Multidisciplinary Design Optimization for Complex Engineered Systems: Report from a National Science Foundation Workshop

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ABSTRACT

Complex engineered systems are typically designed using a systems engineering framework that is showing its limitations. Multidisciplinary design optimization (MDO), which has evolved remarkably since its inception 25 years ago, offers alternatives to complement and enhance the systems engineering approach to help address the challenges inherent in the design of complex engineered systems. To gain insight into these challenges, a one-day workshop was organized that gathered 48 people from industry, academia, and government agencies. The goal was to examine MDO's current and future role in designing complex engineered systems. This paper summarizes the views of five distinguished speakers on the "state of the research" and discussions from an industry panel comprised of representatives from Boeing, Caterpillar, Ford, NASA Glenn Research Center, and United Technologies Research Center on the "state of the practice". Future research topics to advance MDO are also identified in five key areas: (1) modeling and the design space, (2) metrics, objectives, and requirements, (3) coupling in complex engineered systems, (4) dealing with uncertainty, and (5) people and workflow. Finally, five over-arching themes are offered to advance MDO practice. First, MDO researchers need to engage disciplines outside of engineering and target opportunities outside of their traditional application areas. Second, MDO problem formulations must evolve to encompass a wider range of design criteria. Third, effective strategies are needed to put designers "back in the loop" during MDO. Fourth, the MDO community needs to do a better job of publicizing its successes to improve the "buy in" that is needed to advance MDO in academia, industry, and government agencies. Fifth, students and practitioners need to be better educated on systems design, optimization, and MDO methods and tools along with their benefits and drawbacks.

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1. INTRODUCTION

Our nation's ability to develop and deploy complex engineered systems such as aircraft, automobiles, and space systems seems to be approaching a limit [1]. Many large-scale engineering development programs are fraught with exorbitant cost overruns and delays due to a combination of technical, organizational, and political issues. For example, Boeing's new 787 aircraft is two years late to the market due to scheduling and supply chain issues [2] and has already cost nearly $10 billion more than anticipated [3]. GM is back in operation after declaring bankruptcy, yet it still posted a $4.3 billion loss in the fourth quarter of 2009 [4]. Meanwhile, the cost of building its new Chevy Volt is approaching $40,000 per car, nearly double the initial estimates [5]. Finally, NASA is mired in schedule delays and by cost overruns associated with the International Space Station and the Constellation program due to politics as much as organizational and technical issues [6].

There is no question that systems have become more complex and therefore increasingly more difficult to design and manage [7,8]. Government agencies such as NSF and DARPA are among those taking up the challenge to address these problems, and are launching new research initiatives in complex systems design[3]. While a consensus on a universal definition of *complex engineered systems* has not yet been reached, a defining characteristic of these systems is the emergent behavior that current modeling and quantification methods fail to capture. This emergent behavior arises from couplings in the system that we often do not understand and cannot model effectively, if at all. Complex engineered systems also involve multiple disciplines, including disciplines that are still extremely difficult to quantify (e.g., disciplines involving human behavior) and integrate into mathematical models and optimization problems.

When research into Multidisciplinary Design Optimization (MDO) began 25 years ago, the intention was to address these challenges and, in particular, the coupling within design hierarchies and between disciplines [9,10]. MDO has evolved remarkably since then, and the focus of MDO has shifted dramatically, as new faculty and researchers are finding new ways to use MDO methods and tools on a wide array of problems [11,12]. There have been many advances to capture, represent, and propagate couplings in analysis, design, and even organizations, yet the design of complex engineered systems continues to be plagued by schedule delays and cost overruns. Consequently, many question the impact that MDO has had on industry and wonder what advances are needed to improve the design of complex engineered systems. With this in mind, a one-day workshop was organized to:

[3] For example, NSF Program Solicitation 09-610 (http://www.nsf.gov/pubs/2009/nsf09610/nsf09610.htm?org=NSF) and DARPA's META II Program (https://www.fbo.gov/spg/ODA/ DARPA/CMO/DARPA-BAA-10-59/listing.html).

