A Collaborative Model for Connecting Product Design and Assembly Line Design: an Aeronautical Case

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Abstract

*In business or in industry, some entities are in collaboration with each other when they work together with or without common objectives. In this paper, we are interested in this collaboration relationship in the context of aeronautics. More precisely, we focus on a use case in which two actors' objectives are respectively to design an aircraft and to design the assembly line for this aircraft. Following some previous work on coopetition, we analyse the dependency relationship between these actors and propose i*models. In order to solve dependency cycle issues, we introduce a third actor that is in charge of realising trade-offs between the two designs. Finally, we show how existing methodology could be applied for supporting this trade-off activity.*

1. INTRODUCTION

Collaboration means that different actors work jointly together, but not necessarily for the same objectives. The actors share resources, knowledge or can work together, to achieve their own goals which may or may not be common. In the context of business, the notion of cooperation has been extended with the concept of *coopetition* [4]. In coopetition, actors are in a competitive situation, but choose to work together in order to increase their profit. They are simultaneously in cooperation and in competition. Their objective is to maximise personal benefits and minimise personal cost through cooperation and competition. Coopetition relationship between actors is a common configuration in industrial environment. In fact, distinct organizations may need to combine their strengths to reach some of their objectives while there are rivals for others.

Recent works have focused on modelling goals and dependencies between actors in the context of coopetition [17, 18]. Indeed, within this context, an actor collaborates with partners who contribute to provide her what she needs. Therefore, a dependency is established between the partners. This dependency relies on the partners' involvement level in the coopetition.

In this paper, we follow these approaches and focus on the notion of dependency among actors in a collaboration environment. The investment and sharing of resources within a cooperation framework may be more or less interesting, depending on the goals of each actor. Thus, it can be interesting to characterize the dependency in order to support the actors in making choices between satisfying the goals of the collaboration and their internal goals.

Even if we use quite simple modelling in this paper, we believe it helps to understand and solve a real practical problem without the need for extensive and complex systems modelling. In fact, modelling is here used as a thinking aid and not a technical simulation.

We specifically focus on an aeronautical case study, presented in Section 2. This case study consists of designing an aircraft and designing a factory (an assembly line) which produces this

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aircraft. It involves two actors, namely aircraft designers and assembly line designers. Even if the two actors belong to the same company, they have different goals and must therefore be handled as two separate entities. However, these actors are not rivals for any of their goals. Therefore, they really are in a collaborative context.

In Section 3, we follow previous methodological approaches developed for coopetition to elicit and propose several models of dependencies between the actors. The first model represents the current relationship of the actors, which is a subordinate relationship. The second model represents the desired relationship between them, which is a collaboration relationship. We show that there are some cycle issues with such a model. Therefore, we present a third model in which we introduce a new actor in order to realise trade-offs between the two actors and solve the cycle issues.

Then, in Section 4, we focus on a specific part of the aircraft and its assembly process and the trade-off that can be made between the two actors. We formalise the associated dependencies in order to be able to assess the impact of the actor's choices on another in the final approach. More specifically, we adapt an approach to support actors in making choices that affect collaboration in a way that maximises their goals.

Section 5 is dedicated to the conclusion and perspectives.

2. An Aeronautical Case Study

For some complex products, such as an aircraft, some cars or some satellites, the definition of the means of production starts after the definition of the product. In other words, the product specifications are used to define its manufacture. The main risk with this type of approach is that the means of production may face blocking constraints that, sometimes, could easily be solved by changing the design of the product. For instance, in the context of an aircraft, one might have a first design with the air conditioning going through the centre of the cockpit and a second design with the air conditioning split on the right and on the left of the cockpit. These two designs might be equivalent in terms of performance of the aircraft but very different in the way they are produced. In fact, the first design could be hard to produce as it would require several assembly tasks in a busy area of the aircraft whereas the second one allows tasks parallelisation.

This problem of *manufacturability* is a key element in Industry 4.0 [25]. One of the ways to manage the manufacturability problem is *Design for Assembly* (DFA) [2, 15] , which consists of the designing of products for ease of assembly. DFA takes into account the constraints inherent to the means of production, whether it is the prohibitive cost of certain elements or the physical impossibility of producing some designs due to the lack of specific tools. The philosophy of DFA is to solve manufacturing problems at the design stage and thus drastically reduce costs. DFA brings manufacturing and assembly restrictions into product development, it is strictly one-way from production to product design. But production is not only a source of problems, it can also provide new design possibilities. Indeed, new manufacturing methods such as robotics or additive manufacturing open up new possibilities in terms of design, while imposing constraints (size of what can be printed, materials used, *etc.*). Thanks to additive manufacturing special characteristics, designs using it are sometimes very different from conventional designs.

