# Towards thinking manufacturing and design together: an aeronautical case study

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### Abstract

*The construction of complex objects, such as an aircraft, requires the creation of a dedicated industrial system. By industrial system, we mean all the material and immaterial means used to manufacture the object (labour, machines, factories, etc.). Classically, the industrial system is specified when the aircraft design is already engaged. In other words, the specifications of the product are the requirements of the industrial system. This approach presents two major drawbacks: firstly, the industrial system can inherit blocking constraints that could be easily removed by changing the aircraft design, and secondly, both continue to evolve during the lifetime of the aircraft programme. In this paper, we address the problem of having a global view of design and manufacturing. Starting from an industrial case study, the Airbus A320 aircraft manufacturing, we proposed a model-based approach, firsts steps towards tools for specifying together and consistently the design of an aircraft and its manufacturing system.*

## 1. Introduction

Nowadays, the aeronautical market moves very quickly, especially due to the emergence of new airline companies. Indeed, these companies have requirements on their aircraft fleet either regarding the performances of the aircraft, the associated costs, or more specific features. Aircraft manufacturers need to align their current aircraft models with these requirements quickly if they want to remain competitive. But the development cycle of an aircraft is, today, very long compared to the evolution of the market. In fact, the aircraft architectural design is carried out sequentially by first considering the requirements related to the performance of the product (number of passengers, consumption, etc.), defining the major components of the aircraft, and then defining the associated industrial system[1]. This results in a low reactivity to adapt the product to these potential new clients.

On another aspect, the demand for aircraft has been growing for decades, especially for some short-haul aircraft families. In this context, there is a need for increasing the production rate on the manufacturing lines. But the production schedule is already so tight that it has become very difficult and costly to reach higher rates. As the aircraft manufacturers do not wish to deeply modify the current industrial system, they are introducing modifications in the architecture design that ‘“simplify” manufacturing. For instance, a heavy and large aircraft element, thus difficult to handle by operators, may have to be installed in non-ergonomic conditions, like arms raised upward for a long duration. If this element is moved to a more accessible location, or replaced by smaller elements, gains in installation time can be expected. In order to evaluate the impact of a modification of the architectural design on the industrial system, one has classically to go through the whole development cycle and specially define in detail the industrial operations associated

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[1] By industrial system we mean all the material and non-material means used to construct an aircraft (labour, machines, factories, methods, tools, etc.).

to the new design. This process is very time-consuming and results again in a low reactivity in regards with the market demand.

One way to shorten the development cycle and hence increase the reactivity of aircraft manufacturers is to think the design of aircraft architecture and manufacturing system together instead of sequentially, which is also called *simultaneous engineering*. The concept of simultaneous engineering between the design office and production is relatively old [SD94]. Used in the automotive industry, especially in the supply chain [GS13], its implementation in our context raises some issues due to aeronautics particularities. Indeed, an aircraft is a very complex and bulky object, composed of many components, and requiring manufacturing operations that are often manual and relying on a very specific know-how. In addition, aeronautical regulations impose very strong certification constraints on the design and the manufacturing of the aircraft. All of this constrains and limits the evolution of the design and production methods, mainly due to the efforts necessary to provide justifying elements for the compliance with the regulations. Lastly, until today, production volumes, limited to a few hundred aircraft per year, had not yet prompted an evolution of production methods.

In this paper, we present a recent initiative from Airbus to incrementally develop the A320 aircraft family and increase the production rate on a specific manufacturing line. The concepts we describe here are still preliminary but are based on a real industrial use-case for which significant efforts have been provided to collect very heterogeneous data (documents, interviews, plans, etc.). We show how this industrial problem has been addressed so as to think aircraft architectural design and manufacturing system together. Therefore, the contribution is a first step towards an aeronautical simultaneous engineering.