1. Identify and document promising future directions for MDO and related research,
2. Articulate successful industrial implementations of MDO and identify the challenges with practical implementation of MDO methods and tools, and
3. Explore relationships between complex systems design initiatives and MDO.

The workshop immediately followed the *13th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, which celebrated the 25-year anniversary of MDO. The workshop drew a diverse group of participants from industry, academia, and government agencies. A total of 48 people attended, including 26 (56.5%) from academia, 12 (26.1%) from industry, and 8 (17.4%) from government agencies (e.g., NSF, NASA). This total also included 8 (17.4%) international participants from universities and companies in Canada, Turkey, Portugal, South Korea, and the United Kingdom.

The remainder of this paper is organized as follows. Section 2 summarizes the presentations of five distinguished speakers who shared their views on the "state of the research" in MDO in the first session of the workshop. Section 3 summarizes the "state of the practice" based on the industry panel that took place in the second session of the workshop. Breakout groups then identified future research topics in five key areas, as described in Section 4. Finally, recommendations to advance MDO and its use to support the design of complex engineered systems are offered in Section 5.

2. INVITED SPEAKERS: STATE OF THE RESEARCH

Five distinguished speakers were invited to present their views on the "state of the research" as part of the workshop.

1. Dr. Christina Bloebaum, Program Director, Engineering Design & Innovation, NSF
2. Dr. Jaroslaw Sobieski, Distinguished Research Associate, NASA Langley Research Center
3. Dr. Paul Collopy, Director, Value-Driven Design Institute
4. Dr. Tolga Kurtoglu, Research Scientist, Palo Alto Research Center
5. Dr. Soundar R. T. Kumara, Pearce Professor of Industrial Engineering, Pennsylvania State University

These speakers collectively span industry, academia, and government and have complementary, yet distinct, perspectives on MDO and the design of complex engineered systems. Bloebaum is widely known for her MDO research and is organizing a multi-agency effort to investigate the challenges of designing complex engineered systems. Sobieski is recognized by many as one of the founders of MDO and has contributed numerous advancements to the community through his work at NASA Langley. Collopy is an expert in value-drive design and has been leading several parallel workshops on designing complex engineered systems. Kurtoglu worked at NASA Ames prior to joining Palo Alto Research Center, and he is now working on DARPA's META program to improve the design of complex engineered systems. Finally, Kumara is widely known in the industrial engineering community for his research on distributed networks and his work on several DARPA projects involving large-scale complex systems. Summaries of each presentation follow. The presentation materials are available online at the workshop website: http:// mdolab.engin.umich.edu/NSF_Workshop_2010/About.html.

Bloebaum began by asking participants whether or not MDO has a future. Based on her observations and experiences both as a researcher in the field and now as a Program Director at NSF, she stated that MDO has become "everything to everyone" and that it has strayed far from its origins of understanding how one designs systems where "everything affects everything else". She asserted that the MDO community no longer appears to have a unifying vision to guide it and its research, which she said, "consists mostly of small perturbations on ideas generated 25 years ago when MDO originated". When MDO started, computing resources were extremely limited, which in turn inspired many of the proposed approaches for conducting MDO. Although computing power has increased dramatically in the past 25 years, many people are still trying to solve problems the same way. She challenged participants to redefine MDO and identify opportunities to help, for example, systems engineers address the design challenges they are facing. Many of these challenges are at the root of the problems plaguing complex engineered systems design.