Therefore, it is increasingly crucial to integrate manufacturability early in the development cycle to understand the multiple interactions between design and manufacturing. This is exactly what concurrent engineering, or simultaneous engineering, aims to do. The idea of having the design office and production work together is not new [23]. This approach has been used for a long time in the context of spare parts in the automotive industry [12], but its implementation in the context of more complex systems, particularly in aeronautics [19, 20], raises many problems.

The aeronautical industry is precisely the focus of our case study. The aircraft development follows a cascading cycle, from high-level goals, which come from market studies, airlines and also from societal expectations (such as green or noise reduction), to requirements and then to specifications. The production system and its specification are mostly defined after the engineering activities. Manufacturing systems of an aerospace factory is a complex layout of different types of production equipment (forging/bending presses, welding stations, riveting machines, coordinate measuring machines, assembly jigs, *etc.*) that accommodates both flow and batch production process architectures [13]. So, aircraft manufacturers are faced with the challenges of flexibility, productivity, as well as the ever-growing pressure for cost reduction and better performance. As such, concurrent engineering approaches integrating product development and production system development are now a hot topic.

In this work, we focus on the high-level goals for the design of an aircraft and for the design of its production system. The goals we express are based on our experiences in the field. It covers both goals for the aircraft in terms of performance, noise, consumption, and goals for the production system in terms of cost and production capacity. Based on these goals, we apply a method that allows us to make choices both in the design of the aircraft and in the design of the production system. We consider the concept of regional transport aircraft, with an average range of 600 km, 150 seats and a cruising speed around Mach 0.8 [22]. This aircraft has the particularity to have a completely electric propulsion thanks to a set of electric motors integrated in the wing and powered by two turbines located at the back of the fuselage. The technical aspects related to the problems studied in this use case will be detailed in the following sections.

3. Product and Production Designers: Two Actors Trying to Work Together

In this section, we try to characterise, through goal-oriented modelling, the collaboration relationship among the different actors that build the DRAGON and its assembly line. To do this, we first highlight that there currently exists a dependency relationship between the actors. Then, we focus on the dependencies in the case of a collaboration relationship and we show that it raises some cycle issues. Finally, we propose a possible solution to allow actors to collaborate together.

3.1. Aircraft and Assembly Line Goals

Optimising the interaction between product and production system development requires first an analysis of the relations and inter-dependencies of both fields. To do this, it is necessary to elicit the requirements, or more precisely the goals, of each stakeholder. There are various frameworks for doing this, such as SysML [11], Kaos [8] or i^* [7].

Inspired by the work done by Pant and Yu [17, 18] on coopetition we have chosen to use i^*. In the context of our study, we build a Strategic Dependency diagram which aims to elicit intentional relationships between actors. The diagram representing the current dependencies is given in Figure 1. Legend of i^* elements that we use are recalled in Figure 1.

In our case, we have two collaborating actors: *DRAGON designers* and the *Assembly line designers*. Both have their own actor's boundary, which is a graphical container for their intentional elements together as well as their interrelationships. They are not rivals for any resource, but, as within the coopetition relationship, the satisfaction of elements in one actor may depend on the satisfaction of elements in the other.

Regarding goals, for the DRAGON designers' side, we focus on four goals which are range, passenger capacity, cruising speed and the main objective of DRAGON, which is to have an electric