This paper is organized as follows. We first present the specificities of simultaneous engineering dedicated to aeronautics in section 2.1. In section 3, we describe the industrial use-case and we define a first model of the manufacturing line. In section 4, we define a generic pattern for a model of design and manufacturing that can be instantiated at different levels of abstraction. Finally, section 5 concludes this paper by bringing up the short-term and long-term perspectives.

## 2. Simultaneous Engineering for aeronautics

In this section, we describe the specificities of simultaneous engineering for the aeronautics domain. We first detail the current aircraft development cycle. Then, we highlight the main objectives to reach.

### 2.1. A sequential development cycle

In the aeronautics industry, the *aircraft architect* manages the interactions between many different entities and the contribution of many different disciplines. These interactions include negotiations amongst engineering disciplines (e.g. aerodynamics, loads, safety, thermal), business functions (e.g. finance, procurement) and production. In fact, because they have a global picture, the main goal of the aircraft architect is to ensure that the aircraft fulfils its operational performance requirements just as well as its production requirements.

The design and development of an aircraft, such as the A320, follows today a very traditional cascading cycle, starting from very high level requirements refined to lower level requirements that are then transformed into specifications. More precisely, in this sequential cascade approach, the preliminary project steps are devoted exclusively to the overall aircraft specification and sizing. These steps are in fact a consultation between the aircraft architects, the design offices and the European national companies that make up the *European Economic Interest Grouping* (EEIG). After dispatching the main activities between the members of the EEIG, each major component of the aircraft (fuselage, cockpit, wings, tails, systems, landing gear, . . . ) is defined in detail. The result is the detailed aircraft design and constitutes the starting point used for the definition of the industrial system.

Because of this sequential definition, the design of the industrial system is completely out of synchronisation with the engineering activities. Therefore, the difficulties of defining an industrial system that implements the detailed design are only grasped late in the development process. Moreover, this division between design and production is a constraint for the new challenges of the aeronautics industry. First of them is the capability to quickly modify the product to meet the market demand and second the need to increase the production rate.

The spectrum of market demand can be quite large. For instance, one customer might want to improve the performances of the aircraft or make it compliant with a specific regulation. Generally, this implies some modifications of the aircraft design. However, because the demand is expressed when the aircraft is already designed and industrial system build deep modifications of the industrial system are not an option. That is why the architects have to ensure that the current industrial system will be able to handle the design modifications. For that, they need to evaluate the impact of a modification of the design on the production system.

Today, such an evaluation cannot be done directly because the architects use high level abstract elements such as a wing or landing gear while the manufacturing engineers handle screws, cables, etc. In fact, to perform this evaluation, it is necessary to perform all the steps of the development cycle: preliminary design, detailed design and industrial definition. The industrial definition includes the creation of assembly operations dedicated to the new design, the identification of the physical equipment necessary to manufacture along with the associated tooling, and the scheduling of the manufacturing steps. Then, the evaluation is performed mostly manually following different criteria: impact on the production rate, additional costs, etc. This process is time-consuming and has a significant cost.

Regarding the production rate, the increase in air traffic and the arrival of new airlines lead to the need to produce more aircrafts. For cost reasons, the production rate must be increased without deeply modifying the industrial system. Indeed, increase the size of the assembly line or build a new factory requires a very unfavorable financial investment. Therefore, a possible option, with a limited effect of the industrial system, is to introduce design modifications to make manufacturing operations *simpler*.

An example is illustrated on figure 1: after a study of the assembly line, it appears that a bottleneck for the increase of the production rate is related to the installation of an air conditioning circuit (pipe). A part of this circuit passes through a very narrow area, which makes the installation particularly difficult. The architects propose to modify the path of this circuit in the aircraft, and to make it pass through an area more accessible to the operators.

In this case, the process to increase the production rate consists in the following steps:

1. identify the manufacturing bottlenecks and their causes;
2. analyse the installation instructions in order to establish the links between the design elements and the installation operations (duration, aircraft zones, number of operators needed for the operations);
3. create a new architecture design that removes the bottleneck;
4. define the corresponding manufacturing elements as described previously and evaluate the resulting benefits on the industrial system performance.