To gain better insight into the origins of MDO, Sobieski shared his perspective on the state of MDO. He too noted that MDO originated as a "collection of algorithms for searching design space for a constrained minimum", which drew freely from Numerical Methods and Operations Research [10,13]. In return, MDO developed new methods for decomposition of the system design problems into its constituent parts (e.g., [11,14]), and for coordination among analyses and optimizations of these parts [15,16]. MDO also originated methods for sensitivity analysis of coupled systems [9,17,18] and numerous approaches for surrogate modeling [11,19]. As MDO itself evolved, it moved into diverse applications and contributed new methods for dealing with uncertainty and probability during systems design. Meanwhile, he noted that MDO algorithms to search the design space matured, migrated into commercial systems (e.g., Excel, Matlab, DOT [20], ModelCenter [21], iSight [22]), and now find widespread use in many companies. To confirm this, Sobieski reported finding over 1 million hits on Google when he searched for optimization applications in aerospace, spacecraft, space trajectory, and automotive industries; however, he found that this was only about 13% of the total activity that was occurring in industry (i.e., about 7 million hits were from areas other than these four). Thus, he concluded that MDO is missing out on opportunities in areas such as manufacturing, health care, transportation, marketing, telecommunications, financial services, and energy. Only by broadening MDO's scope can the research community hope to amplify these efforts.

While there are still many opportunities to improve MDO search algorithms, Sobieski stated that optimization takes up a relatively small fraction of time in the development of a project—analysis still consumes the majority of resources. He argued that large gains could still be obtained by processing data concurrently through improvements in decomposition methods, surrogate modeling techniques, and taking advantage of advances in multi-processor computers, field-programmable gate arrays, and graphical processing units. However, he added a caveat in that inter-processor communication will limit the parallel adaption of many legacy codes that are still widely used today. In view of this, he noted that codes that now take several hours to run could be executed in fractions of a second, provided they are redeveloped and tailored to massively multiprocessor computers, thus rendering MDO qualitatively different. He also argued that MDO could provide the core infrastructure for engineering design and development of complex engineered systems (see Figure 1), but he stated that more research and development is needed to integrate engineering models with manufacturing and fabrication models, which still tend to be separate in many organizations. The benefit, however, would be unprecedented design agility within an organization, allowing it to return upstream to act on new information unimpeded by the cost of the already sunk effort. In closing, he argued for a new paradigm that can expand the design space and not just be reductionist in nature. MDO needs to break out of its "gilded cage", he said, and find ways to help conceive new designs, not just search the design space defined by the user. He cited topology optimization as a good example in that it often produces shapes that surprise designers and mentioned that MDO needs to find ways to work in the function space so that it will help find innovative solutions like those often found in nature.

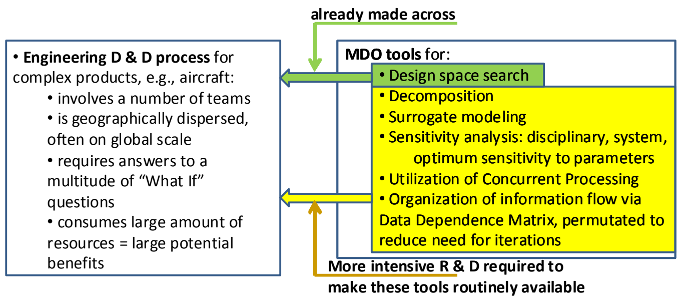


Figure 1. Potential for MDO in engineering design & development (D&D) process [23]

After Sobieski's talk, Collopy summarized the companion NSF-sponsored workshop, "Design of Large-Scale Complex Systems," that preceded the *13th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*. His workshop was a follow-up to a workshop held at NSF in February 2010 [8]. Collopy discussed the challenges in the design of large-scale complex engineered systems, focusing mainly on the issues that arise within the hierarchical approach and requirements flow-down process that most companies use to design such systems. During his workshop, participants divided into two groups to debate the advantages and disadvantages of using requirements in the flow-down process versus using objective functions. Examples are illustrated in Figure 2. On the left, requirements for thrust, fuel burn, and maintainability are shown as they are typically "flowed down" in a design hierarchy. On the right, objective functions for weight, lift, cost, and reliability are flowed down instead, to provide more flexibility to designers. To further complicate matters, this hierarchy goes many layers deep (e.g., 8-12 layers) for large-scale complex engineered systems. The result is that it is very difficult for engineers working at the lowest levels to see the "big picture" and understand how their decisions impact everything else.