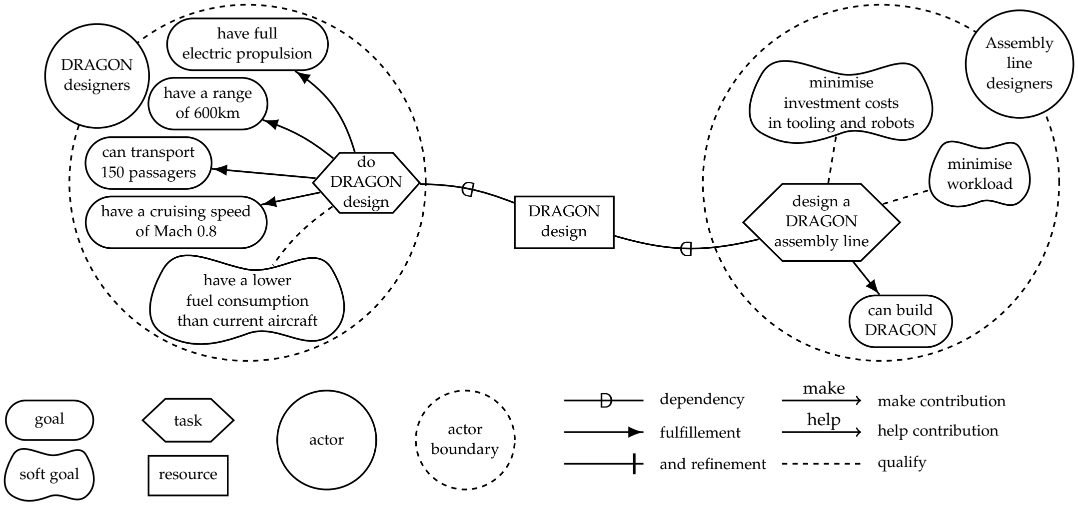

Figure 1: *Current relationship between DRAGON designers and assembly line designers*

propulsion. All these goals are fulfilled by task *do DRAGON design*. In addition, there is one *soft goal*[1]: DRAGON must use as little fuel as possible and perform better on this criterion than the present-day aircraft (*have lower consumption than current aircraft* in Figure 1). Soft goal is a goal with no clear-cut criteria,*i.e.* a goal that cannot be clearly and formally qualified as satisfied [6]. The *lower consumption* objective is not quantified, so its satisfaction is necessarily subject to interpretation. In this diagram, the soft goal is linked to the task by a *qualify relationship*, it means that the task should take into account the soft goal when being performed [7].

From the assembly line designer's side, there are one goal and two soft goals. The task of the designers here is to design an assembly line, but not just any assembly line, an assembly line that must build the DRAGON aircraft. This is why the task *design a DRAGON assembly line* is qualified by the goal *can build DRAGON* attached to the task *design an assembly line*. Regarding the soft goals, the first one is to *minimise investments costs in tooling and robots*. The second is to minimise a specific operational cost: the workload (*i.e.* hourly labour).

Of course, many other important aspects should also be considered. For example, because of the noise pollution, DRAGON must make as little noise as possible, or even less noise than the current aircraft. Regarding building the assembly line, the non-recurring costs associated with the construction of the factory, of the workstations or land purchase could also be taken into account. For the sake of readability, we have chosen to keep a limited number of elements for both actors.

The dependency relation (represented by the D-arrow) connects two actors, here the two design teams, through elements. It expresses that an actor (the *depender*) depends upon another actor (the *dependee*) for something (the *dependum*). In other words, it describes the fact that one actor needs another one in order to satisfy or do an element. In the i^* model presented on Figure 1, assembly line designers depend on DRAGON designers to have the *DRAGON design* in order to design the assembly line to build the DRAGON aircraft. Assembly line designers are the depender, DRAGON designers are the dependee and *DRAGON design* is the dependum.

Indeed, the design of DRAGON is required in order to define a building process. The building process corresponds to the list of high-level tasks, along with their precedence relationship. The building process is directly deduced from the DRAGON design. We have chosen to represent

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[1] For the purposes of legibility, we have chosen to use the term *soft goal* instead of the term *quality* used in i^* 2.0.

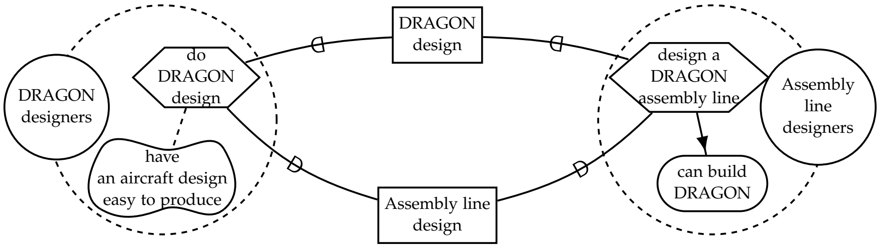

Figure 2: *Cyclical dependence between DRAGON design and assembly line design*

it as a resource in the sense that it is specific information produced from the task *do DRAGON design*. The building process allows assembly line designers to define the tools, machines, robots required to build the aircraft. It also allows them to define, by refinement, the assembly tasks as well as a first planning of the assembly line. Of course, the production of the building process is not automatic and is carried out by a specific actor which is part of the assembly line designers. However, at our level of abstraction, we have chosen to leave out these details.

