembly Station Product quality through materials degradation Energy consumption through needed cooling in high tempreratures	Ambient temperature Electrical energy consumption
3	Equipping Line	Economic Environmental	isImpactedBy	Supply chain sustainability and raw material sources Waste reduction when products are produced with low-quality materials can lead to defects, rework, and increased waste during the final assembly process	Material flow
4	Logistic System	Economic Environmental	isImpacting	Transportation emissions Packaging waste Energy consumption Supply chain sustainability	CO2 Footprint Electrical energy consumption Material flow
5	Regulator	Economic Environmental	isImpacting	Environmental regulations to limit pollution, greenhouse gas emissions, air and water pollution and hazardous waste Energy efficiency standards that require production to use energy efficient machinery Waste management regulations that require production station to reduce, recycle, or properly dispose of their waste Sustainable business practices to encourage sustainable practices by providing incentives for production station that adopt sustainable practices e.g. by offering tax credits for using renewable energy sources, implementing energy-efficient practices, and reducing waste	Electrical energy consumption Water waste Material waste CO2 Footprint
6	Worker	Environmental Social	impacting&impactedBy	Environmental conditions Health and safety Ergonomy and working effort	Acoustic noise Ambient temperature Ambient humidity Mechanical vibration

Fig. 9 Specification of contextual elements and their sustainability attributes

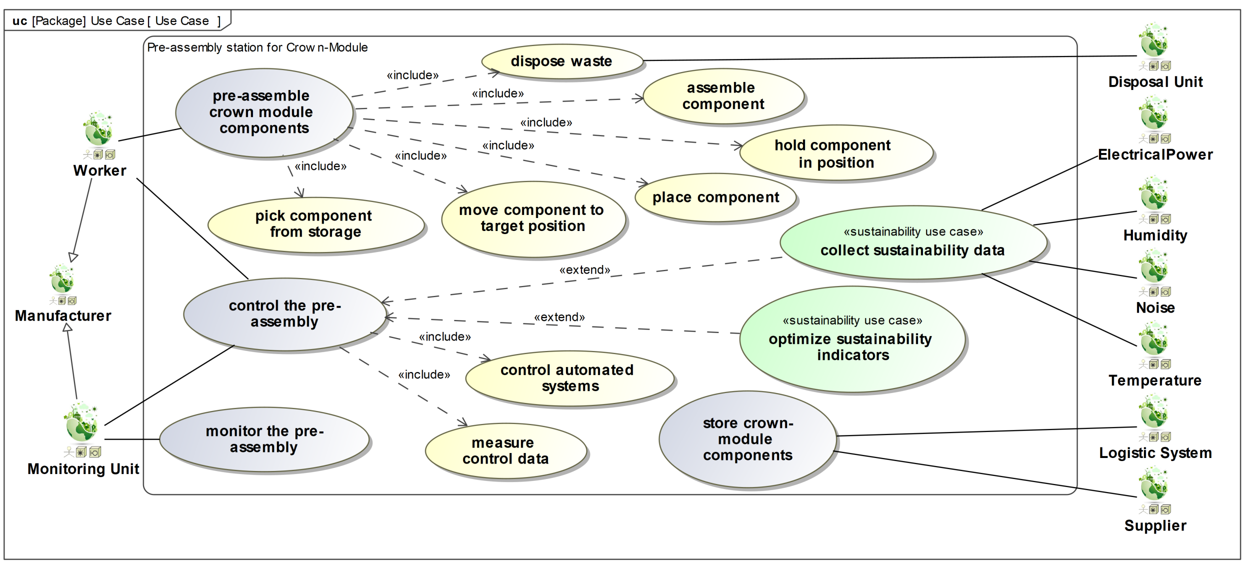


Fig. 10 Use-case diagram for functional analysis of sustainable pre-assembly process

Moreover, it is crucial to convert the identified use cases into unit processes in accordance with ISO 14044. To accomplish this, unit processes typed by the ontological element *ProcessOperator* (as described in Section III.A) are derived for each use case. These unit processes are interlinked with each other, as well as with contextual elements, using an internal block diagram, as shown in Figure 11. For interconnection, previously specified ports typed by the corresponding flow elements are utilized. Thus, a functional architecture is presented, which illustrates the flow of energy, information, products, emissions, and waste within the different functions of the analyzed process.

Concerning the process context, crown-module product information is imported using the interface to FUGA. This information primarily include the structure of the products used in the crown module and their assembly locations. For each unit process, information related to the components that are assembled in this step is specified as input, while sub-assemblies that are generated are defined as output.

