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A Preliminary Ontology-Based Engineering Application to Industrial System Reconfiguration in Conceptual Phase

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Abstract

Unforeseen events like COVID-19 pandemic force immediate mayor changes to the aerospace industrial systems, putting them out of the resilient production scenarios to which they were originally designed for. In that moment of the industrial system lifecycle, a new design process is launched to redesign or reconfigure it in order to fulfill the new set of requirements.

Ontology-based Engineering techniques emerge as a new generation from earlier knowledge-based approaches to support the industrial system design. Together with interoperable digital design tools, they provide means to capture knowledge and automatically generate complex models, simulations, and trade-off analyses to decide on best performant and flexible options. This work shows a further application of the Industrial System Design ontology by reusing the captured knowledge, applied on previous work for a new industrial system design case, to the reconfiguration of the same system in production mode when receiving a mayor requirement change. This is illustrated with a case study where the industrial system undergoes similar unforeseen crisis events like the ones lived in the aerospace manufacturing industry during COVID-19 pandemic.

Keywords

Reconfigurable Manufacturing Systems, Models for Manufacturing, Ontology-based Engineering.

1. Introduction

The pandemic times has made visible the stress the industrial systems can suffer during an unforeseen crisis event, and the resilience levels they have before leading to a redesign or reconfiguration phase [1]. This health crisis decreased or even stopped the aerospace operations in many areas of the world at different moments in time as the pandemic propagated worldwide. The aerospace manufacturers needed to aid their customers to overcome such uncertain times by delaying aircrafts deliveries, and therefore adjusting their production rates drastically, while securing their supply chain resilience. In addition to that, several health & safety measures needed to be adopted in the production plants, respecting restrictions and rules per country to be able to maintain operations.

During the aerospace industrial system lifecycle several changes can arrive due to crisis of this type, but also due to fluctuation in markets, legislations, new products introduction, among others, which push the system out of their design limits and force a redesign or reconfiguration process. This can be at different levels of the system like at global industrial system level, at assembly line or even machine level. Thanks to a collaborative engineering process between the product and the industrial system,

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flexibility points can be defined by design in their industrial resources, giving the possibility to reconfigure and maintain an optimal system during its complete lifecycle.

An Industrial System lifecycle is composed by several loops of development, resilient production and dismantling phases. The development phase is carried out following an Industrial System Design Process (ISDP), which can be launched by three different triggers: (1) a new product design, (2) a change of industrial requirements, and (3) a major product change. The first and third trigger will launch an ISDP collaboratively with a Product Design Process (PDP).

At every ISDP, new design of resources will be combined with reused resources as part of the development phase, to complete an industrial system design (ISD). The reused resources can be for example raw materials, hangars, equipment or human resources among many others. Once the development phase is finished, a resilient production phase starts, where the industrial system will produce at the required performance with a certain resilience level. Later in time, a new ISDP can be triggered for the same industrial system, obtaining a new ISD which will go into a resilient production phase, until the end of life of that system with a final dismantling phase.

Ontology-based Engineering (OBE) techniques together with interoperable digital design tools emerge to improve the collaborative engineering process, providing means to design the best performant products and flexible industrial systems. Nevertheless, domain modelling complexity and limitations of ontology based applications to support aircraft products industrialization prevent from a wider implementation of current tools and techniques [2, 3]. To tackle these problems, Models for Manufacturing (MfM) methodology was coined to support OBE development in the manufacturing domain [4] overcoming previous KBE systems limitations, and a framework was set defining the open points on resource modelling in the ISD at concept phase [5, 6].

A preliminary Industrial System Design (ISD) ontology was developed using MfM methodology to support the ISDP at concept phase in [7], illustrating its application during the first type of ISDP trigger "(1) a new product design" being the concept aircraft product named DA08, a dummy used by the authors for several research [2], and finding an optimal global industrial system design that produced this aircraft in the shortest time and lowest costs. This paper address the second ISDP trigger "(2) a change of industrial requirements", in which a reconfiguration of the same industrial system of DA08 aircraft is needed due to industrial requirement changes similar to the ones caused by the COVID-19 pandemic. The reconfiguration is made by applying the same ISD ontology, demonstrating its applicability and reusability at both ISDP triggers.

The paper is structured as follows. Section 2 reviews and updates the ISD ontology models generated using MfM methodology to support the industrial system design process at concept phase. Section 3 summarizes the previous industrial system design made for DA08 product using this ontology. Section 4 illustrates a new application of this ontology to the reconfiguration of DA08 industrial system triggered by a scenario close to the one lived during the pandemic crisis. Section 5 closes the paper with the conclusion of this work and future research points to undertake.