3.2. Collaboration: a Dependency Cycle

In a concurrent engineering logic, the design of the factory and the product must be conceived together. Indeed, aircraft designers do not just want to make a aircraft, they want to have an aircraft design easy to produce. This is materialised by the addition of a new soft goal for the DRAGON designers (see Figure 2). In the concurrent engineering context, the aircraft and assembly line designers must work together collaboratively to support each other. So, we have dependencies between actors. In our case study, we choose to model the collaboration with two dependency links. The first dependency is the one described previously, where the assembly line depends on the DRAGON design. For the second dependency link, it is the product design that depends on the factory. Indeed, in order to have an aircraft design easy to assemble, DRAGON designers must know the design of the factory (with its capacities, its know-how, *etc.*). The overall i^* model is presented on Figure 2.

Adding this new dependency results in a cycle of dependencies between DRAGON design and assembly line design. On the one side, assembly line designers need to know how the aircraft is designed before planning their own. On the other side, DRAGON designers need to understand what constraints their design will impose on the assembly line to conceive the aircraft. Thus, at the same time both design teams expect and need information and knowledge from the other team: this is a deadlock problem.

In practice, this problem can be circumvented by an iterative process. The aircraft design is created, then the factory design, which in turn feeds into the aircraft design and so on. Nevertheless, such a process still does not really correspond to a true collaboration relationship in which the factory and the product are designed together. It is more a DFA approach where the aircraft designer must take into account the constraints and objectives of the assembly line.

If we want a true collaboration in which the aircraft and its factory are jointly designed, we are in a deadlock: each actor, at the same time, needs an action to be done by the other in order to execute its own. This is cyclical form of dependence where each actor is waiting for the other to satisfy the element of its expectation. So, we must find a way to address this circular dependency problem, *i.e.* to break the cycle of dependency and propose a win-win solution for both actors.

3.3. Addition of a Third Actor

In Pant and Yu work, a similar circular dependency problem is stated as both actors face a blocking situation ([17, 18]). However, in their articles the dependency problem is not due to a simultaneous need for the dependum but to the presence of lose-lose or win-lose strategies. Despite this difference, a similar solution can be used, namely adding a third actor. In their problem, the authors chose to introduce a knowledge-sharing facilitator.

In the same spirit, we propose to introduce here a new actor to mitigate our circular dependency: *Global designers* (see Figure 3). The global designers actor is able to perform the task *trade-off between DRAGON/assembly line designs*, which consists in a trade-off between both designs. This actor can be seen as a collaboration facilitator. In fact, the global designers actor is a team composed of people from the product design team and people from the production design team. Together, they collaborate to perform trade-offs between the aircraft and assembly line.

Before describing more precisely this third actor, we briefly describe why other approaches that do not involve this actor are not suited for our use-case.

A first simple solution that does not involve a third actor would be to get the two actors around a table to work out a draft of collaborative designs together. However, in our use-case, the two actors are not two individuals but entire departments. If a solution based on interaction between the department that designs the aircraft and the one that designs the factory was still possible a few decades ago, this solution is unfortunately unfeasible today. Indeed, due to the complexity of current systems, the number of stakeholders and the diversity of fields involved, it is necessary to find other ways to recreate a full collaboration between the product design and the assembly line design.

