THE ROLE OF MULTIDISCIPLINARY DESIGN OPTIMIZATION (MDO) IN THE DEVELOPMENT PROCESS OF COMPLEX ENGINEERING PRODUCTS

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Abstract

The work presented in this paper explores several concepts related to the design of complex engineering products and emphasizes on the effects of considering Multidisciplinary Design Optimization (MDO) in the development process. This paper is by no means a comprehensive literature review, but instead, the aim is to discuss some key points through theory and references to common MDO applications. In this respect, the central topics which are addressed herein are the enhancement of the generic product development process, the road towards a better integration of the organization's functions, the methods to manage complex system architectures, and finally, the shortcomings of the MDO field. As a link to more tangible industrial applications, Unmanned Aerial Vehicles (UAVs) are chosen as an illustrative example due to their technical complexity as well as the demanding requirements of the corresponding market. Overall, the paper shows that despite the current state-of-the-art limitations, MDO can be a valuable tool within the "traditional" design process that has the potential to enable products of better quality while simultaneously reducing the total development time and effort.

Keywords: Design methods, Design process, Optimisation, New product development, Multidisciplinary Design Optimization

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1 INTRODUCTION

Over the past decades, the development of complex engineering products has experienced an accelerated growth, while at the same time the struggle for economic success among the involved actors has increased the competition to a whole new level. In this environment of uncertainty and risk, companies are continuously faced with new challenges, and as a direct consequence, they are inevitably forced to enhance their conventional design processes with more systematic tools but also more efficient development methods. To no surprise, the ultimate goal is, and has always been, to be able to produce better and more profitable products which can primarily increase the market share of the organization and in turn secure its strategic advantage over the competition. Overall, the financial success of the firm is still in the centre of its vision, and for that reason, innovation, faster idea-to-market times, better quality, and lower costs are all critical concepts that should hold a significant position in every contemporary Product Development Process (PDP).

A very common approach as a first step towards the improvement of the PDP with many successful applications has proven to be the adaptation of a structured methodology for mapping the various anticipated management, production, and product design stages. This kind of engineering practice has been over the years advocated by many authors, and some of the most notable results show that its implementation can reduce the required development time but also enable a higher level of product quality (Ulrich and Eppinger, 2012). Some key and elementary points of the aforementioned methodology are according to Cooper (1990) the introduction of a so-called “stage-gate” system, the integration of the different activities within the organization, the change to a more adaptive organizational format, and the swift towards a more iterative as well as flexible development process. In total, it can be argued that the final outlook of the chosen PDP will ultimately depend on both the specifications of the product but also the company's strategic visions, while nowadays, a wide range of conceptual tools and knowledge-based methods are available to the designers in order to help them enhance all possible aspects and variations of the process (Cooper, 2014).

Multidisciplinary Design Optimization (MDO) is a method that has the potential to increase the knowledge of the design early on in the development process. In a nutshell, it can be said that MDO is about the concurrent consideration of various engineering disciplines under a common framework in order to explore the design trade-offs by using numerical optimization. MDO has been frequently applied in the conceptual design phase of many complex engineering products, and two central prerequisites for its successful implementation are the accurate modelling of the disciplines and their robust integration in a common framework. Commonly expected outcomes from the implementation of MDO in a development process are the supplementary knowledge on each possible product configuration and the quantification of several performance metrics regarding one or more requirements of the design (Agte et al., 2010). On the whole, it has been shown that MDO can support the decision making process both at the early as well as the later stages of the PDP, while as an activity, it can help accelerate the total realization time of the product and promote better communication between the involved organizational functions (Simpson and Martins, 2011).