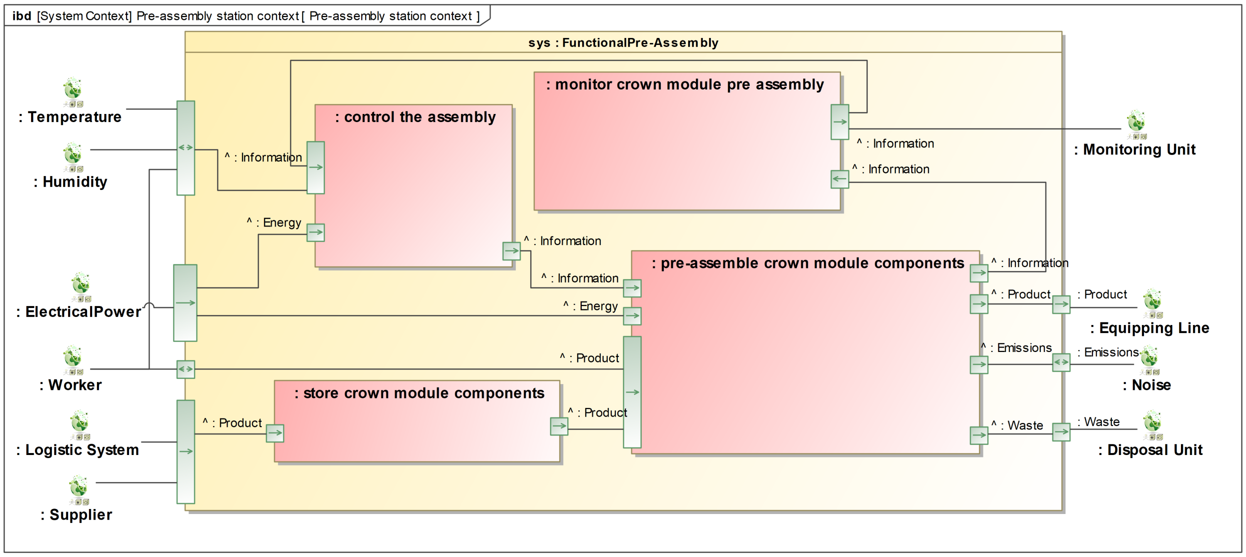


Fig. 11 Functional architecture for unit processes in the pre-assembly station context

B. Model-based Inventory Analysis

This study follows the procedure outlined in ISO 14044 for Life Cycle Inventory Analysis (LCI), which begins with preparing for data collection. The first step is to identify sustainability targets for each contextual element that constrain the pre-assembly processes. Each target is specified with measures, measuring tools, and units and linked to the value properties of the *ProcessOperator* for later automated validation.

Subsequently, data collection is performed by executing the model with specified processes while communicating with the actual hardware according to the architecture presented earlier (see Figure 6). To facilitate this, a state machine and corresponding activities for process control and data collection are implemented (see Figure 12). The state machine retrieves the processes that must be executed and sends commands to the UR10 robot. A parallel state that runs continuously communicates with the Kafka pipeline to obtain PLC and HoloLens data from their digital twin. These data pertain the status of process resources which are in this case the UR10 robot and human worker. For example, when the status of the robot switches from busy to idle, the state machine automatically triggers the next process to be executed.

The next step in the inventory analysis is to relate data to the unit process and functional units. Collected data are imported during execution and assigned to the corresponding unit process by saving values in the model's corresponding instance. To do so, sustainability data that are collected from the sensor suite are imported into the model after each process is finished (see activity "getProcessData" in Figure 12) and used to trace and validate sustainability targets. Once all the unit processes are executed, data aggregation is performed by scaling up the results of unit processes to the functional unit level. The ramp-up model functionality enables the automatic merging of unit processes results in the functional unit context. The data aggregation provides indicator values for the entire process of pre-assembling the crown module and enables automated validation for functional units through the link to specified sustainability targets. Figure 13 shows the validation of targets for the functional unit. The model view displays the value of the measured property, as well as the target's bounds and margin. The results that correspond to the target boundaries are passed and automatically shown in green, whereas not achieved targets are shown in red.

The Inventory analysis is delivering relevant results to conduct an impact assessment and optimization. Both are not part of this study's scope and will not be described in this work.