Another solution would be to use qualitative or quantitative satisfaction analysis techniques on the As-is diagram, to propagate the impacts of the alternatives on the goals of our actors, as presented in [14]. Then, the trade-offs between the goals could be made with trade-off analysis tools as described in [10, 1]. Nevertheless, some issues make the previous proposals difficult or even impossible to realise. Firstly, for the sake of simplicity, we chose to not give importance to our goals but we could use the importance addition to i^* presented by Vik Pant in [16]. However, in our problem, the order of importance between soft goals is not fixed and may change depending on their satisfaction. For instance, *minimise workload* could be high-level priority soft goal at the beginning of the process, but once it is Weakly Satisfied, its priority would become lower than the one of the soft goal *minimise investment costs in tooling and robots*. Secondly, at this level of conception, we do not have enough information about contribution of alternatives to the goals to assess their impact with techniques of quantitative satisfaction analysis. We need expert intervention to define them. In addition, softer techniques such as qualitative ones are not precise enough for the designer to make a decision based on their recommendations. Finally, another choice of simplification in our model is to not represent all the alternatives allowing the satisfaction of the goal, *i.e. do DRAGON design* OR-refinement. In fact, there is a multitude of possible design alternatives, some of which may not yet exist at the beginning of the process. They are constructed by Global designers through the use of the Integrated Morphological Chart presented in 4.

As shown in Figure 3, the only task performed by the global designer achieves one soft goal: *have the best DRAGON/assembly line system*. Indeed, unlike the other actors, global designers do not aim at optimising one design, but the quality of the combination/union of the two. To do this, the trade-off task performed by designers must fulfil all the goals of DRAGON designers and assembly line designers and also maximise all their soft goals. Rather than overloading the diagram with dependency or part-of links, we decided to simply indicate all these relationships

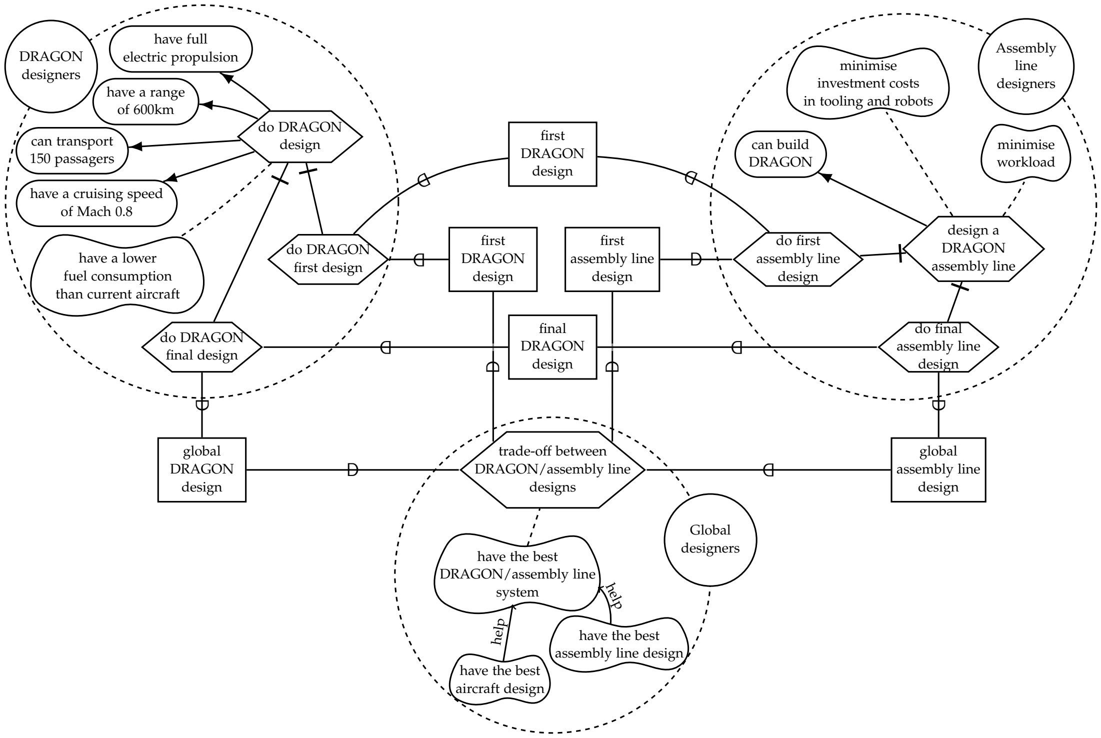

Figure 3: *Addition of the actor* Global designers *for solving the collaboration dependency cycle*

by adding two sub-soft goals of the main goal: *have the best aircraft design* and *have the best assembly line*. These two new soft goals are a refinement of the main global designers' soft goal.