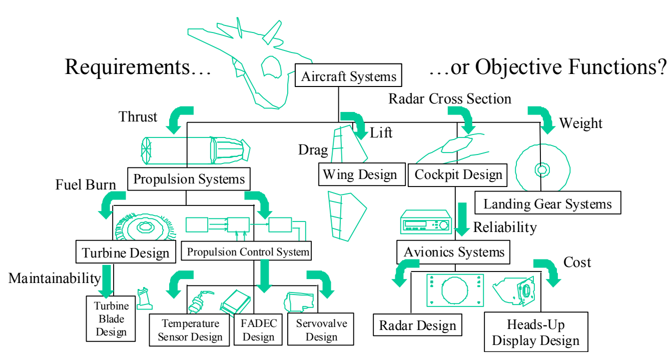


Figure 2. Example of requirements (left) versus objective function (right) flow down [24]

Based on the debate and discussion at that workshop, a list of topics was generated to guide research in the design of large-scale complex engineered systems. The top four were:

1. Modeling the behavior of teams deep in the hierarchy of a large-scale complex system;
2. Exploring how the flow-down of objective functions impacts outcomes through a combination of scholarly research, case studies, controlled studies, and modeling;
3. Investigating hybrid approaches that combine requirements and objective functions; and
4. Examining the relations of large-scale complex systems to chaos theory and connections with systems of systems.

Additional research questions dealt with handling changing requirements, working with incomplete models, coordinating work in small groups, and understanding the role of team size, location, and culture in complex systems design. The complete list of questions can be found in Collopy's slides, and they will be detailed further in his report to the NSF.

Kurtoglu discussed ongoing research addressing many of the same questions raised in Collopy's talk. Funded by DARPA's META Program, Kurtoglu is part of a team that seeks to revolutionize methods for design and verification of complex engineered systems. Their work follows several seedling projects performed by UTRC that were presented at the conference [7,25,26,27] prior to the workshop. Kurtoglu discussed a novel model-based approach to systems engineering that aims to eliminate most hardware-in-the loop testing for verification. Their objective is to introduce an enabling suite of automated design tools to manage design complexity. Specifically, they want to compress design and verification timelines for complex cyber-physical systems by reducing delay-inducing design issues and by accelerating redesign. The proposed ARRoW (Adaptive, Reflective, Robust Workflow) approach entails three threads of investigation:

1. Model-based qualitative and quantitative analysis that tolerates abstraction imperfection by providing a "design look ahead" capability early in the design process,
2. Model-based diagnosis that identifies design flaws in order to direct redesign, and
3. Probabilistic verification for computing certificates of correctness based on given set of design requirements.

ARRoW will interlace these three workflow threads to allow for the continuous design, testing, and diagnosis of a complete system through progressively more concrete abstraction layers.

Kurtoglu explained how ARRoW will ultimately offer a unique multi-level hierarchy of design abstractions, a qualitative reasoning engine for "design look ahead", metrics for assessment of dynamic design complexity and adaptability, model-based diagnosis for design flaw analysis, model integration and an accompanying Meta design-language, and finally, probabilistic verification for issuance of design "Certificate of Correctness". The key to the proposed approach is a qualitative reasoning engine that will enable the tractable construction of exhaustive behavior traces, which will create the scaffolding necessary to incrementally and efficiently derive probabilistic certificates of correctness. There were several questions from participants about the ability to enumerate all possible behaviors and whether qualitative reasoning would live up to its promise. Regardless, the proposed approach will also be used to compute practical measures of complexity based on dynamic behaviors. Metrics for design complexity, robustness, and adaptability will be developed at varying levels of abstraction to address the full range of lifecycle uncertainties (e.g., requirements creep, design space complexity, structural complexity, behavior complexity, development complexity). Kurtoglu emphasized that the new approach will assist designers in selecting components and subsystems that achieve optimal performance, while also being able to tradeoff complexity and adaptability during the design of complex engineered systems.

