Development and Implementation of a Methodological Approach to Support MDO by Means of Knowledge based Technologies

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1 STAGE OF THE RESEARCH

The research started in mid-October 2013 with an introduction into the European Community project "iProd" (iProd Integrated Management of product heterogeneous data - FP7 project of the European Community, Grant agreement no. 257657). Over the course of the first year, the research has focused on project work and becoming accustomed to the tools and methods of the current state of the art within multi-disciplinary design optimization (MDO) and knowledge engineering. Currently, an initial MDO-advisory system is under development, coupled to an MDO architecture design system, with the end-goal in mind to formalize MDO knowledge to achieve automation and a lower accessibility level. This first concept is under development together with two other PhD candidates at the department of Flight Performance and Propulsion, R.E.C. van Dijk and D. Steenhuizen.

2 OUTLINE OF OBJECTIVES

Although the concept of MDO is not new at all, the discipline is not yet fully exploited. For industrial applications, this seems a missed chance to improve product quality and cut design cycle time and cost. The reasons are the currently not addressed intrinsic complexity of MDO problems and the mathematical background, as well as the lack in awareness and understanding of MDO architectures. The main purpose of this PhD research is the development of an methodological approach, with knowledge based technologies to support MDO, and specifically address the two issues mentioned above. This will include the following objectives and sub-objectives:

- **Objective: Development of an MDO Knowledge Base**
  A knowledge base will be developed to capture, formalize and organize dispersed knowledge on MDO approaches and architectures, as well as guidelines concerning the applicability of certain MDO strategies to problems of different nature. Excellent surveys on MDO architectures and their performance evaluation are available in specialized literature such as Tedford and Martins (Tedford and Martins, 2010) and Perez et al. (Perez et al., 2004). Other MDO system knowledge will be obtained from the activities carried out in the iProd project.

- **Sub-objective: Development of an MDO Dedicated Ontology**
  Storing and structuring this type of knowledge will require the investigation of existing suitable ontologies and/or the development of an ontology dedicated to MDO. This will build on the work currently being finalized by R.E.C. van Dijk (PhD candidate) and the work within the iProd project. A categorization approach of different MDO architectures, as well as solving algorithms, exists in literature and will provide a suitable starting point.

- **Objective: Development of an MDO Advisory System**
  An MDO advisory system will be developed to enable the user i.e. an engineer who is not necessarily an MDO expert to describe the problem at hand, specify a number of selection criteria (accuracy, speed, etc.) and obtain in return (based on the knowledge stored in the knowledge base) a ranked list of suitable MDO architectures, with (links to) relative documentation, and a template to support its implementation.

- **Sub-objective: Implementation of Interactive MDO Architecture Design**
  The MDO advisory system will also provide some interactive design capabilities of MDO architectures, allowing the user to define in an intuitive and interactive way his own MDO

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strategy, either from scratch or based on available templates (MDO architecture meta-model).

- **Objective: Develop MDO Work-flow Instantiations for Assembled MDO Architectures**
  Finally, capabilities will be developed to translate (hence automate all the software intensive operations) the selected or assembled MDO architecture, into an MDO work-flow instantiation by means of a commercial work-flow management system such as, for example, Optimus by Noesis or the open source framework RCE, developed by DLR.

3 RESEARCH PROBLEM

Multidisciplinary Design Optimization can provide designers with the methods to further improve the performance of already mature solutions, and to support the exploration of innovative complex engineering products. The best design of a complex system can only be found when the interactions between the systems disciplines are fully considered (Tedford and Martins, 2010). MDO provides the structured approach and the mathematical formulations to capture such interactions.

Although the very first MDO implementations have been presented about 50 years ago, at date, the discipline is not yet fully exploited at industrial level, apart from limited application (Agte et al., 2010). This seems a missed chance to improve product quality and cut design cycle time and cost. Some of the reasons for the limited exploitation of MDO in industry (in contrast with the growing interest and body of knowledge being developed in academia) can be found in the following:

1. Lack of adequately flexible, accurate and robust parametric models to support MDO using high-fidelity simulations.
2. Limited availability of computation resources to solve complex problems of industrial interest.
3. Intrinsic complexity of the MDO discipline and its mathematical foundations.
4. Lack in awareness and understanding of the many available MDO architectures and their specific suitability to problems of different nature.