In this new model, the designs of the DRAGON aircraft and its assembly line follow three main steps. At first, as in the model given Figure 1, we consider the one-way dependency from DRAGON to assembly line designers. So DRAGON designers propose a first DRAGON aircraft design and assembly line designers use it to propose a first assembly line design. Next, global designers optimise the global system from these first designs by realising trade-offs between them and propose better alternatives to each design team, denoted *global DRAGON design* and *global assembly line design* on Figure 3. Finally, the two other teams can build their final design by optimising their own soft goals. In this last step, the one-way dependency between the two original actors is back again. In fact, each DRAGON design choice has an incidence on the assembly line design. Thus, at this last step the collaboration is broken. Nevertheless, we are still not in a competitive configuration since DRAGON designers have no interest in hurting the other actors. Our proposition in Figure 3 allows designers to reach a more satisfying solution than the one presented on Figure 1 as the worst scenarii is discarded. It would possible to reach an even better solution for the global system by iterating the *first design - trade-off - final design* again with global designers, until an optimal solution is achieved.

In this new proposal, the soft goal *have an aircraft design easy to produce* is removed of DRAGON designers boundary since global designers actor is now the one who works for this goal through the goal *have the best DRAGON/assembly line system*. It should be noted that this approach is motivated by the fact that technical teams are not familiar with goal modelling approaches, and even less with the *i** language. Therefore, we try to avoid complex modelling with several sorts of dependencies among DRAGON design and assembly line design and cover them by adding an intermediary human role to deal with them. As presented later in the paper, we also provide a realistic tool to assist in rationalising the type of decisions to be made for this intermediate role.

4. Building The Collaboration Between Design And Production

The introduction of the new actor *Global designers* and its associated goals and tasks raises new problems with regards to the evaluation of the system, *i.e.* the aircraft and its assembly line. One such new problem is that a trade-off must be made between the two designs. In this section, we focus on this trade-off capacity and apply an existing methodology that could be seen as a first step in defining framework and support tools for the global designers team.

4.1. The Integrated Morphological Chart Method

Stoffels and Vielhaber introduce the use of an *Integrated Morphological Chart* (IMC) as a method for multi-criteria evaluation of product alternatives with production system solutions [24]. In their work, the authors evaluate and refine existing product/production development methods. Their objective is to improve existing methods in the context of concurrent engineering. They propose IMC as a decision support tool for considering together product and production. Their cae study is the optimisation of the energy consumption of the product and production life cycles.

The first step for the creation of an IMC is the proposal of possible product solutions and production solutions. These solutions must, of course, satisfy all the goals but they do not necessarily satisfy all the soft goals in the same manner, *i.e.* with the same level of satisfaction. The second step is the definition of several evaluation criteria by the decision maker in order to assess all combinations of solutions. Then, domain experts give a value between 0 and 3 (3 being the optimal value) to each solution combination (*i.e.* for each product solution and for each production solution) and for each criterion. This score represents how optimal each combination is with regards to the criteria. So, for each criterion, a view of the best combinations of product/production solutions is obtained. Finally, as done classically for multi-criteria problems, it is possible to define an aggregation method to globally evaluate each combination of solutions. The objective is that the decision maker can make an informed and optimal decision by choosing for each criterion the solution that best satisfies the cross-domain goals.

4.2. Application to the DRAGON Case Study

We have adapted the IMC methodology to our case study. More precisely, we focus on two aircraft designs alternatives for the connection between between the electric fans positioned at the rear of the wing and the inverters positioned at the front of the wing. Inverters are devices that change direct current into alternating current. They are wired to the fans by an electric harness. This harness can be installed either by drilling through the wing (first design alternative) or by following the shape of the wing (second design alternative). For the assembly line side, we consider two alternatives. The first one is to use manual tools and the second one to automate the assembly process with robots. It is important to understand that each of these design alternative is contained in the tasks *Design the DRAGON aircraft* and *Design an assembly line*. In fact, *drill through the wing* and *follow the shape of the wing* are subtasks that refine *Design the DRAGON aircraft*. The same holds for the assembly line tasks. The idea behind the adaptation of the IMC methodology is to allow the global designer actor to perform trade-offs among different design alternatives.