2. ISD Ontology

The Industrial System Design (ISD) ontology is reviewed and refined in this section, considering the progress of the MfM methodology and supporting metamodels. Models for Manufacturing (MfM) is a novel OBE methodology where computer aided graphical modeling tools are used to define and specify data, functions, and behaviors of a system under study [4]. This is made through four model types that conform an Ontology Layer: scope models, behavior models, data models and semantic models. Simulation tools will instantiate the defined system behavior using the data sources defined in the semantic model to design and optimize a complex system under study. The metamodels supporting MfM methodology are presented in [8].

The ISD ontology contains at this stage the scope, behavior and data models described below.

2.1. Scope Model

A Scope model defines the scope limit where the ontology is applicable, describing the elementary functions in which the behavior of the system under study will be defined, and also all main Data model objects. In the ISD ontology, the scope is the activity "Create Conceptual Industrial System Design" of the ISDP, described in the scope models of Figure 1 and 2 done using IDEF0 modeling language which implements MfM scope metamodel.

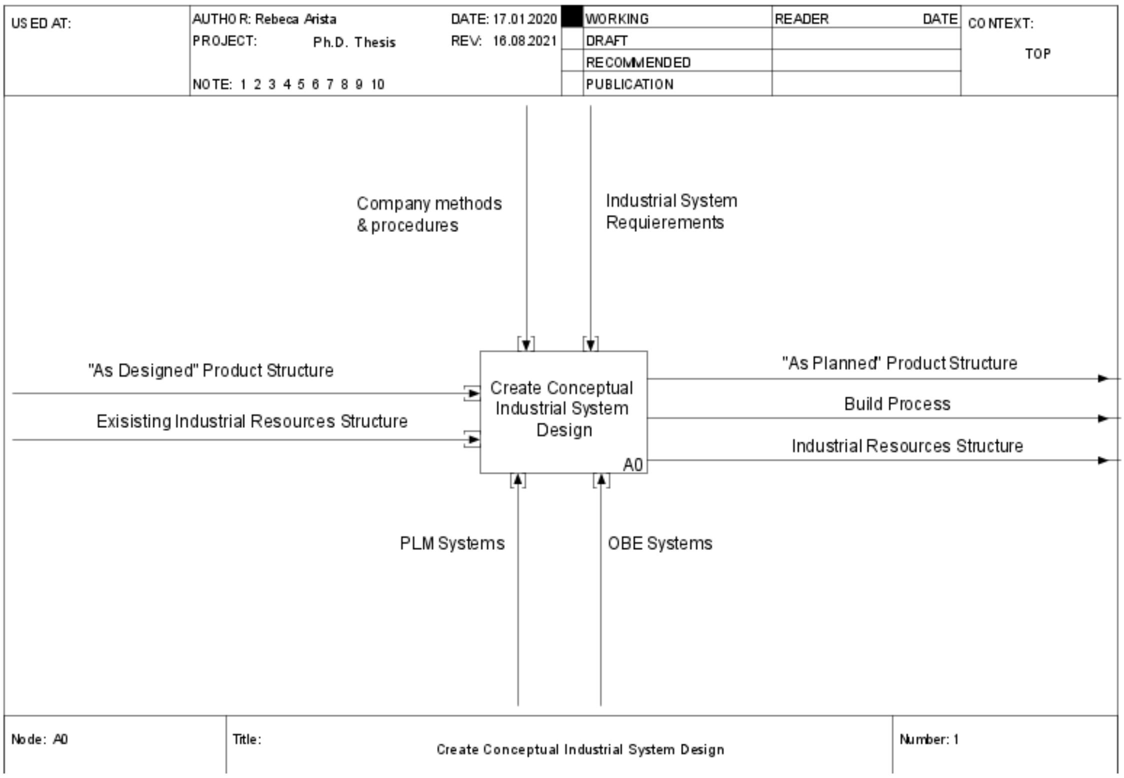

Figure 1: Top-level context diagram of function A0 *"Create Conceptual Industrial System Design".*

The Top-level context diagram in Figure 1 describe the function A0 *"Create Conceptual Industrial System Design"*, which receives as input the "As-Designed" Product Structure and the Exiting Industrial Resources Structure, providing as output the "As-Planned" Product Structure, the Build Process and the Industrial Resources Structure. The controls of this function are the Company methods & procedures and the Industrial System Requirements. The mechanisms supporting this function are the PLM systems and OBE systems.