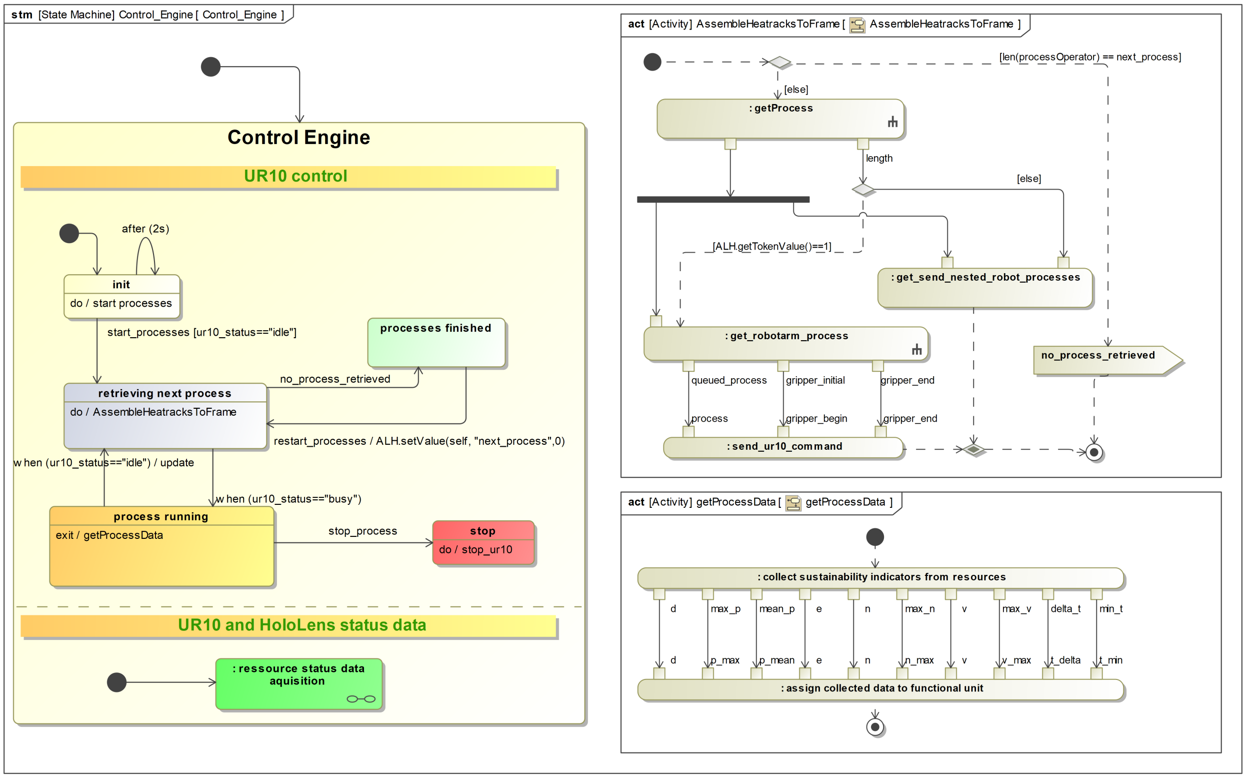


Fig. 12   State machine and activities to retrieve processes, control robots and collect resource data

#	Name	Text	Property	Bounds	Margin	Value
1	1 Energy consumption	The electrical energy consumed during the assembly process shall not exceed 100 Wh	energy_consumption : Energy [Watt hour]	<=100	-56.78	156.78
2	2 Power limit	The UR10 shall use a power up to 100 Watt	max_power : Power [Watt]	<=100	-30	130
3	3 Environmental temperature	The ambient temperature at the shop floor shall be between 18 and 26	min_temperature : Temperature [Degree celsius]	[18;26]	2.89	23.11
4	4 Environmental noise	The acoustic noise at the shop floor shall be between 0 db and 80db	mean_noise : Noise [Decibel]	[0;80]	8	8
5	5 Vibration Interference	The mechanical vibration on the JIG at the working station shall be between 0 and 5 Hz	mean_vibration : Vibration [Hertz]	[0;5]	0.24	0.24
6	6 Robot performance	The robot shall operate on a mean power equal*or lower than 80 Watt	mean_power : Power [Watt]	<80	-11	91
7	7 Process duration	The process duration shall not exceed 20 seconds	process_duration : time[second]	<=20	-139	159
8	8 Vibration limit	The maximal vibration at the shop floor shall not exceed 10	max_vibration : Vibration [Hertz]	<=10	8.5	1.5
9	9 Noise limit	The maximal noise at the shop floor shall not exceed 100 db	max_noise : Noise [Decibel]	<=100	86	14

Fig. 13   Results of automated validation of sustainability targets with view on values, margin and bounds

C. Traceability of Sustainable Indicators in Production Model

Ontological modeling with SysML has a notable advantage in the traceability of stereotyped elements within the model. The use of SysML elements or newly created stereotypes enables the highlighting of relationships among selected elements based on their type and the type of their relationship. The generation of a traceability map can be automated with the tool *Cameo Systems Modeler* by specifying these elements in the traceability map configuration. Figure 14 illustrates a traceability map for functional analysis and physical allocation of resources.