The relevant criteria for trade-offs come from the *i** goal model. Indeed, this model elicits the set of soft goals to be optimised. Note that the goals must be met and there is therefore no

		Assessment according different product / production				
Product solution 1	Product solution 2	AC1/AL1	AC2/AL1	AC1/AL2	AC2/AL2	
AC1 = Drilling through the wing	AC2 = Follow the shape of the win	2	3	1	1	**C1**
		2	1	3	2	**C2**
		2	1	2	1	**C3**
		AL1 = Manual		AL2 = Robot support		

Table 1: *Integrated Morphological Chart (IMC) Matrix*

associated negotiation. Therefore, the criteria studied in our IMC are:

C1 minimise investment costs in tooling and robots, *i.e.* the cost of machines and production equipment; (assembly line designers soft goal)

C2 minimise workload, *i.e.* the cost of labour. In practice, it comes to minimise the number of hours worked to build the aircraft (assembly line designers soft goal);

C3 have a lower fuel consumption than current aircraft. Fuel consumption is directly related to the aircraft design and more specifically to its aerodynamics and weight (aircraft designers soft goal).

Based on the two alternatives for each product and production, we build an IMC matrix, given in Table 1. The values for each combination of alternatives are assigned by experts.

The use of robots is inherently costly and requires additional electricity resources. Therefore, the usefulness of using robots depends on the benefits it provides with respects to a specific task.

Concerning *tooling and robots cost* (C1), robots are expensive regardless of the aircraft design solution. Thus, in our study, in terms of investment costs, solutions without robots are always preferred. When considering the use of *manual tools* (AL1), *following the shape of the wing* (AC2) is the preferred option. This is because the equipment needed to drill the wing is much more expensive.

Regarding workload, the proposed solutions are to use *manual tools* or to automatise the process with *robots support*. In our case, using robots, is always beneficial for *workload reduction* (C2). For this criterion, *drilling through the wing* (AC1) appears to be a slightly better solution than *following the shape of the wing*. This is due to the speed of the process. We also find this same difference in the case of the use of *manual tools* (AL2).

After performance study, the experts came to the conclusion that *drilling through the wing* consumed less fuel (C3). Indeed, laying a cable on the leading edge of an aircraft's wing is not good for aerodynamic performance and therefore for fuel consumption. However, none of the solutions is optimal for the experts, as drilling weakens the structure of the wing. It is important to note that the structural criterion is not taken into account in our study (but it should be in the future). Unsurprisingly, the manufacturing alternatives have no impact on the fuel consumption criterion, judging only by the criterion *have a lower fuel consumption than current aircraft*. Thus it is equivalent to drill the wing with the help of robots, or with hand tools.

If we consider all the criteria, three configurations emerge: *drilling through the wing with manual tools*, *follow the shape of the wing with manual tools* and *drilling through the wing with robots support*. All of them are Pareto optimal, *i.e.* none of these solutions is better than the others on all criteria. For instance, the second solution (AC2/AL1) is the most efficient on the costs criterion (C1), while the third one is the best on the workload criterion (C2).

Since no solution is optimal on all criteria, many multi-criteria aggregation methods can be used to make a choice [3]. They all have their advantages and their drawbacks and choosing one is out of the scope of this article.

Note that, the IMC matrix could be further expanded when considering additional soft goals for product and production. Advantages of this methodology are its scalability, and its potential for cross-domain integration. New soft goals can be added each with its set of possible solutions, whose combinations have to be assessed in the context of each given criteria and integrated on a global assessment.

5. Conclusion And Perspectives

In this paper, we have shown how to model, in a goal-oriented approach, the collaboration relationship between the product design and manufacturing teams for an aeronautical case study. This collaboration can only really take place through the mediation of a new actor who has a more global vision of the system and who is therefore able to make the right trade-offs. In addition, to support this new actor, we have presented a possible trade-off method, related to our goal modelling.

Our work has so far been limited to a single case study. We now need to apply it to more complex cases, whether they are whole aircraft or other products such as satellites. This might allow us to generalise a method which starts from high level goals and systematically introduces a mitigating actor like the global design team.

Future work could also focus on the structure of this new actor, the global designers. Multidisciplinary teams of experts in fields such as architecture, manufacturing, procurement and sales have recently proposed work on similar issues in their respective industries [9]. Moreover, it is not easy to get people with different skills and areas of expertise to work together. The work on *tiers-lieu* could be an approach to the implementation of such a team [21].

Finally, with regards to manufacturing in particular, further work could seek to integrate elements of the value chain beyond the basic assembly objectives to consider the whole assembly system [5].

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