Again, this process is too time-consuming compared to the required reactivity. Moreover, it can sometimes reveal to be a waste of time if a new design does not have the expected positive effects on the production.

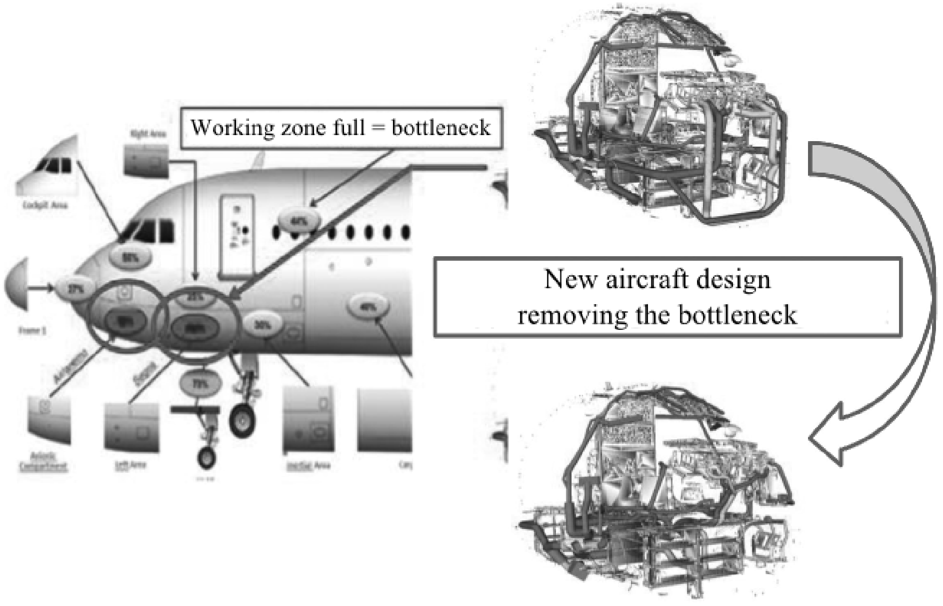


**Figure 1:** *New aircraft concept design to remove a bottleneck*

## 2.2. Objectives of the simultaneous engineering

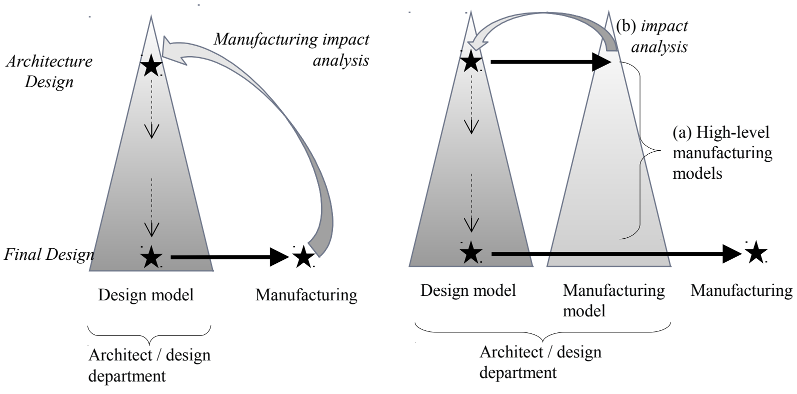
As we have seen, the architectural work begins at high-level of abstraction and finishes at complete detailed description design level. However, due to the successive design refinements, it is excessively difficult to evaluate the impact of new architecture proposals on the production. To reduce the time and cost, there is a real need for tools allowing to assess the impacts on the manufacturing without the detailed definition of the final product, i.e. tools that can be used at the same level of abstraction as the one used by the architect. To address this, Airbus has decided to carry out a simultaneous engineering activity between the design office and the production department.