At conceptual phase the elements considered from the product, process, and resource structure are only the elementary objects, which will latter on be designed in detail during definition phase [9]. The Product Elementary Objects (PEO) are black boxes of the product and joints between them (e.g. body, wing, joint body-wing, etc.), which create the common layer for the "As-Design" and "As-Planned" product structures at conceptual phase.

The Process Elementary Objects (PrEO) are the processes black boxes, which are defined in type by the REO capabilities (e.g. manufacture, transport, etc.) an in need by the PEO. The Resource Elementary Objects (REO) are the resource black boxes at production plant level with attributes (e.g. location) and capabilities (e.g. manufacturing capability) [10]. Detailed notions such as capability, capacity, flexibility, among others, could be described for the REO but are not part of this work.

The iDEF0 child diagram in Figure 2 shows the main sub-functions of A0. The function A1 *"Reuse & Modify Product Elementary Objects"* uses the "As-Designed" Product Structure to define the PEOs which are the first product split including interfaces. The PEOs control the function A2 *"Define, Reuse & Modify Process Elementary Objects"* which provide the PrEOs needed to manufacture, assemble or transport each PEO, considering existing technologies and regardless of the REOs capabilities. If no PrEO is possible for a given PEO, a Product Change Request is sent back to function A1 to generate a new set of PEOs.

The PrEOs control the function A3 *"Define, Reuse & Modify Resource Elementary Objects"* defining the REO from the existing industrial system capability to fulfill the PrEOs. If no REO can fulfill the PrEO, a Process Change Request is send to A2 to modify the set of PrEOs.

The three set of objects (PEOs, PrEOs and REOs) control the function A4 *"Generate Optimal Process Sequence"* where different PrEOs sequences are generated considering business rules and precedence constrains. One PrEOs sequence defines one complete "Build Process" scenario.

The optimal PrEOs sequence is selected against a defined criteria, obtaining the optimal "Build Process" to be performed using the set of REOs to fulfill the PEOs. The optimal "Build Process" creates thus the "As-Planned" product structure with the PEOs attached to the PrEO sequence, and the Industrial Resources Structure with the REO attached to the PrEO sequence. If no optimal process sequence is found that fulfills the given requirements and objectives, an "Optimization Request" can be generated to modify either the PrEO, running again A2 to A4 functions until reaching a solution.