A representative case-study that is considered in this paper and can illustrate the advantages of applying MDO within the PDP is the design of Unmanned Aerial Vehicles (UAVs). Compared to fighter and passenger aircraft which are similarly complex engineering products, UAVs are currently in high demand by both the military as well as the commercial domain and therefore have the unique characteristic of being developed at a very fast pace but also in significantly larger quantities. The global market is indicative of this situation, and in fact, it is expected that the total number of operational UAVs will increase five times by the year 2030, while at the same time it is estimated that the unmanned operations will eventually surpass those of manned aircraft (Volpe, 2013). In addition to this, the design of UAVs is inherently prone to further critical development challenges, and indeed, it can be argued that it is highly depended on the dynamic nature of the end customer demands, the product family and commonality restrictions, and the uncharted uncertainties induced by the environment and the operator. Apart from that, the system architecture of UAVs is comprised of several sub-systems with complex interactions that are typically difficult to accurately map, and as a direct result, the development of successful designs becomes a complicated task where the organization should allocate substantial human resources, implement the latest technology, and apply the most efficient state-of-the-art design tools.

In light of the above, the present paper emphasizes primarily on one central research theme which is namely the role and placement of MDO within the "traditional" PDP with particular focus and parallel references to its effect on the design of UAVs. On the whole, the main focus is to explore how MDO can be integrated with the rest of the development activities that are commonly defined in engineering design, and what would be its ultimate impact towards the organization as well as the final product. In total, four principal topics are addressed herein, and it is shown that MDO is at present a valuable enhancement method for all stages of a generic PDP (section 3); it conveys a strong incentive towards a better integration of the various organizational functions (section 4); it provides significant assistance and useful insights regarding the design of products with complex architectures (section 5); and lastly, it possesses great potential to enable further improvements on the design quality as well as the efficiency of the process (section 6). Overall, the paper is comprised of 7 sections with the introduction and the UAV design particulars being the first two, followed by a discussion of each main topic (sections 3 to 6), and finally concluding with some general comments in section 7.

2 DESIGN CHALLENGES OF UNMANNED AERIAL VEHICLES

Like many other complex engineering products, the development of UAVs starts with the "planning" activities where the customer requirements are initially quantified, and ends after the design has been tested and a production scheme has been established (see Figure 1). Once the essential characteristics (e.g. surveillance performance, operational effectiveness) have been identified, the process moves forward and enters the design stages where the product must be gradually refined from an abstract concept to a more detailed engineering drawing. To no surprise, there are different demands depending on the design stage, and the paradox is that in the beginning there are several possibilities but incomplete information, while conversely, in the later phases there is sufficient knowledge but limited freedom to make the necessary changes (Ulrich and Eppinger, 2012).

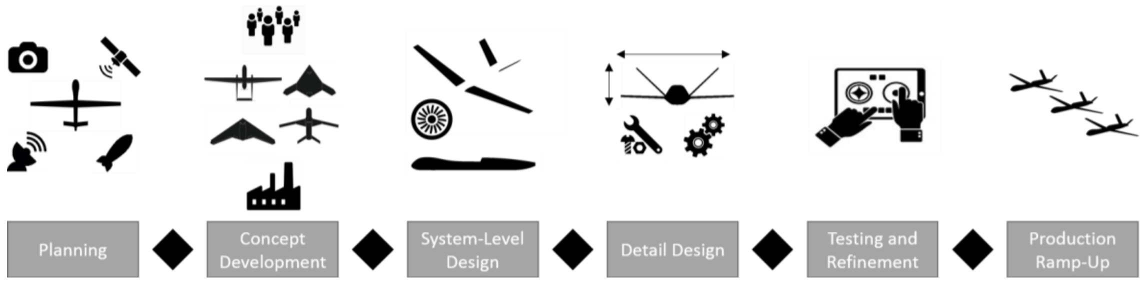

Figure 1. An example of a PDP for UAV design, adapted from Ulrich and Eppinger (2012)

The primary challenge in the concept development stage is to be able to quickly explore several airframe configurations in order to find the optimum layout (e.g. high aspect ratio or delta wing) that meets with the specified target requirements. Here, it is crucial to perform this process as efficiently as possible, while at the same time, it is undoubtedly beneficial to consider all the available inputs like for instance the behaviour of the on board systems, the marketing of the product, and the production possibilities. Once the alternatives have been narrowed down, then the different components can be designed in more detail, and hence, it becomes increasingly important to include more accurate disciplinary analyses in order to capture the operation of each system and the key interactions. As a result, domain-specific work and experts are often required to develop individual elements such as the wing as well as the fuselage structures, while it is also vital to understand the critical dependencies, like for example the wing aero-elasticity or the coupling between engine and mission performance.