Advances in knowledge-based parametric CAD (Computer Aided Design) modeling, e.g. KBE (Knowledge Based Engineering) applications (La Rocca, 2012), and robust pre-processing tools to support high-fidelity analysis seem to successfully address the first issue. This PhD research will demonstrate the benefit of deploying KBE applications to support some knowledge intensive engineering process, as defined in the EC project iProd.

3.1 Flexible Problem Formulation

In multidisciplinary design optimization (MDO), the problem definition is considered fixed. I.e. the problem formulation in terms of the number of design variables is not flexible. However, in true engineering design optimization problems, the engineer continuously varies the product model, thereby also altering the mathematical problem description. Agte, et al. (Agte et al., 2010) presented an assessment and the direction for advancement of MDO in their paper summarizing the 2006 European U.S. Multidisciplinary Optimization Colloquium in Göttingen, Germany. While discussing vertical growth of MDO, described by the authors as treading new grounds, the issue of implementing creativity, cognition and flexibility to MDO is raised. Not only allowing for requirements to change over time, but also the possibility of adding design variables, and thereby adding new dimensions to the design space, is considered an important, though difficult direction for future research. As Agte, et al. (Agte et al., 2010) note: Generalization of the very concept of the design space to enable qualitative transformation of that space by adding, refining, and removing design variables simultaneously with the numerical search would simulate what to a competent designer comes naturally and apparently is one of the intrinsic capabilities of the human mind. In other words, allowing the optimization to adapt the problem formulation and design variables itself will mimic the way the human mind works when solving design problems. For optimization, e.g. using a genetic algorithm, this would mean that every iteration, or design mutation, has to consider a redefinition of the design space and at the same time let the mathematical model of the optimization manifest this redefinition (Agte et al., 2010). These topology variations have an influence on the optimization problem, and have to be taken into account. Implying specific knowledge of the mathematical problem formulation and its attributes of the problem at hand. A feat that is not necessarily applicable to engineering optimization problems, which are often complex, highly non-linear and may involve changes in the problem definition.

Flexible problem formulation in MDO is also addressed by Welle, et al. (Welle et al., 2012) who claim that no current MDO literature addresses flexible problem formulation. Though focusing on Architecture, Engineering and Construction (AEC), the intrinsic problem is similar for any discipline. Welle, et al. (Welle et al., 2012) achieve to link the product model to the CAD model, allowing changes to be made to the attributes of the product model. Their example relates to the design of a building with 4 walls and 10 windows per wall, changing attributes of either one window or the windows on one side of the building or all windows individually. As Welle, et al. (Welle et al., 2012) indicate; design decisions are made upstream of any analysis modules, requiring flexible problem formulation in terms of the product model, in contrast to conventional MDO where flexible problem formulation relates to flexibility in problem formulation construction in terms of the ability to employ various optimization algorithms or the sequencing of optimization algorithms. However, Welle, et al. (Welle et al., 2012) provide only limited flexibility to the product model (and mathematical problem definition), as only the attributes of the windows can change, yet the construction of the building remains unchanged. A fully flexible problem formulation would also allow the building to change, as the engineer, in his creative design phase, may consider a building with either more, or fewer walls and varying the amount of windows per wall. This requires a higher level of flexibility in problem formulation and dynamic definition of slaves in a master-slave MDO set-up. I.e. slaves can exist in one branch of the optimization, but may not exist for another branch of the optimization.

Also Amadori et al. (Amadori et al., 2012) present a certain form of problem flexibility their MDO problems. Their use of High Level CAD templates is similar to the High-level Primitives as described by La Rocca and Van Tooren (La Rocca and van Tooren, 2007). However, the implementation of flexible problem formulation for these CAD templates is limited to a first optimization where only morphological changes are allowed and a second run where only the topology of an optimized morphology (geometry) is allowed to change.

3.2 Knowledge based Technologies

Implementing creativity, cognition and flexibility in MDO, requires a flexible optimization work-flow environment that can reconsider and reformulate the design problem at hand and adapt the optimization architecture accordingly. Referring to the aforementioned issues 3 and 4, the intrinsic complexity of MDO and its mathematical foundation as well as the lack in awareness and understanding of the many available MDO architecture makes the implementation difficult. This is where a methodological approach through knowledge based technologies can help.