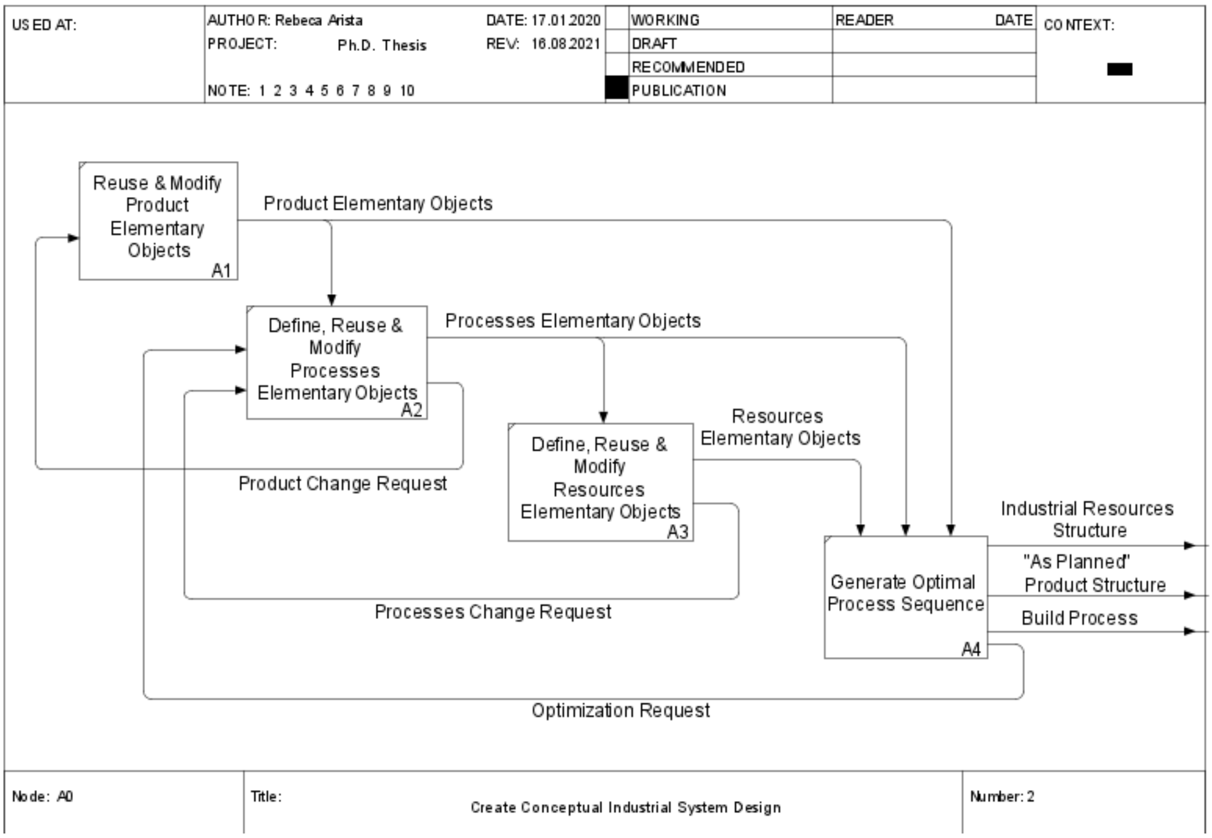

Figure 2: Child diagram of function A0 "Create Conceptual Industrial System Design".

2.2. Behavior Model

From the scope model, one behavior model is created per each sub-function in the iDEF0 child diagram (Figure 2), defining the behavior of the system under study including rules and constrains. The behavior models were done using MfM metamodel, and only the behavior model of the function A4 *"Generate & Test Optimal Process Sequence"* is shown in this paper as representative case due to the extension of this paper.

Figure 3 shows the behavior model of function A4. The first task is to validate the product split into the PEOs, considering the needs of PrEO and the available REOs capabilities. If failed it triggers a change request of two types, one to the REOs to consider or design new resources that fulfill the PEO/PrEO needs, or one to the PEOs to consider a different product design or split into PEOs.

If the first task is valid, next task is to generate the sequence between PrEOs, considering the PrEO rules and precedence constrains being: the sequence should start with the manufacturing process of a PEO, and an assembly processes of PEOs should appear after the manufacturing process of that PEOs. Next, an optimization of those sequences is made selecting the optimal solution(s) against the criteria given by the industrial requirements. The optimal process sequence(s) selected define the "Build Process" structure with the PrEOs sequence to be performed, the "As-Planned" product structure with the PEOs attached to the PrEOs sequence, and the Industrial Resource Structure with the REOs that will carry out that sequence.