Finally, Kumara shared his views on ways in which research in complex systems and networks could support MDO in the design of complex engineered systems. In his talk, he focused on three important aspects of complex systems: (1) modeling, (2) information, and (3) interactions. For modeling, he discussed work involving multi-agent systems to support product design decision-making, and as an example, he referenced work by Kroo [28,29] that explored the use of multi-agent systems to perform distributed optimal control of a blended-wing-body concept. In terms of information, he likened design synthesis to a query retrieval process and suggested looking at recent research in web services composition for potential synergies [30]. While web services were developed with business services in mind, they could find use in identifying and linking disparate disciplinary codes that are geographically distributed within an organization or supply chain. Kumara also reviewed work in social network analysis and network theory to help study the interactions in complex systems and in their design processes. Network theory and analysis has been used in early MDO research, leading to novel approaches to system and task decomposition based on Design Structure Matrices [31]. This work is now finding applications in product design (e.g., modularity analysis [32], product development tasks [33,34], and change propagation [35]), and the work holds promise for MDO and complex engineered systems design as well.

3. INDUSTRY PANEL: STATE OF THE PRACTICE

3.1. Summary of Panelists' Opening Remarks

The industry panel consisted of five practitioners who were asked to discuss (i) an example of a successful application of MDO in their company and (ii) the challenges their company has faced implementing MDO. Dr. Evin Cramer (Technical Fellow, Boeing) opened the panel by stating that people are the most important resource within an organization, yet no one is an expert in everything. Therefore, teams of people are necessary to have expertise in different areas. Likewise, no single "tool" can be used to solve every problem; it is important to apply the right tool to the right problem at the right time. Understanding both of these aspects during the design of complex engineered systems is important and has led to MDO becoming a "state of mind" within their organization. She said that despite the shift in thinking, MDO still relies on a solid foundation (e.g., aerodynamics, structures, weights, noise), but it now supports multiple needs and plays multiple roles within their organization. She conveyed this using Figure 3, which shows how the processes and tools must be matched to the level of analysis and fidelity, and be used in the right trade space at the appropriate program milestone. With this capability, MDO has become valuable in industry due to its ability to integrate, automate, and explore trade spaces. However, she said that there still is room for improvement. Cramer emphasized two areas that need more attention: (1) optimization and (2) multi-fidelity modeling. For optimization, she stressed research in problem formulation, process steps, mixed integer nonlinear programming, and multi-objective programming. For multi-fidelity modeling, she said that many issues are still not well understood (e.g., getting the right fidelity for the right application, mixing and matching models at different levels of fidelity, and using several multi-fidelity models at once) and that the methods are not yet mature to the point of being "commoditized", making industry hesitant to adopt them.

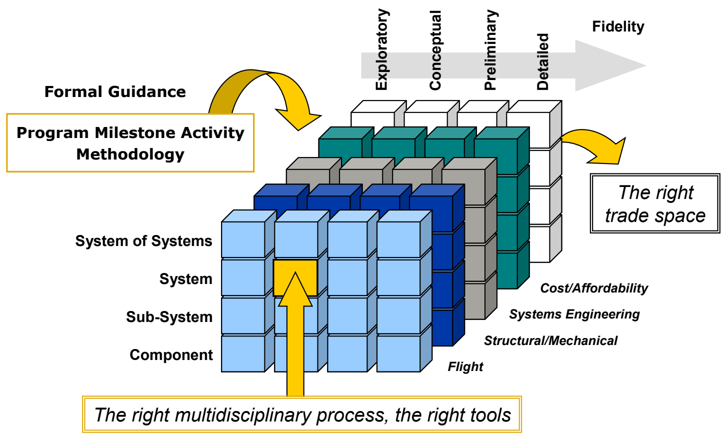
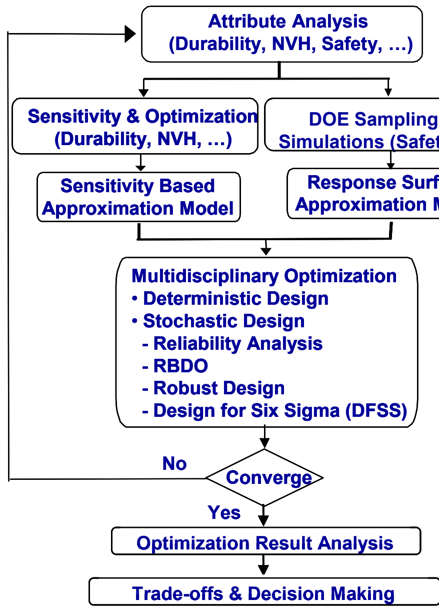