Through the formalization of MDO knowledge, for example through a dedicated ontology, this knowledge can be made available for re-use and automatic implementation, also to engineers who are not MDO-experts. The stored and structured knowledge can be used to automatically implement an MDO work-flow, according to user inputs for the problem at hand. By also providing relevant documentation, or sources of documentation, the accessibility level of MDO is significantly lowered. The intrinsic complexity and mathematical background of MDO are thus not directly exposed to anyone implementing MDO and knowledge and understanding of all available architectures and their implementation and appropriateness is not required.

Also the implementation of KBE applications that automate repetitive, non-creative work and allow for rapid design iteration can boost the use and ease of implementation of MDO. These application also use captured design knowledge and rationale to automatically create geometric engineering designs, from high-level geometric primitives.

The combination of knowledge based technologies and these KBE applications can lower the accessibility level of MDO and increase its level of implementation in engineering product development.

4 STATE OF THE ART

4.1 Engineering Knowledge Management and Concurrent Engineering

The engineering of complex products, such as airplanes, automobiles or any kind of appliances is highly knowledge intensive and requires vast amounts of knowledge and data to be handled and managed in a very precise way. The whole product life cycle is built on an information model of the product with all its aspects and related processes. Information about the design and expertise, the know-how which resides in the knowledge workers is combined along the engineering process. The shortening timescales, widening geographic distribution and increasing complexity of the design task in all these aspects make the effective management of this know-how even more important, as observed by Wallace et al. (Wallace et al., 2005) and Scholl et al. (Scholl et al., 2004). The Concurrent Engineering (CE) approach was proposed as collaborative approach to support the development of products (e.g. as described by Clarkson and Eckert (Clarkson and Eckert, 2005)) to achieve faster, better, cheaper products. CE emphasizes the importance of frequent iterative interaction between traditionally separate functional teams.

This PhD research builds on the above by accessing and collecting the information and design expertise residing in engineering and making it available for (automated) reuse, through a knowledge base. The knowledge and information is formalized and stored.

4.2 Multi-Objective and Multi-Disciplinary Design Optimization

In the design process in highly networked and interdependent industrial contexts, such as the aeronautical industry, the effective design of components and systems and processes is essential for improving products cost-efficiency but requires the achievement of multiple and, often conflicting, objectives in presence of multiple and multi-criteria constraints. To accomplish such tasks, appropriate design optimization strategies using effective constraint-handling techniques must be carried out. In these procedures, updated design rules have to be developed to optimize product design in order to meet the more and more increasing requirements for performance, weight, survivability and cost reduction. Presently there are several methods to deal with such design problems. They can be roughly summarized into two categories:

1. Trial and error methodology (often referred to as heuristics), supported by engineering knowledge based on numerical simulations and/or experiments.
2. Computer-assisted optimization.

Trial and error methodology has been the standard design procedure in industry for a long time and still is regarded as very important. This is an experience based method that is used to reduce the need for calculations pertaining to general equipment size, performance, or operating conditions. Heuristics are therefore fallible and they do not guarantee an optimal solution although they may be of value because they offer time saving approximations in the preliminary design process. Examples of heuristics in aeronautics are almost uncountable: in particular, most of the experimental work for product development makes to some extent substantial use of it. On the other hand, the multidisciplinary nature of aeronautical engineering problems has led researchers to investigate formal optimization methods (i.e. featuring a solid mathematical basis alternative to heuristics) for the component design process. Sobieszczanski-Sobieski and Haftka (Sobieszczanski-Sobieski and Haftka, 1997) give a review of developments in multidisciplinary design optimization for aerospace problems and Giesing and Barthelemy (Giesing and Barthelemy, 1998) provide an industrial perspective of multidisciplinary optimization research. The common basis joining the works above is that considerable effort is spent building efficient optimization method coupled with numerical solvers (which led to the so-called computer-assisted optimization), particularly aerodynamic and aero-elastic ones. Computer-assisted optimization methods applied to aircraft are mainly of two types: gradient-based and non-gradient-based. Moreover, the theoretical approach to multi-objective optimization is somewhat weak in that multiple objectives are always resembled into one objective function using arbitrary weights. To some extend, computer-assisted optimization makes use of KBE applications to rapidly create and vary geometries according to a set of design rules. However, the implementation of KBE applications is still limited.