3 AN ENHANCED GENERIC PRODUCT DEVELOPMENT PROCESS

In a nutshell, a well-defined development process is essential for the conception, design, and commercialization of new products, while it has been shown in many instances that its implementation can enable higher end-quality, increased coordination among the teams, better planning of the overall project, and continuous improvement of the entire life-cycle (Cooper, 1990). One elementary example of this generic process layout can be according to Ulrich and Eppinger (2012) divided in six principal phases (see Figure 1) which in most cases includes several sub-activities and requires the simultaneous collaboration of different departments of the organization (see Figure 2).

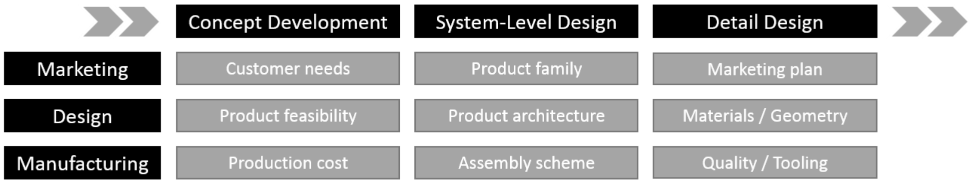

Figure 2. An example of departmental sub-activities for different development stages

Starting with the "concept development" (Ulrich and Eppinger, 2012) or “preliminary assessment” (Cooper, 1990) phase, MDO can help increase the knowledge especially in the area of design and subsequently enable better decision making regarding the feasibility of the product. The main reason is that this part of the process is generally characterized by increased uncertainty, and there is also a vast number of potential solutions for the same problem which have to be screened in a fast, but yet reliable, way. Product quality is naturally, and as always, of utmost importance for the organization, and as a result, complex engineering products must be ideally addressed in a multidisciplinary way in order to ensure that all the engineering disciplines as well as the marketing and manufacturing inputs are concurrently taken into account.

In this respect, MDO appears as a suitable tool for especially the "concept selection" as it offers the possibility to quickly explore the underlying trade-offs between the competing design objectives, and hence, it enables the team to make better judgements before the next gate. A good example of the above MDO contribution can be traced in the work of Amadori et al. (2006) as well as Jeon et al. (2007) where the authors developed a framework for the design of UAVs that included simple models for the geometry, aerodynamics, structures, stability, and performance (see Figure 3). In the former, the authors conducted three optimization test runs with different settings which on an average required less than 30 minutes, while in the latter it was shown that even faster evaluation times can be achieved with approximation models. In total, both case-studies were able to quickly provide metrics on the design targets for each generated configuration, but also to assist in the identification of the most suitable concepts which were clearly the "best suited" to fulfil the predefined mission.

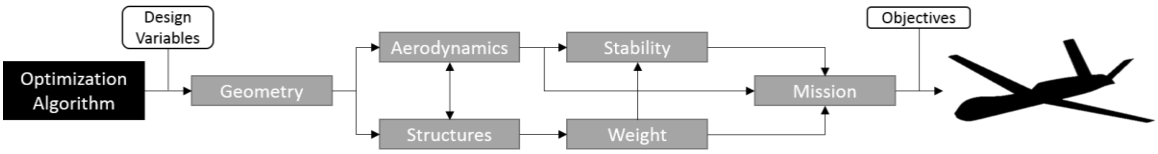

Figure 3. An example of the typical disciplines in MDO frameworks for conceptual UAV design according to the work of Amadori et al. (2006) as well as Jeon et al. (2007)