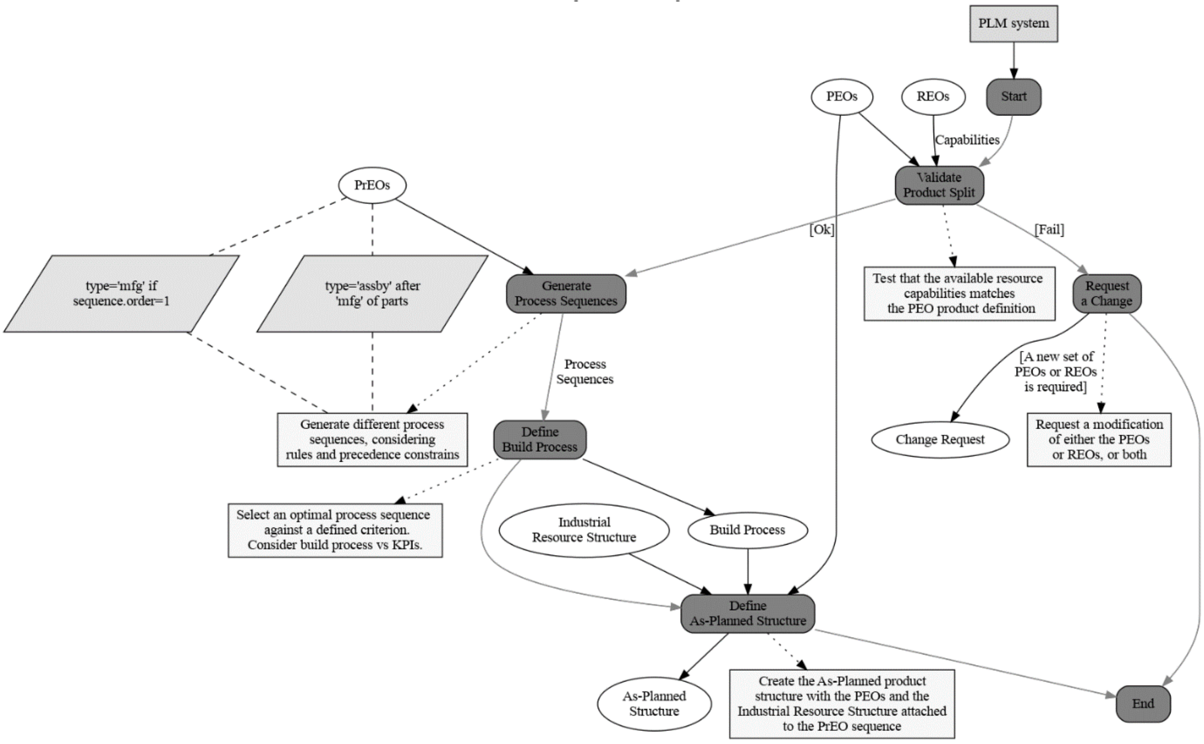

Figure 3: Behavior model of Function A4 *"Generate & Test Optimal Process Sequence"*.

2.3. Data Model

The data model defines the information handled in the selected scope, and should be instanced with real data coming from different databases. The ISD data model is shown on Figure 4, and contains all the data objects used in the previously shown scope models and behavior models.

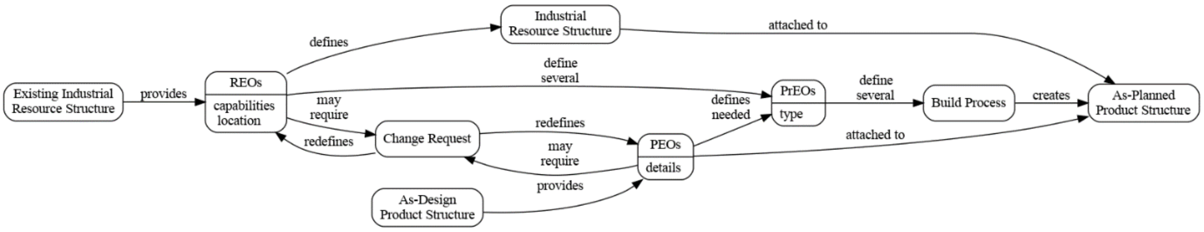

Figure 4: Data model of Create Conceptual Industrial System Design.

3. Previous work: ISD Ontology Applied in a New Industrial System Design

An instance or application of the ISD ontology was made in [7] using DA08 artifact to design a new global industrial system which would produce this artifact, illustrating the use of this ontology in a new industrial system design process at concept phase. This artifact has been used as a mean of demonstration in several research [2, 5]. The optimization problem proposed was to find an industrial system configuration and process sequence that would produce the DA08 artifact meeting the industrial requirement of production of 70 aircrafts per month, in the shorter production time and with less costs.

Function A1 of the scope model *"Reuse & Modify Product Elementary Objects"*, used the input product preliminary decomposition of the DA08 aircraft or "As-Designed" structure retrieving its product elementary objects, which are: Wing (PEO1), Fuselage (PEO3), Tail (PEO5) and the assembly drawings of the Wing-Fuselage joint (PEO2) and Fuselage-Tail joint (PEO4).

The function A2 *"Define, Reuse & Modify Process Elementary Objects",* defined one PrEO by each PEO making a first verification of the product design and breakdown (e.g. material, technology, dimension, etc.). Function A3 "Reuse & Modify Resource Elementary Objects" reused the available resources in quantity, including their capabilities and geographical location: one Manufacturing plant with manufacturing capability at Kourou, French Guiana (REO1); one Assembly plants with Assembly capability one in Jacksonville, USA (REO2); one Assembly plants in Saint-Nazaire, France (REO3); one Logistic mean with Transport capability and non-applicable location (REO4). The full set of PEOs, PrEOs and REO are represented in Figure 5.