This research aims at going one step further and to develop a methodology for choosing the most applicable solver, optimization architecture and algorithm for the problem at hand. This will be done through an MDO advisory system, that suggests an MDO strategy and implementation to the engineer. Formalizing this knowledge can make MDO more accessible.

5 METHODOLOGY

To address the objectives stated in Section 2 and develop, and implement a methodological approach to support MDO by means of knowledge based technologies, the following top level tasks have been identified:

1. Review of the current state of art in the field of MDO (and supporting technologies, such as KBE, integration frameworks, etc.) and Knowledge Technologies (Knowledge bases, reasoning mechanisms, ontology engineering, etc.).
2. Definition of knowledge base(s) and ontologies to capture MDO architectures/strategies.
3. Development of an MDO advisory system to suggest suitable MDO strategies and support the definition and implementation of the actual MDO framework.
4. Verification and validation of the developed tools and methods.

The methodology of the research requires becoming accustomed with current tools and technologies used in the field of MDO and knowledge technologies, for example during the work performed in the iProd project. The actual basis for the framework, acting as an MDO advisory system, that is to be developed and implemented is a knowledge base, which is structured on an ontology and can capture MDO architectures and MDO problem descriptions. As such, this ontology will also be linked to an optimization ontology which is currently being developed in iProd. Using this semantic description for the knowledge base, a graph-database stored in Allegro Graph, it is possible to reason on this structured knowledge and the knowledge can be easily reused and extended. The development of such a framework consists partly of the development of an advisory system for multidisciplinary design optimization (MDO) that can enable the user to specify an MDO problem, suggest optimization strategy and algorithm and guide the user during the implementation of the suggested approach. The MDO advisory system that is to be developed, will enable any user, i.e. engineers who are not necessarily MDO experts, to describe the optimization problem and specify certain selection criteria. These selection criteria could e.g. be accuracy, speed, etcetera. In return, the system will provide a ranked list of suitable MDO architectures, based on the knowledge that is stored in the knowledge base. This also requires a specification of the mathematical problem formulation of the optimization problem at hand. Based on mathematical specifications, e.g. the type of design variables or the decomposition into coupled or non-coupled subproblems, the system will be able to return a list of MDO architectures that are most suitable to the specific problem. In addition to the ranked list of architecture (or strategies), (links to) related documentation will be provided. After selection of an architecture by the user, the advisory system will provide a template (from the knowledge base) that supports the implementation in simulation workflow management software. This interaction allows the user to still influence the optimization strategy to his desire, for example for user with more expert knowledge on MDO that are looking for a specific implementation. The interactive design capabilities of an MDO architecture allow the user to define, in an intuitive and interactive way, his own MDO strategy. This could be from scratch of based on the availabel templates (or MDO architecture metamodels). This “new” knowledge will then be added to the knowledge base for future use. The possibility to select a desired algorithm, which is part of an MDO strategy, from the ones stored in the knowledge base. The knowledge base will be structured through a dedicated MDO ontology. This ontology will contain the different MDO strategies and algorithms, structured and linked through the different classes, properties and restrictions. The development of an MDO Advisory System, implementing an an interactive MDO Architecture Design, building on the knowledge bases and reasoning mechanisms developed within the iProd project, is focusing on the following questions:

1. Can a methodological approach, to support MDO by means of knowledge based technologies, help non-MDO-experts in industry and academia in the implementation of MDO in engineering?
2. Can this methodology reduce the number of iterations and the time consumed for optimization and improve the designs of coupled KBE applications and analysis tools? (through workflow management software)
3. Can the design framework lower the accessibility level of MDO, allowing also non-experts and students to use proper and applicable MDO architectures and optimization algorithms in engineering optimization problems?

The developed methodologies and implementations will be tested on use cases from the different research projects, such as the Pininfarina and Fokker Aerostructures use cases from the iProd project, involving KBE applications and optimization. Validation will focus on achieving better solutions (in terms of design objectives) for the projects in equal or less time, or having similar solutions in the less time.