In addition to this, an activity which also starts in the "concept development" phase and can be further enhanced by MDO is the process of prototyping both in its physical as well as its virtual form. In particular, MDO can support the development of fast prototypes by either including this discipline directly in the optimization process or provide a working basis for early simulation prototypes through the reuse of the Computer Aided Design (CAD) as well as Computer Aided Engineering (CAE) models. As a representative example of the former case, Ceruti et al. (2011) developed an optimization framework that included a special model for considering the interactions between geometry and hot-wire manufacturing, which consequently lead to optimized configurations that also took the feasibility of this construction method into consideration. In a similar manner, Amadori et al. (2010) used MDO in order to correctly select and place components on a Micro Aerial Vehicle (MAV), and then, by coupling the results with additive manufacturing techniques they were able to obtain flyable physical prototypes which they could use to collect information from flight testing.

Apart from the above, a number of case-studies have also addressed the "system-level" design phase where it has been shown that MDO can take into account the interaction of several sub-systems in order to offer a holistic view of the system's performance. The work of Allison et al. (2012) is typical of this category, and in fact, it was shown that designs of increased quality can be obtained if supplementary models for capturing the effects of the propulsion system, on-board systems, and Radar Cross Section (RCS) are added to the "traditional" conceptual design framework. On the same note, Perez et al. (2006) presented a framework that included the flight control system in a MDO study and showed that this systems engineering approach can bring higher freedom to the design, but also enable the full exploitation of an efficient control configuration even earlier in the system definition process.

Finally, the implementation of MDO expands in the later phases of the development process as well, and indeed, it can be an effective method for refining the design even after the concept and the system architecture have been established. To illustrate this, Rajagopal and Ganguli (2009) developed a framework with high fidelity models for optimizing the airfoil as well as the planform of a UAV wing and therefore managed to capture the design trade-offs of the conflicting objectives with high detail and accuracy. Choi et al. (2010) also followed a multi-fidelity approach, but instead, they focused more on the optimization of the entire vehicle and not just one sub-system. In this work, the authors validated their analysis results against real data, and showed that the increased fidelity can be a valuable assistance since it can provide more reliable values which are a critical factor when determining the outcome of the decision making process.

4 ACHIEVING INTEGRATION OF THE ORGANIZATION'S FUNCTIONS

The concept of integrating the various development processes has been frequently stressed in the referenced literature and it has been shown that it is a critical organizational function towards enabling more competitive products at lower costs (Andreasen and Hein, 1987). The problem herein is that over the course of time companies tend to grow larger, which leads to a division of duties as well as departmentalization that in turn reduces communication and hence affects the success of the developed products (see Figure 4). Through proper integration, product development activities become both professional and efficient which is one of the fundamental factors that can secure the economic survival and competitiveness of the organization (Cooper, 2014). The most common methods to improve integration within the organization are also versatile, and according to Griffin and Hauser (1996) they often include organizational structural changes, personnel as well as facilities management, and mapping of the development approach in an even more strict structure.

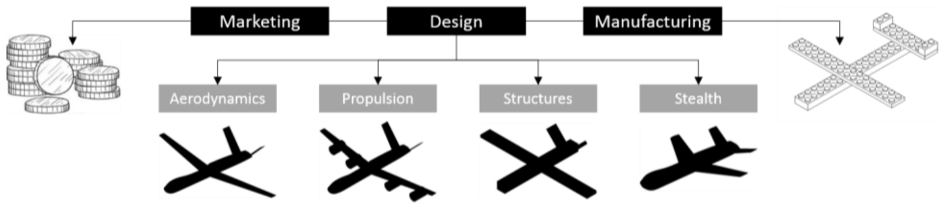

Figure 4. An example of organizational departmentalization in the development of UAVs

Nevertheless, achieving proper integration becomes a complicated task, and therefore, the conventional enhancement practices might not always be adequate enough to enable proper communication and safeguard the quality of the product. In particular, it is possible to bring the groups within a department together by changing the location of the facilities and the layout of the offices, but it is not always possible to bring all the departments of the company together. This is especially true in large UAV corporations where the marketing, the production, and the design can be in different and in some cases international locations or not even owed by the same firm. Furthermore, changing the organization structure to a more project-based layout might be able to give additional support to the each project, but it will eventually lead to some loss of competencies that in aircraft design can be of critical importance. Lastly, mapping the development process with more details may be a solution that can increase collaboration, however, this requires time and planning well in advance which is not always a possibility in a fast-paced development environment like that of UAV products.