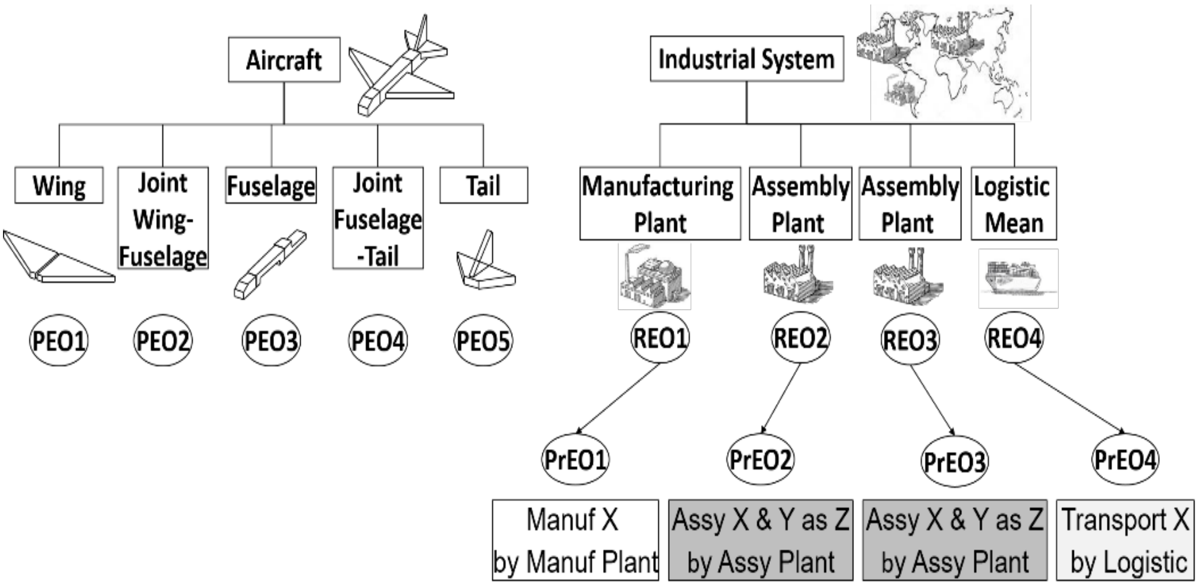

Figure 5: Product, Resource, Process Elementary Objects of DA08 and Global Industrial System.

Function A4 *"Generate Optimal Process Sequence"* built all possible sequences with the business rules and processes precedence constrains defined in the Behavior Model. An optimal process sequence was selected against the defined time and cost criteria, obtaining the final "Build Process" (illustrated in Figure 6) with the PrEOs sequence to be performed using the set of REOs, to produce the PEOs. This concept design of the DA08 Global Industrial System should go through the next design phases of the ISDP, obtaining a physical industrial system which goes into a resilient production phase of its lifecycle.

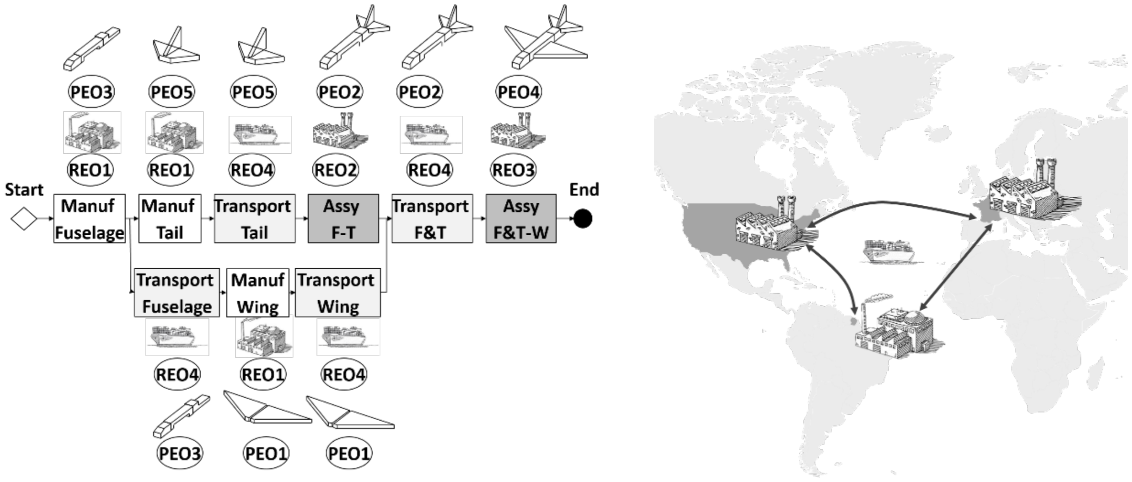

Figure 6: Optimized "Build Process" in worldwide network

The optimized “Build Process” defines as well the “As-Planned” product structure with the PEO attached to the PrEO sequence, which is the product manufacturing breakdown structure. Both “As-Design” and “As-Planned” product structures are shown in Figure 7.

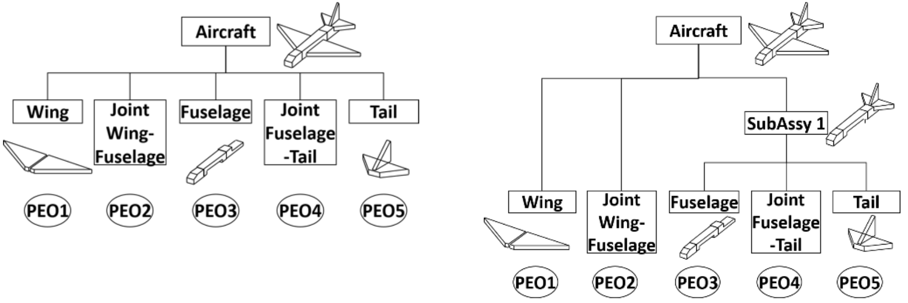

Figure 7: “As-Designed” and “As-Planned” product structure.