Figure 3. Selecting the right tool for the right problem at the right time [36]

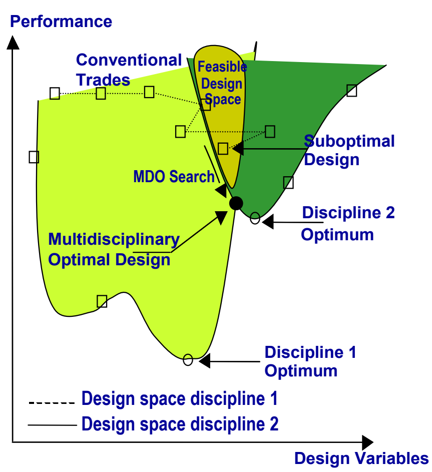
In contrast to Boeing, which has been using MDO since it emerged as a field, Dr. Julian Norato (Product Development & Global Technology, Caterpillar) discussed the challenges of a more recent adoption of MDO. The use of MDO at Caterpillar is being driven by three primary needs: (1) customer business needs such as productivity and operating cost, (2) emissions regulations that are compressing development schedules and increasing weight due to added after-treatment technology, and (3) costs, such those related to manufacturing processes and materials. Adoption began in the early 2000s and has mirrored the evolution of the field of MDO itself. For example, application of MDO went from a single discipline (i.e., structures) to multiple disciplines and domains (e.g., hydraulics, transmissions, engines, manufacturing), problem formulations have evolved from single objective to multi-objective, and expertise is shifting from a specialized group of individuals to a wide user base with well-documented guidelines. MDO appears to be quickly on its way to becoming a "state of mind" at Caterpillar, like Cramer described it at Boeing. Today, MDO has demonstrated tangible and realized benefits (e.g., cost and weight savings, improved performance), and MDO practice within Caterpillar is moving from after-design improvements to design exploration for product development. Nonetheless, many challenges remain, particularly because some of the MDO problems and needs are specific to their applications. Because of this, they are not only using off-the-shelf MDO tools (e.g., iSight) but also performing research and development of MDO methods and tools tailored to their needs. One of these major challenges is the lack of MDO methodologies that can cope with changing needs during product development (e.g., varying design spaces and constraints) and that can incorporate engineers "in the loop" for feedback. Another major need is the ability to incorporate Design for "X" (e.g., manufacturing, serviceability) into MDO. While in the long-term they would like to automate as much as possible of the MDO process from the beginning to the end of development, he believes that a more realistic short-term goal is to develop MDO methodologies that incorporate engineer-in-the-loop feedback—an issue raised by several other panelists.

Dr. Ren-Jye Yang (Senior Tech Leader, Optimization & Robustness, Ford Motor Company) described several automotive applications of MDO. In the automotive industry, Yang said that MDO problems are typically characterized as being large-scale and multi-physics, requiring multiple models and simulation codes, having large numbers of design variables (continuous and discrete) and constraints, having highly nonlinear responses, and having computationally intensive high-fidelity models (e.g., a crash simulation). Vehicle disciplines are coupled through common design variables and entail analyses related to weight, safety, NVH (noise, vibration, and harshness), body structure, chassis and vehicle durability, vehicle dynamics, and thermal and aerodynamics systems engineering and climate control. The elements of the MDO process that he advocates are summarized in Figure 4a, while Figure 4b depicts how MDO benefits the design space search. To illustrate this approach, he gave an example of using MDO at the vehicle level to minimize the weight of a truck body employing their new tailor-rolled blank technology.