Apart from the benefits in terms of accelerating the development process, it can be argued that MDO can also be a valuable tool which can indirectly increase collaboration and consequently lead to a better integration of the various organizational activities (Simpson and Martins, 2011). The main motivation for this is that successful MDO requires experts from all engineering disciplines, all functional departments, and all levels of the company to work together in order to develop a framework which will eventually enable the exploration of the design space (Safavi et al., 2012, 2015). Overall, the disciplinary models should be able to "talk to each other" which means that the different organizational groups can no longer work in isolation, but instead, they have to strive for increased collaboration in order to reach the central goal of the project. According to Simpson and Martins (2011), this new requirement allows the members within every group (even at the lowest hierarchy levels) to see the “big picture”, and hence, it creates increased awareness which then leads to products of better quality and reduces the back-and-forth iterations within the process.

An example of how this integration can be achieved in the design of a complex product with MDO was presented by Safavi et al. (2012) where it was argued that the development of specialized disciplinary models should not be the work of only one engineer, but it should be a collaborative effort of experts. In this case-study, the authors explored the interactions between four engineering discipline experts during the optimization of aerial vehicles and concluded that this approach could achieve better results both in terms of computational accuracy (augmented modelling competencies), but also in terms of efficient framework integration (better model interfaces). In addition to this, integration can also consider different functions of the organization like marketing, and in fact, this can be seen in the case-study of Thokala et al. (2012) who enhanced the "traditional" design MDO framework with two additional models for estimating the cost and the survivability of each configuration. In this way, the authors were able to make early and accurate predictions about the acquisition and operating costs, while simultaneously they managed to investigate how the input from a purely marketing factor like the customer demands (equipment options) could ultimately drive the design.
As far as the effect of MDO on the integration among the different management levels of the company is concerned, it can be argued that it is an advantageous addition which can bring people from all the hierarchies of the organization closer. More specifically, MDO requires some coordination among the involved teams, and as a direct consequence, even the higher levels (i.e. the project leaders) are now interested and have a direct input to the work of the lower level groups (i.e. the discipline experts). The main reason is, of course, to ensure that the models and the framework can handle the expected and desired inputs, but at the same time information is indirectly flowing among the different layers of the organization which thus leads to better knowledge of the product design. Accordingly, this knowledge is manifested in the higher levels as an indication of what is possible and what not, while in the lower levels it is perceived in terms of what the ultimate “objective” behind every task is.

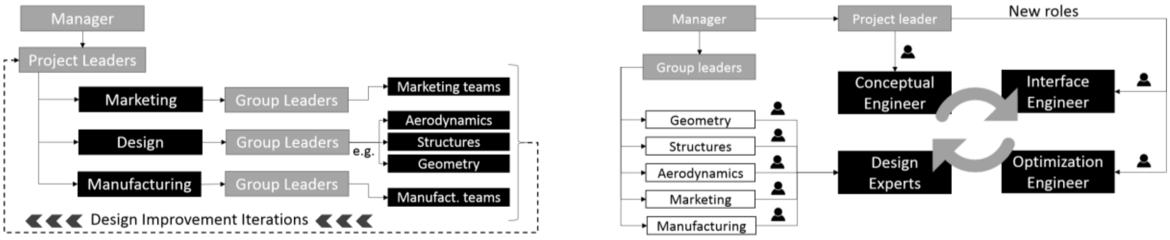

Figure 5. Left: A "traditional" project structure adapted from Andreasen and Hein (1987); Right: The functional roles for MDO implementation adapted from Safavi et al. (2015)