4. ISD Ontology Applied to an Industrial System Reconfiguration

This section illustrates a further application of ISD ontology in a reconfiguration case, illustrating a similar scenario to the one experienced during the COVID-19 pandemic crisis. During this health crisis the aerospace manufacturers needed to help their customers to overcome such uncertain times by delaying aircrafts deliveries, adjusting their production rates drastically, while securing their supply chain resilience. Due to its complexity, the aerospace industry still rely considerably in human workforce, therefore it was necessary to adopt heath & safety measures in the production plants, cope with potential outbreaks of COVID-19 cases in their workforce, respect travel and import/export rules per country, to be able to maintain production levels. Drastic changes appeared in the original industrial system requirements (e.g. production rates, costs, human factors) to which the systems were designed for, urging to study alternatives to reconfigure the global industrial systems into a new design that could support the new scenario.

The use case is defined as follows: the production rate of DA08 Global Industrial System needs to be changed from 70 aircrafts per month to 20 aircrafts per month. Lockdowns scenarios of all countries part of the DA08 aircraft footprint need to be analyzed, to obtain Build Concept options and critical scenarios. Industrial system elements of another concept aircraft called DA10 (similar to DA08 but with bigger passenger capacity and longer autonomy range) can be used if needed, as the DA10 aircraft production rate is lowered to a minimum level. Also a new warehouse could be built if necessary. The objective is to find optimal concept designs for this new rate and different outbreak scenarios, maintaining low times, costs, and CO2 emissions.

From the scope model, the function A1 reuses the DA08 aircraft “As-Designed” structure as the aircraft design is not changed: Wing (PEO1), Fuselage (PEO3), Tail (PEO5) and the assembly drawings of the joint Wing-Fuselage (PEO2) and joint Fuselage-Tail (PEO4). In function A2, the PrEO defined for each PEO are also reused until verifying in A4 that the new industrial system requirements are achieved or else receiving a change request.

Function A3 reuses the available or potentially available resources of the current industrial setup and consider as well DA10 resources availability. Dimensions, CO2 emissions and location are defined per resource, and potential new industrial resources are only studied after a change request from function A4. Function A4 defines the optimization process starting from Product, Process and Resources elementary objects. The optimization is made selecting the optimal solution(s) against the criteria given by the industrial requirements using the appropriate KPIs. The loop continues where none of these resources would fulfill the process constrains and/or industrial requirements.

Table 1 shows the complete set of PEOs, PrEOs and REOs available as start point to generate the PrEO process sequences that should fulfill the new industrial requirements. Function A4 *“Generate Optimal Process Sequence”* verify which available REOs capabilities match the PrEO and PEO requirements (e.g. material, technology, dimension, etc.). If fulfilled, an allocation is made between the REO and PrEO for different scenarios, linking indirectly the PEO and REO. If no REO fulfills the production process needs, a change request is sent for a new REO design which fulfils the needs.

Table 1
First set and correspondence between REOs, PrEOs and PEOs.

			PEO1 *dimension 7*15m*	**PEO2** *dimension PEO1+PEO3*	**PEO3** *dimension 20*8m*	**PEO2** *dimension PEO3+PEO5*	**PEO5** *dimension 7*12m*
REO1	*Capability: manufacture* *Max part dimension 12*15m* *CO2 emission: 16.5 g CO2/hour* *Location: French Guiana*	**PrEO1**	x		x		x
REO2	*Capability: assembly* *Max part dimension 10*15m* *CO2 emission: 16.5 g CO2/hour* *Location: USA*	**PrEO2**		x		x	
REO3	*Capability: assembly* *Max part dimension 12*15m* *CO2 emission: 16.5 g CO2/hour* *Location: France*	**PrEO3_1**		x		x	
	Capability: manufacture *Max part dimension 15*20m* *CO2 emission: 16.5 g CO2/hour* *Location: France*	**PrEO3_2**	x		x		x
REO4	*Capability: transport* *Max part dimension 15*20m* *CO2 emission: 127.5 kg CO2/km* *Transport mean type: maritime*	**PrEO4**	x	x	x	x	x
REO5	*Capability: transport* *Max part dimension 10*12m* *CO2 emission: 151.8 kg CO2/km* *Transport mean type: aerean*	**PrEO5**	x		x	x	x

Once having all possible assembly sequences which can fulfill the production needs considering rules and processes precedence constrains, an optimization is made to find the optimal sequence that could be available in the different scenarios, in order to produce DA08 artifact at a rate of 20 aircraft per month, maintaining costs and considering the least CO2 emission options.