Despite its maturity and demonstrated value in vehicle development, MDO still faces several challenges according to Yang. Legacy tools, solvers, and scripts are still routinely employed, and there are challenges in synchronizing people, processes, models, naming convention, and objectives. Scaling these methods companywide also remains an issue. In closing, he articulated opportunities for MDO research to improve both software (e.g., integration, automation, licensing, collaboration, visualization, and decision-making) and hardware (e.g., high performance computing, networking, and data storage, which now ranges between 1-3TB of data per program). He also called for the improvement of MDO tools in order to facilitate collaboration between multiple departments within a large and geographically-distributed organization.



(a) Elements of the MDO process



(b) Notional depiction of the benefits of MDO

Figure 4. MDO usage in the automotive industry [37]

Dr. Rubén Del Rosario (Fundamental Aeronautics, NASA Glenn Research Center) summarized the MDO research that is being conducted under the subsonic fixed wing project that he is leading. He stated that fuel efficiency, emissions, and noise were the three main drivers for future aircraft, and that the end result will necessitate a high level of integration within a vehicle's capabilities (e.g., active control aerodynamics, propulsion airframe integration, aeroacoustics, aeroelastic-lightweight structures, advanced cycle aeropropulsion). This will require advances in MDO tools to predict the performance of unconventional vehicle configurations. Given these challenges, MDO is unquestionably important to the aerospace community. Del Rosario provided several applications of successful COTS (common-off-the-shelf) MDO frameworks, as well as new analysis tools that had been developed. In particular, he reviewed the status of NASA's OpenMDAO software, which is an open source project. Readers are referred to the OpenMDAO website (http://openmdao.org) and the paper by Gray, et al. [38] for more details. In closing, he stressed how important advanced MDO tools are to address the environmental challenges facing the aviation industry (e.g., to help assess future "game changes") and strong research partnerships between industry, academia, and government agencies to accomplish this.

Finally, Dr. Ritesh Khire (Senior Research Engineer, United Technologies Research Center) focused his talk on the challenges of using MDO to design large-scale energy efficient systems. While several of UTRC's aerospace business units (e.g., Pratt & Whitney, Sikorsky) are already well-versed in MDO, the use of MDO in UTRC's power solutions (e.g., Carrier, UTC Power, Otis) and building systems (e.g., UTC Fire & Security) units is much more nascent. Integrated building systems are a natural application for MDO, as they need scalable and robust design methods to achieve energy efficient solutions. To highlight the challenges they face, he gave an example of a micro-grid application within distributed power systems (see Figure 5).

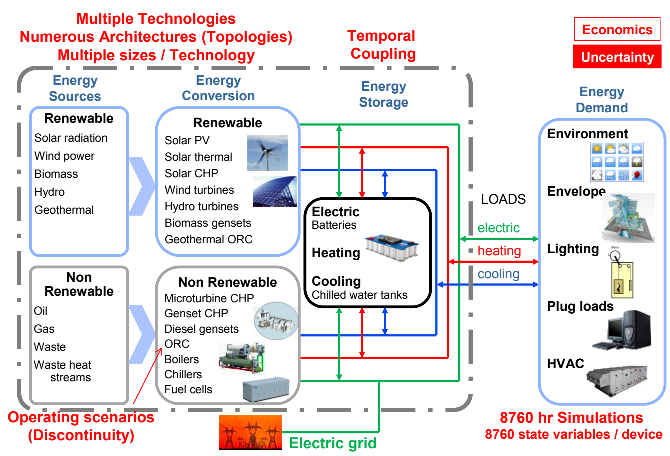


Figure 5. MDO challenges in micro-grid design [39]

As shown in Figure 5, micro-grid design involves selecting multiple technologies that can be integrated into countless arrangements of architectures (i.e., topologies) that must be then sized and optimized for numerous loading conditions. Current simulations typically optimize each device for every hour for every day in a year (i.e., simulate system performance for 8,760 hours) in order to take into account different loading conditions and demand levels. The temporal coupling and uncertainty in the models makes this all the more challenging, not to mention that different operating scenarios introduce discontinuities into the design space. As a result, he stated that more research is needed to down-select promising architectures and quickly eliminate infeasible combinations of technology. He also stressed more research on the solution of large-scale optimization problems with mixed discrete, continuous, and categorical variables, and on the integration of gradient and non-gradient based optimization algorithms.