A representative case-study which delves into the organizational changes that are required for successful MDO employment by considering and evaluating the element of interdisciplinary collaboration was presented by Safavi et al. (2015). In this work, the authors focused on the identification of the different functional roles that typically occur in a MDO environment and concluded that the conceptual engineers are not always able to address the increased responsibilities without external and specialized help. Hence, they documented the most important activities that can lead to better integration, and created an application roadmap that included people from all levels and departments of the company in order to enable MDO with more expert models at even earlier phases of the development process. The four main roles which were established by this work can be seen in Figure 5 on the right, while it was further stressed that support and collaboration between the top and lower management levels is also an important and critical prerequisite for achieving a truly functional integration. Compared to the "traditional" management system defined by Andreasen and Hein (1987) (see Figure 5 left), the whole process is now aimed towards a more efficient organizational layout (see Figure 5 right) where the project leader can have a better control over the resources, share technical and marketing expertise, work with more apt cross-functional teams, and lastly, have members that are dedicated and give maximum effort to the project.

5 MANAGING COMPLEX SYSTEM ARCHITECTURES

The development of simple products within a generic PDP may be a relatively straight-forward task both in terms of integration and process management, but it becomes a highly complicated activity when complex systems like for instance UAVs must be decomposed in order to achieve a functional design. In general, systems engineering is a set of management activities that verifies possible technical solutions in order to satisfy a set of customer needs. Moreover, it is an iterative process of top-down synthesis, development, and operation that aims to solve the given problem in an interdisciplinary and socio-technical approach while considering the entire life-cycle of the product (Haskins et al., 2006). Development is usually done in distinct phases starting from a concept idea and progressively moving towards the entire system description as well as the sub-system selection. On a general level, the main responsibilities during systems engineering include to be able to balance factors such as the cost of the project, the scheduling of the development activities, the quality of the delivered product, the possible future operating changes, and the financial risk for the company (Crawley et al., 2004).

Given the above definitions, it is easy to argue that MDO can be a valuable tool throughout the entire systems engineering process, and in particular, it can provide several important functions that are desired in complex system architectures (see Figure 6). First, by modelling all aspects of the system and exploring the design space it offers a supplementary understanding of the underlying behaviour that each sub-system demonstrates. Second, it is easier to design the complete system since the development team is fully aware of how the desired performance can be reached but also which are the potential undesirable effects. Third, by considering uncertainty in the framework, possible future changes, as well as the impact of a varying environment and operator, it is easy to map the entire or at least a large part of the expected product life-cycle.

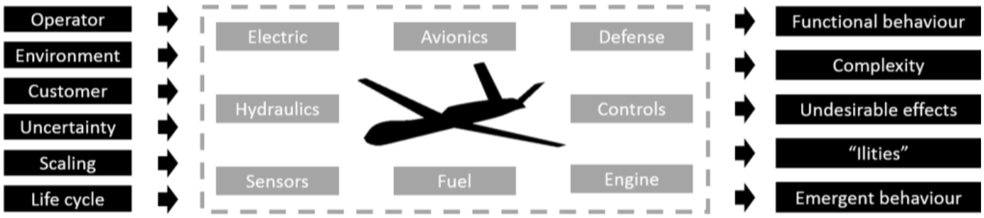

Figure 6. A MDO system engineering approach for UAV design

In this respect, Krus and Ölvander (2003) pointed out that there are several levels in a systems engineering process ranging from requirements analysis to detail design and argued that a successful PDP should "permeate" all layers in order to provide a holistic view of the total system. They further stressed that this can only be achieved if all the design teams work towards a common system model, but also on the condition that there is a suitable computational environment where all the sub-systems and the whole aircraft interactions can be simultaneously studied. To exemplify the above, they considered a flight dynamics model coupled to the control surfaces, and by performing numerical optimization they managed to show that this can enhance the performance of the aircraft in turns while concurrently reducing the total weight of the actuation system.