The purpose of this activity is to switch from the sequential development cycle as described in the previous subsection and illustrated on figure 2a to a progressive development cycle as illustrated on the figure 2b. More precisely, on figure 2a, the pyramid represents the evolution from high-level design (top of the pyramid) to a final design (bottom of the pyramid) from which a manufacturing can be implemented. The manufacturing impact can only be assessed when a final design is achieved. The aim of the simultaneous engineering is to allow the architect to quickly study aircraft design proposals regarding the expected benefits on the production. It can be split up into two objectives:

(a) *consider consistently about design and manufacturing at any level of abstraction*. As illustrated on figure 2a, it is currently possible to reason about design at several levels of abstraction. Hence, the objective is to have high-level abstractions of the manufacturing model, one for each level of the design. On sub-figure 2b, this corresponds to the right pyramid;

(b) *assess the manufacturing performances thanks to its abstract models*. If such an evaluation is possible at any abstract level, then it allows to have a feedback on the impact of the design at any time. On sub-figure 2b, this feedback is represented by the left arrow that goes from the right pyramid to the left one.

With such a structure, the first advantage is the capacity for the architects to evaluate at



**(a)** *Current development process.* **(b)** *Enhanced development process.*

**Figure 2:** *Towards an enhanced model for the aircraft architect*

any time the foreseen impact on the manufacturing process, which avoids the current time-consuming process. The second advantage is the possibility to specify much earlier the industrial system associated to a design. In fact, such a specification based on conceptual models allows all stakeholders to anticipate the difficulties in the industrial implementation of an architecture design, even for high-level ones.

In a long-term perspective, the evaluation could consist in a complete chain of methods and tools. For instance, at each abstract level of design, one could consider several high-level industrial systems and choose the one that gives the best performances, or even optimize the overall industrial system. Tools could also support the architects in design tasks by automatically checking properties directly on the model and finding the best possible configuration according to a set of constraints as it is done in [DDPP11, DP13] with logic-based solvers.

In a short-term perspective, we focus on an essential part of the evaluation: the estimation of the impact on the production rate. More precisely, we want to plug our model to automatic tools that would generate the optimal sequence of high-level installation operations and therefore give a clue of an expected production rate. This means that conceptual manufacturing models must be compliant with operational research tools dedicated to scheduling [Gra66, PV13]. In order to reach this short-term objective, we first need to achieve the first sub-goal and model the manufacturing at different abstract levels. Hence, for the time being, starting from raw data, we focus on the definition of high-level manufacturing models. More precisely, we first model the current assembly line and we abstract this model while taking into account architecture design elements. Contrary to approaches developed in [SM15, DYE$^{+}$11, BEHK14], we do not aim at defining a generic framework for simultaneous engineering but a framework dedicated to aeronautics. Nevertheless, we hope that this preliminary work will support a larger reflection in the future.

## 3. Modelling the production line

### 3.1. The aeronautical case study

The industrial use-case of this work is the production assembly process of *forward sections* of single-aisle A320 aircraft. The forward section covers the nose fuselage, the cockpit and the forward section of the cabin. Note that the junction with the wings is performed on another production line dedicated to the central section of the fuselage. The forward section's production line is located in the French site of Saint-Nazaire and is organized along two sub-lines. The first one is dedicated to structural assemblies, i.e. the building of the aircraft body, and the second one, COMETE, is dedicated to the installation of all the non-structural elements such as the heat insulation and soundproofing, electrical harnesses and equipping, air conditioning circuits, etc.

In this use-case, we focus on the COMETE production line. It is composed of 14 stations on which manufacturing activities, i.e. equipments installation, are distributed. The installation process is organized as a *pulse line*, meaning that the section to equip and the associated tooling are transferred every $X$ hours from one station to another. The equipments installation always starts in station 1 with a completely unequipped section, and always finishes on station 14 with a completely equipped one.