Starting with the pre-assembly of the crown-module at DLR's pre-assembly cell, the associated context elements are depicted in the map, along with those that have a direct interaction with the intended use cases. The *refine* relationship highlights the implemented unit processes for refining the functional use cases. Additionally, the allocation of these functional unit processes to selected physical resources is demonstrated using the *allocate* relationship. By following the same methodology, specific relationships and elements can be highlighted in multiple views within the model.

Traceability is not only crucial for comprehending the intricate relationships developed during analysis and modeling activities but also serves as an essential tool for validating the completeness of the production architecture in case of modification at any abstraction level. Particularly in the context of sustainability assessment where regulations and constraints evolve rapidly, the analyses and assessment model must remain consistent and supports in identifying any missing elements in the architecture.

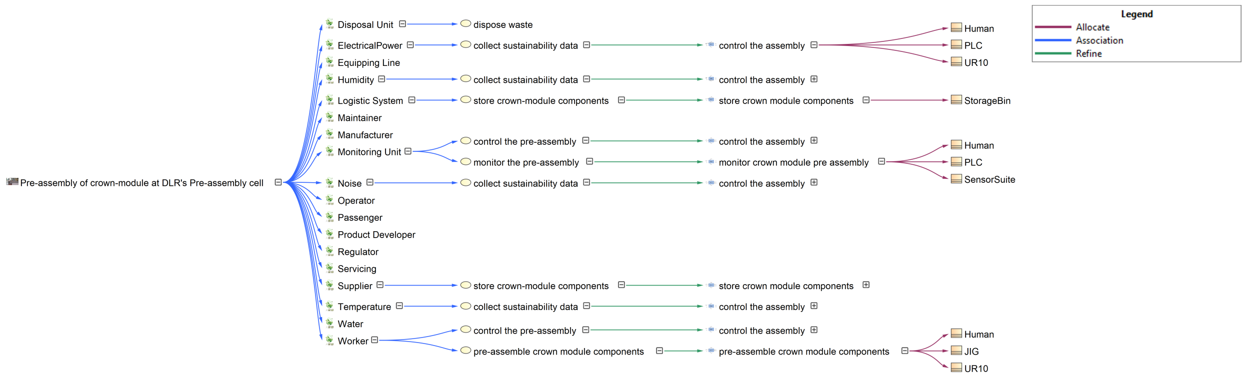


Fig. 14 Traceability map showing relationship between context elements, use cases, unit processes and resources

V. Conclusion and Outlook

In conclusion, this work presents a model-based approach for analyzing and assessing production systems in the aircraft industry from a sustainability perspective. The approach is based on the use of MBSE and SysML concepts and elements, and integrates ontological guidelines defined in VDI 3682 and NIST standards to provide semantic and relational modeling and analysis of the production system. Starting from the analysis of the production system's scope, processes were derived as functional units, taking into account the contextual environment. By integrating a knowledge-based product design, assembly processes for the products were developed based on selected aircraft and cabin configuration. The execution of the model while interacting with CPS network enabled the collection and aggregation of sustainability data. A validation of sustainability targets could be realized automatically in the model, providing the possibility to optimize toward more sustainable assembly processes. The integration of IoT technologies within the SysML model enabled tracing sustainability results to key indicators and targets. This helps reduce complexity and identify synergies for sustainable behavior of flexible production systems. By analyzing the production system's scope elements and tracing their impacts on sustainability indicators, the goals defined for this study were achieved.

It is important to note that this work only considers the scope and inventory analysis steps of the LCA standard. Future research should extend the analysis to include impact assessment and interpretation. Additionally, integrating the production model developed in this work within LCA models could provide a holistic view of sustainability assessment for aviation products. Further work should also include trade-off analyses and optimizations comparing different products and processes, to fully realize the benefits of the approach and enable early assessment and sustainable development within the aviation industry.

Overall, the approach presented in this work provides a foundation for the assessment and optimization of aircraft production systems based on sustainability indicators, contributing to DLR's efforts to promote digital and sustainable aviation.

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