As a result, the optimal process sequences are provided against the defined criteria, which are the "Build Process" options with the PrEOs sequence to be performed using the set of REOs, to the set of PEOs, as the one shown in Figure 8.

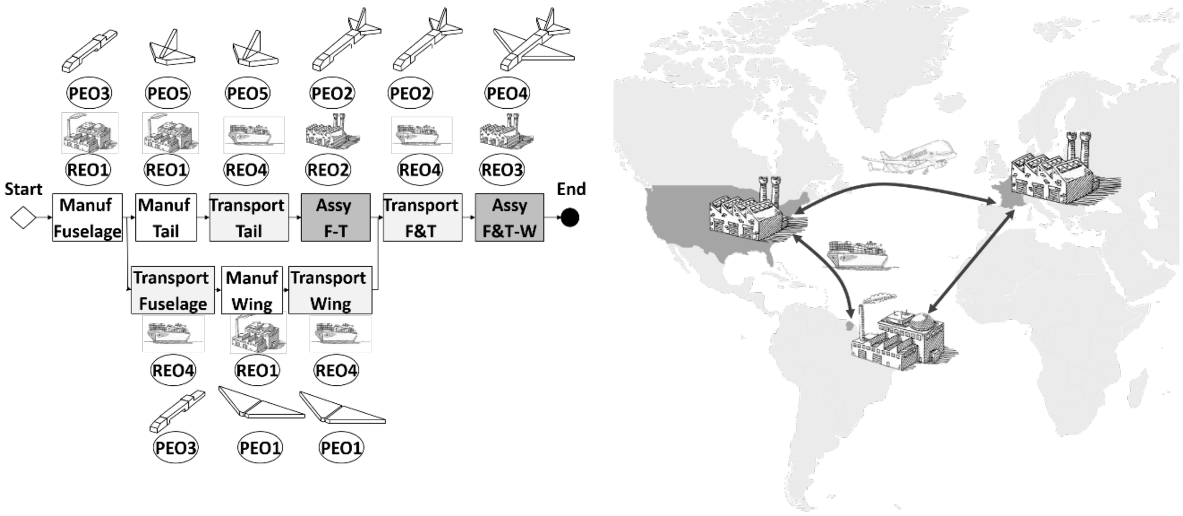

Figure 8: One optimized "Build Process" option in worldwide network.

5. Conclusion and Further Work

This paper address the Industrial System Design Process and how Ontology-based Engineering (OBE) techniques can support the reconfiguration of industrial systems in resilient production mode, to cope with unforeseen crisis events like COVID-19 pandemic where drastic changes to the industrial systems requirements appear.

The ISD ontology made to support the ISDP at concept phase was reviewed and updated in section 2, which is generated following the MfM methodology and adopting the last updates of this methodology and associated metamodels. A first application case of the ISD ontology was evoked in section 3, where a new industrial system was designed for the concept aircraft DA08. This industrial system would be at present time on a resilient production phase of its lifecycle. A new application of the ISD ontology is presented in section 4 for a crisis reconfiguration case, illustrating a similar scenario to the one experienced in the aerospace industry during the COVID-19 pandemic crisis into the DA08 aircraft industrial system. This demonstrates the applicability of the ISD ontology to the different triggers of an industrial system design.

OBE techniques supporting the conceptual design phase are highly valuable to collect, maintain and use manufacturing domain knowledge to define possible industrial system reconfiguration scenarios during unforeseen crisis events. These techniques evolve from previous Knowledge-based Engineering systems, methods and tools, which limitations for wide implementation still need to be solved (e.g. highly complex modelling languages, maintainability and usability of the models, among others).

The ISDP still relies strongly on human experience of manufacturing domain experts not captured or capitalized. The advantage brought by MfM methodology is to provide easy-to-use modelling techniques to capture, share and exchange knowledge with manufacturing domain experts, creating ontologies that support ISDP at different triggering scenarios.

Further work will continue maturing the MfM methodology. Also will enrich with domain experts the behavior models and semantic model of the ISD ontology, and demonstrate its application to the third ISDP concept phase trigger of a major product change.

6. Acknowledgements

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