As the A320 aircraft family is quite old, its production was not foreseen for high production rates. At this time, a production rate of one plane per month was a remarkable performance. Nowadays, the rate reaches 50 planes per month in order to meet the market demand. Nevertheless, due to the weight of this program's history, most of manufacturing activities are still manual ones. Technologies used on the line are highly reliable and low cost but have almost not evolved since the beginning. Moreover, work zones are still cramped and make operators' tasks quite tedious, especially with high production rates.

The objective is to develop solutions that allow to reach a rate of 63 planes per month. In order to minimize industrial risks, these solutions cannot deeply modify the production line. Moreover, the solution that would consist in building a second identical production line is out of scope.

## 3.2. Data retrieval and analysis

Modelling the manufacturing process requires an in-depth understanding of its building blocks and the interactions between them. In fact, many competences and trades are involved and they can sometimes be quite far from the architect's world. Thus, the first part of the study, which is still on-going work, consists in retrieving and analysing data about the manufacturing line.

Due to the A320 program's age, significant part of the documentation is still not digitalized, the human knowledge is quite tremendous but is mostly shared orally and some rules can even be implicit. Consequently, we had to go to the Saint-Nazaire site regularly in order to interview the different actors, understand and question their practises.

From those interviews and from the engineering and manufacturing database, we have built and/or retrieved several relevant pieces of information:

- the PERT (Program Evaluation and Review Technique) diagram - this diagram contains the manufacturing scheduling, i.e. the order in which the equipment are currently installed on the section. For the A320 program, this scheduling is manually built by a *Time Evaluation Agent*;
- equipment installation descriptions - documents detailing the sequences of activities performed during the installation, the impacted geographic zones of the forward section, the list of physical parts concerned and the number of operators required;
- a list of all the physical parts to be installed on each station of the line.

Note that most of these pieces of information are paper documents with heterogeneous structures and formats and therefore have been analysed manually, which represents a significant work. From this analysis, we have identified seven major concepts in the COMETE manufacturing line. They are connected together as presented in the UML model of figure 3.

The concepts and their features are:

- **Part**: physical elements of the aircraft.

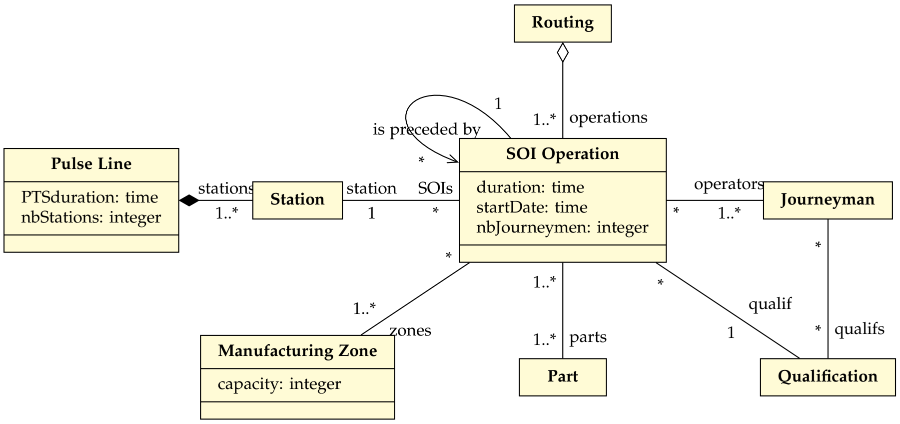


**Figure 3:** *UML model of the manufacturing line*

- **Station**: the physical space in which the section is equipped along with the associated tools and parts. Because the physical space and the time during which the forward section stays at the station are often merged, station represents also a temporal interval called the *Product Time Slot* (PTS).

- **Pulse Line**: set containing *nbStations* stations that altogether deliver completely equipped forward sections every $X$ hours, where $X$ denotes the duration of the *Product Time Slot*.

- **Manufacturing Zone**: physical space in the forward section. In fact, forward section is divided into manufacturing zones that are characterized by their geographic perimeter and the maximum number of operators that can simultaneously work in them (i.e. its $capacity$).