To summarize, an MDO advisory system will be developed that is able to suggest a suitable MDO strategy, based on the knowledge and rules that are collected from literature and projects, such as the iProd project. In addition, the choices made by users of this framework will be collected and stored for future research when implementing other MDO problems. The advisory systems will also be able to assist in the definition and implementation of the actual MDO framework and, where possible refer to relevant literature and information sources during the implementation of an MDO problem. The automatic work-flow instantiation of an assembled MDO architecture relates to the latest work within the group of Flight Performance and Propulsion, such as the new methodology for the development of simulation work-flows in the thesis of Chan (Chan, 2013).

6 EXPECTED OUTCOME

This PhD research will deliver a knowledge base, an MDO advisory system and an interactive MDO architecture designer system. These will enable - also non MDO experts - to find knowledge related to MDO system architecture, get advice on the most suitable method for the problem at hand, get assistance in the actual definition of a MDO architecture and finally obtain an MDO framework implementation that is ready for use, without the need to go through (all) the software specific operations required to operate the given MDO framework system (e.g. NOESIS Optimus). Figures 1 and 2 show the example interface for a first prototype of an MDO architecture design system.

Figure 1 shows that problem definition tab, where it is possible to specify the objective function, select design variables from the product tree, specify constraints and select the desired responses. These are all directly related to the KBE application that holds the parametric geometrical model to be optimized. This allows for the suggestion of e.g. design variables from the code of the KBE application, but also gives room to adapt the mathematical model interactively, which may also be constructed to be reflected in the code. The idea for this interactive approach and the variability is the flexible problem formulation. E.g. an actuator mechanism, where not only the size of actuator arms and location of actuation points and actuators is variable, but also the number of arms and actuation points. This means that the number of design variables is variable throughout the optimization and also that the product tree that is shown on the left, is variable.

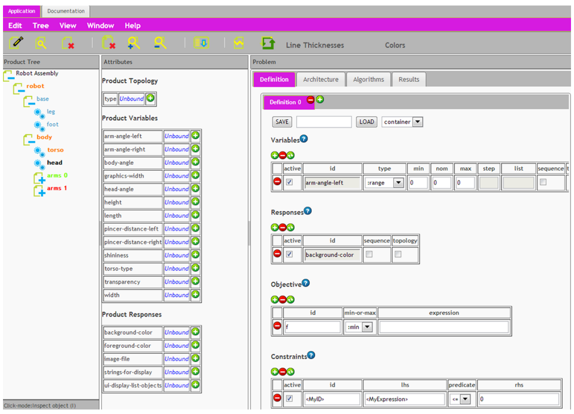

Figure 1: Example interface for the first prototype architecture design system, showing the problem definition tab. (©Van Dijk, Steenhuizen and Hoogreef, 2013).

Figure 2 shows the architecture design tab, where the flow through the problem architecture can be specified. Building on the problem description made in the previous tab, where the objective function and subproblems of the optimization can be specified, the design variables, desired outputs and constraints can be selected and the product structure (or topology) of the model to analysed, an optimization strategy is suggested. The user can then, interactively, relate inputs and outputs of the different modules (or subproblems) to each other, constructing a flow. This flow can later be translated to an actual simulation workflow in simalution workflow management software.

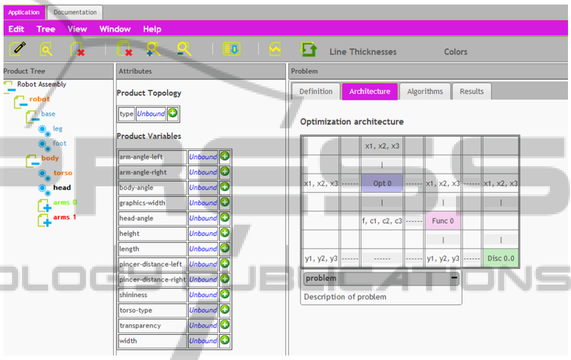

Figure 2: Example interface for the first prototype architecture design system, showing the architecture design tab. (©Van Dijk, Steenhuizen and Hoogreef, 2013).

The knowledge base will provide the functionalities to store also knowledge relative to business process, hence it will enable engineers to leverage their experience both in human-oriented tasks as well as in simulation and optimization work-flows. In this case the human-oriented tasks can provide the rationale behind a certain simulation or technical work-flow implementation.

While the proposed approach is innovative in nature and goes behind the state of the art (no MDO advisory systems are discussed in literature), it will leverage on the experience and demonstration tools developed by Delft University of Technology in iProd and other currently running research initiatives.

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