Apart from the delivery of the basic functions, the architecture should also ensure that additional properties called "ilities" such as robustness, adaptability, flexibility, scalability, and safety are also delivered (Crawley et al., 2004). By using the example of a UAV system, it is easy to understand that except from the basic function of flying, it should also possess other attributes like performing in a variety of missions, be able to adapt to the environment, undergo changes with ease, be free of accidents, and maintain the desired properties within a reasonable scaling range. With this in mind, MDO can be adjusted in order to capture those supplementary modelling properties, and in turn steer the system design towards the optimum performance by knowing what is both possible and probable to happen. In the current state of practice, this is typically done by considering uncertainty inputs or more elaborate simulation models, while it can be seen that research is on-going with the main focus being on how the "traditional" frameworks can be improved to include more features. As an example, Gavel et al. (2008) described how probabilistic analysis can be used in the conceptual design phase of an aircraft fuel system, and they showed that by adding uncertainty in an optimization study it is possible to explore the entire range of a system behaviour instead of just one or more "worst case scenarios" as it has been traditionally the case.

Finally, the design of complex engineering systems is not entirely about developing a technical system in isolation, but the customer needs and its marketing should also be taken into account (Simpson and Martins, 2011). One good example is often the creation of a product family which should not come as an "after though", but instead, it should be integrated early on in the development process (Jiao et al., 2007). According to the same authors, designing families of products can be seen as an increased development complexity, which inevitably requires both a front-end (customer, functional, physical) as well as a back-end (production, logistics) support. Consequently, in its capacity as an integration tool, MDO can also enhance this process by delivering at an initial stage some preliminary configurability and scalability information as well as metrics regarding the modularity and commonality of each proposed solution. To illustrate the above, Tarkian et al. (2011) argued that the trade-offs between product performance and product family should be carefully balanced in order for the company to meet the market requirements and obtain an "economy" of scale. Thus, in their work they studied platform and commonality characteristics under the same framework and showed that MDO can help engineers gather more knowledge on the scalability of the design, and accordingly, take more critical decisions at a much earlier stage in the development process.

6 TOWARDS PROCESS IMPROVEMENT AND FUTURE POSSIBILITIES

Adaptation to changes and striving for improvement in the modelling as well as management of the design process are two critical elements for the advancement of the product development field. The traditional process may be well suited for traditional products, which are often the majority, but more innovative and bolder projects tend to rely more on uncharted technology and address increasingly riskier markets (Ulrich and Eppinger, 2012). Consequently, those projects are faced with a number of new challenges, and therefore, require the implementation of more efficient tools in order to render the process more “adaptive”, “accelerated”, and “agile” (Cooper, 2014).

Despite the fact that MDO has many advantages to offer as a tool within the development process, the current state of research and practice are still very limited, and in fact, it can be seen that the industry is very reluctant to adopt it as a standard method (Simpson and Martins, 2011). As an example, the same authors give several reasons for this, which generally point to a shortage in technical publications, problems in bringing the research teams together, educational and knowledge transmission barriers, lack of proper modelling tools, and finally, a tendency on behalf of the management to adhere to conventional development tools and methods (see Figure 7). At the same time, Agte et al. (2010) stress that the possibilities of MDO in the initial design phases are numerous, and they argue that those can be projected in two orthogonal directions with the vertical being about including entirely new features, while the horizontal about improving the existing ones (see Figure 7).

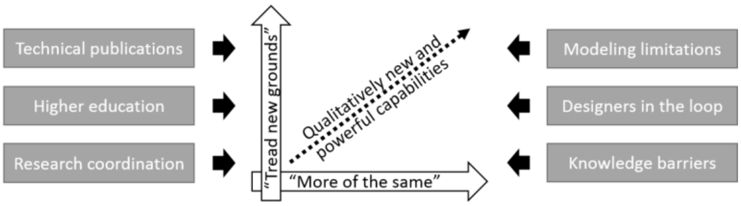

Figure 7. The improvement directions of MDO adapted from Agte et al. (2010)