- **SOI Operation** (Standard Operating Instruction): sequence of atomic manufacturing activities on the forward section.
  The set of parts that are assembled in the nose section during these activities is associated to the SOI operation. One SOI operation cannot fall on more than one station. The realization of one SOI operation requires $nbJourneymen$ operators that have a specific qualification. It starts at $startDate$ and lasts $duration$. The SOI operation covers at least one manufacturing zone. Finally, there are precedences constraints between SOI operations, meaning that some SOI operations cannot start before some other are finished.

- **Routing**: set containing SOI operations that correspond to interconnected parts. A routing groups operations into high level tasks.

- **Journeyman**: operator that performs the SOI operations. Each journeyman has at least one qualification.

For instance, all *harnesses* and *cables* are physical parts. An instance of a SOI operation is the *connection of one specific harness and a specific cable*. An instance of a routing is the *connection of a specific harness to a calculator* that involves several connections between the harness and cables and other SOI operations.

In the COMETE use-case, there are approximately 500 routings, 3500 SOI operations and 10000 parts (exclusive of hardware).

# 4. ABSTRACT GENERIC MODEL

## 4.1. General idea

In order to have a model allowing the architect to perform simultaneous engineering of the aircraft design and the industrial system, we must create a correspondence between dynamic elements, in our case manufacturing operations, and static elements. Let us take the simple example of an air conditioning circuit. In the design world, such a circuit, pipe, is defined by static attributes such as geometry, materials, etc. In the manufacturing world, it is linked to the operations necessary for its installation. The concept of pipe object makes sense in both worlds and can therefore be seen as a bridge between them. More generally, we consider that the physical elements constituting the aircraft, are the contact points of these two worlds.

The junction between design and manufacturing could be achieved by coupling two distinct models along with transformation rules for instance [HKR$^{+}$07]. We did not choose this solution for three reasons. First, there is a significant risk of drift between the two models. Indeed, in the future, it is possible that the models change without their coupling being updated, or even worse that they become completely incompatible with one another. The second reason is more practical. Whether in the design or the manufacturing worlds, there is only one aircraft. Therefore, it is better to have a unique model of the aircraft that can be shared by all stakeholders, rather than heterogeneous models that would suggest that the real object may be different depending on the context. Finally, the third reason is related to our goal, which is to enable the architect to understand the interactions between architecture and production. Hence, it is not a matter of having two distinct models, but rather an integrated model of the aircraft, with a design part and a production part.

On the other side, we do not intend to merge inextricably the production and the design models. We must foresee that models of each world may evolve in the future, without each evolution of the one necessarily impacting the other. Hence, our idea is to define a global model with two parts and a very limited number of objects shared between the parts. In this model, shared objects define a "*contact area*", i.e. the bridge, between the manufacturing and the design. This allows each trade to update its model without impacting the other as long as it does not touch the objects of the contact area.

As discussed previously, we need to define high-level of abstraction for the manufacturing model. Like [WV04] with architectural frameworks, we have chosen an approach in views, where each view corresponds to a layer of abstraction. However, unlike the macro-models defined in [SME09] that are composed of layers of abstraction with rules explaining how to pass from one level to the other, we have privileged simplicity. For the moment, we choose to define a high-level abstract model with *abstract* classes that can be specialized in *concrete* ones for each level of abstraction.

## 4.2. Pattern

An outline of this abstract model is illustrated on figure 4. This model must be specialized in each view, i.e. in each abstraction level. For reasons of legibility, we chose to include only the most important attributes and classes. On the generic pattern of this figure, concepts relating to design are on the left and those relating to production on the right. The bridge between the two worlds is represented here by the abstract classes *Physical Element* and *Zone*.

*Physical Element* is specialized as follows:

- at high-level of abstraction, in the class *Sub-element*. A Sub-element is a set of parts that has a business meaning in a stage of the production process. A set of sub-elements defines a component of the aircraft which corresponds to a part of the aircraft (wing, front section, etc.), manufactured by different production sites and delivered for assembly to the factories which realize the final assembly;

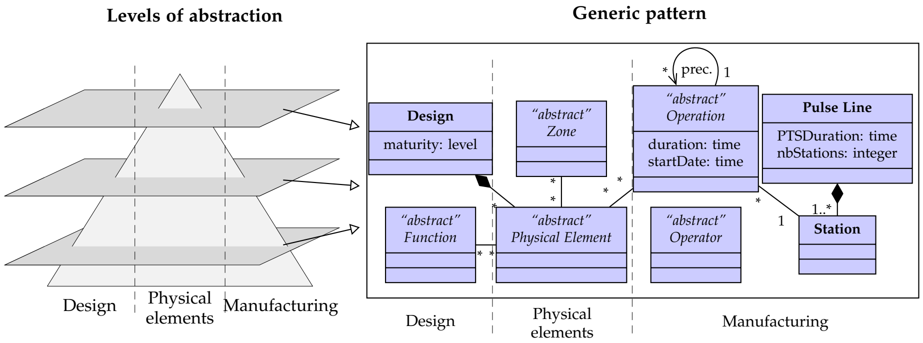


**Figure 4:** *Prototype of a generic class diagram for aeronautics simultaneous engineering*

- at low-level of abstraction, in the class *Part* presented in section 3.

For instance, the air conditioning pipe as mentioned in the example of section 2.1 is a *Sub-element* and belongs to a high-level view. All the pipes sections are instances of *Part* and belong to the low-level view.

The abstract class *Zone* corresponds to the location of physical elements in the aircraft. At low-level, it specializes in *Manufacturing Zone* as defined in section 3.

On the design side, an aircraft architecture proposal is represented by a *Design*, which is associated with a maturity level and composed of physical elements. Here, a Design is the realization of an architecture, i.e. the definition of all physical elements (parts, sections, etc.) composing the aircraft, the technical way they are assembled together and associated to the *Function* which are fullfilled. So, each *Physical Element* is connected with an aircraft *Function*. These functions are related to the aircraft operational life: power generation, fuel storing, providing means of communication etc. The class *Function* is abstract and it generalizes as follows:

- at high-level of abstraction, in service functions to users (pilots, passengers, cabin crew, etc.), without presupposing how these functions are performed;
- at low-level of abstraction, in *Elementary Functions* which are all the technical functions necessary to perform the hight-level users services.

On the manufacturing side, the pattern contains two concrete classes for the manufacturing: the *Pulse Line* and the *Station* as described in the section 3. In fact, these elements constitute the structure of any industrial system and must consequently be present at any level of abstraction. Operations, represented by the abstract class *Operation*, are carried out on each station and correspond to actions performed on a station. An operation has *duration* and a *startDate*. At a high-level of abstraction, operations are specialized in the class *Action* which consists in equipping the aircraft with a *Sub-element* like fixing a pipe. At low-level of abstraction, operations are specialized in SOI operations (see section 3). Finally, the abstract class *Operator* corresponds to the actor performing the *Operation*. An operator could be a human or a robot. We choose not to represent the relation between *Operator* and *Operation* in this generic pattern. Indeed, for higher abstract levels, architect might not be able to express such a relation. However, it could be useful to characterize the different kind of operators.

The figure 5 represents two specialisations of the generic pattern for the manufacturing side. The lower part of the figure shows how the UML model of manufacturing defined in the section 3 and illustrated on figure 3 is transformed to be compliant with the generic pattern. We can remark that there are no robots on the current production line, so *Journeyman* is the only class specializing *Operator*.