As far as the modelling of the processes in the design of UAVs is concerned, it can be especially argued that MDO is still very elementary in terms of what is usually modelled. Figure 3 is a good example of what is typically included in common UAV case-studies, whereas Figure 6 shows how much different the ideal MDO for a complex system should be. In general, the more features and fidelity the MDO method has to offer, the better are the chances for a more reliable employment like for example in early concept selection phases (Safavi et al., 2015). The latter point is especially critical since one of the primary concerns regarding the use of MDO is currently the quality of the calculations and how the optimization process can become more efficient in order to be used even earlier in the design (Simpson and Martins, 2011). Overall, everything is about enabling additional knowledge over most aspects of the design, which can help shorten the stage times, and subsequently reduce the total number of iterations within the process.

A representative example of the above can be found in the work of Papageorgiou et al. (2016) where the authors considered both directions of MDO enhancements, and therefore, developed a framework for UAV design in which they worked towards the improvement of the existing functions but also studied the effect of including entirely new features. More specifically, it was shown that the consideration of supplementary models for the estimation of the radar signature and sensor performance can assist in the evaluation of the sub-systems' operation against the total aircraft performance, while at the same time, a metamodeling methodology was proposed in order to enable the use of reliable results from the high-fidelity analyses as early as possible in the development process. In addition to this, the framework

included the novel feature of a trajectory analysis, and hence, it was possible to show that this extra factor can affect the final outlook of the optimal design, but also to demonstrate that it is possible to include the customer preferences through the use of an explicit three-dimensional mission profile as an input to the process.
Nevertheless, MDO would never be completely integrated in the traditional PDP unless the right mind-set towards its application is adopted by the management and its "unconventional" methods are embraced by the engineers (Agte et al., 2010). Clearly, replacing the entire development process is an impossible task, while relying solely on MDO can also lead to unsuccessful products because industrial design as well as human intuition are still a large part of the process (Simpson and Martins, 2011). Thus, the most critical element is to make the engineering teams understand that MDO is not there to replace them, but it is a means to make the decision making tasks easier and in turn the PDP better and faster. In this respect, it is often stressed that there is a lack of education which also needs to be addressed both in academic institutions but also internally within the company. Given the simulation, modelling, and hardware advancements, MDO possibilities are going to grow larger in the near future, and hence, organizations should be adequately prepared to adopt them in their activities.

7 CONCLUSIONS

To sum up, it can be argued that MDO can find several possible uses within all phases of a generic development process and it has been shown in many case-studies that it can provide additional information on the target requirements and better overall knowledge on the design. Hence, this enables designers to make faster and more supported decisions earlier in the development cycle, which in turn can accelerate the overall process and enable better product quality.
One of the most important benefits of using MDO is that the organization can achieve better integration of the marketing, design, and manufacturing departments, and in this way, allow engineers from all groups and sub-groups to see the "big picture". By helping the teams which work at the lower levels of the hierarchy understand the objectives more clearly, the communication becomes better, there is a coordination of data as well as information, and most importantly, every task is performed at a better quality because there is knowledge of what is expected by the higher level management.
Moreover, it can be said that the use of MDO tools can help design even more complicated system architectures, manage the complexity more efficiently, and include the marketing inputs in the design loop. Due to the concurrent way of addressing the problem early on in the process, it is easy to see the dependencies of the system modules, identify the undesirable behaviours, estimate the correlation to the market desires, capture the risk factors, and get an overview of the system's complexity.
Finally, like every other method, MDO comes with several limitations which prohibit its full implementation and raise several challenges for future improvements. The most notable examples are the lack of adequate modelling and simulation techniques, shortage of publications with explicit technical information, restriction in the sharing of industrial information, and reluctance on behalf of the company's management to adopt it. Consequently, it is important that research should move towards modelling new features that can capture the entire process, but also towards improving the existing ones in order to enable faster evaluation times and more accurate calculations.
Overall, it should become clear that MDO is definitely not a replacement of the conventional development activities, but instead, it should be treated as a support tool which can increase the available knowledge holistically and provide engineers with more information on the design during all stages of the process.

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