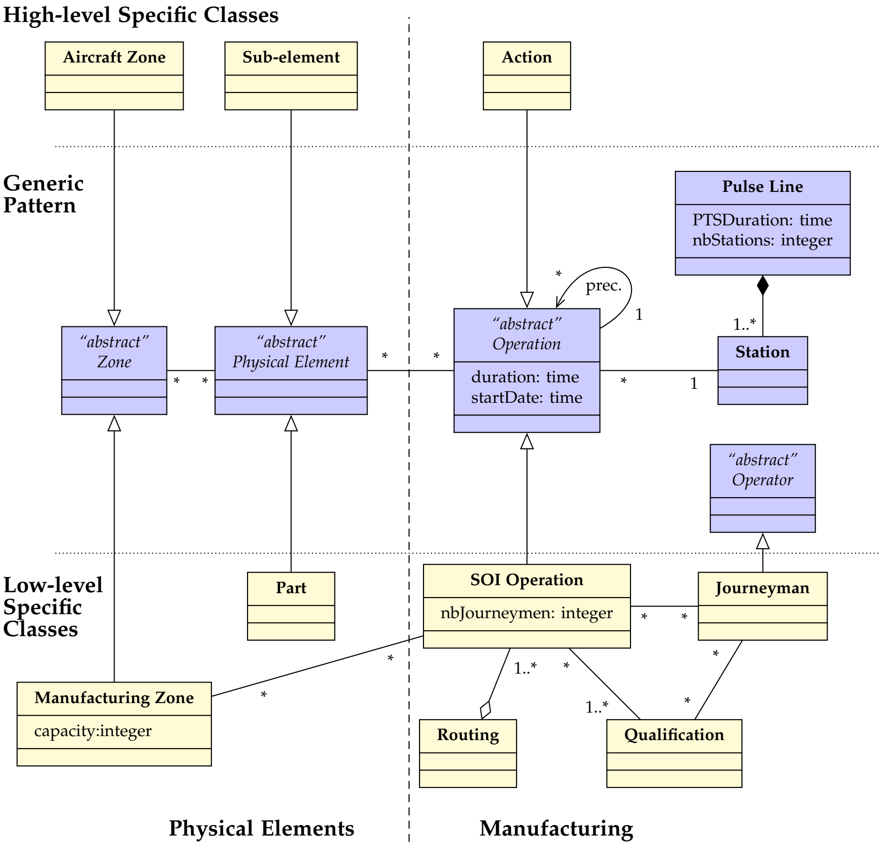


**Figure 5:** *UML class diagram, manufacturing part, low-level.*

## 5. Conclusion and perspectives

In this article, we present an industrial case study and demonstrate the need for having a model-based framework to embrace design and industrial system of complex products such as aircraft. After studying the manufacturing reality, especially the data retrieval and the precise understanding of the domain which have mobilized most of our efforts so far, we have given a first draft of a model for a simultaneous engineering of the aircraft design and its production. This model-based approach allows the definition of the different concepts, the analysis of the problem and the communication between the design and manufacturing teams by providing a common system of reference. Moreover, it is a first step towards a simultaneous engineering digital framework to carry out studies of impact of architecture on the production.

In future work, we will refine the manufacturing part of the model in order to build a simulator of the production chain. This simulator will allow the architect to estimate production rates according to design choices. We have already conducted initial investigations using operational research tools such as the one presented in [PV13]. Like in [DDPP11], we will also combine our conceptual models with formal tools that deduce the missing links and objects of the models. In our case, the links would be the ones between tasks, operators and stations, according to some optimization criteria, such as the production rate. Our first basic experiments in this way are promising.

Today, our models are a static view of the aircraft and its production system, but the manufacturing process has a time component that could only represented in a behavioural view. To model the static and the behavioural views together, another perspective of this paper is to adapt the works that tend to unify these two views through SysML diagrams as in [BM12].

Finally, in a completely different way and in the line of [BAV15], it could be interesting to use a manufacturing-oriented ontology in order to allow architects to have high-level abstraction reasoning on very detailed data, by establishing the link between physical elements and high-level functions.

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