3.2. Summary of Panelists' Discussion

After all the presentations by the industry panel members, a discussion session was held where participants were invited to ask questions to the whole panel or to a particular member. Most of the discussion gravitated towards either education or MDO software tools.

On the topic of education, a participant asked if 25 years of education in optimization methods and tools have had any effect on company managers. Several panelists responded to this noting that if a program uses MDO and is a success, then management will allow other programs to use it. However, MDO does not seem to be well understood managers in industry, as pointed out by Cramer, who returned to her analogy of complex engineered systems design as an orchestra in need of a "good conductor". The need for someone that coordinates the whole design process does not seem to be very much in the minds of managers, yet the coordination role of the conductor in the design process has never been more important than it is today. MDO has been valuable in this coordination process because it forces engineers to think about the interactions between the disciplines and highlight features of the system that may not have been noticed before.

In order to broaden the use of MDO in industry, increased funding and bringing people from different disciplines together were viewed as critical. Institutionalizing the MDO process and making it part of the company culture (e.g., a "state of mind") was another point that was raised. The need to include more MDO methods and tools in the undergraduate curriculum was stressed by many panelists to enable this. On a related note, when panelists were asked, "What do you want to be able to do? What capability, no matter how wild, do you want?", Cramer immediately replied "smart, creative coworkers". However, it was also argued that education "beats the creativity out of people in the current system". Thus, there is a need for universities to be aware of how their curricula align with this need for creative graduates.

The needs of MDO software tools were also discussed at length. Several MDO software and optimization packages are readily available (e.g., DOT, ModelCenter, iSIGHT) and have been successful in industry. Companies are becoming more aware of them; however, some see these tools and think that MDO and optimization are easy to do, which is a mistake. It is important to have experts that are well-versed in the proper use of these tools to ensure they are applied correctly. Others wanted tools that both experts and non-experts can use. All agreed that MDO tools should not replace designers, but they should empower them instead. As such, MDO should be used to support human decision-making and exploring new design spaces, and one panelist wanted an MDO tool that incorporated human thought into the process. Finally, several panelists also stressed the need for effective MDO tools to tackle large-scale discontinuous and discrete problems.

In terms of supporting MDO software tool development, panelists were asked about the best balance of research funding in terms of return on investment: should this research be done internally, via university collaborations, or by other companies? Many panelists stated that internal development is always needed to some extent, but the question remains: "Who will maintain it?" Off-the-shelf solutions do not usually do everything that is required, and vendors do not usually listen to one company. A solution might be to collaborate with universities to create flexible and state-of-the-art algorithms complete with source code that can be adapted to specific company needs in the future. Finally, product customization was also discussed briefly, and whether or not it was a good trend in MDO. From UTRC's perspective, all buildings are different, and there is not much commonality; so, the answer was definitely yes. From Boeing's perspective, the question is whether—and more importantly how much—customers are willing to pay for that customization.

4. BREAKOUT GROUPS AND FUTURE RESEARCH

During the speaker presentations and panel discussion, participants were given Post-It® Notes to write down questions or important points that they wanted to discuss further. These comments were then collected and sorted into groups. Five distinct topics emerged:

1. Modeling and the Design Space
2. Metrics, Objectives, and Requirements
3. Coupling in Complex Engineered Systems
4. Dealing with Uncertainty
5. People and Workflow

Breakout groups were organized around these five topics, and participants self-selected their discussion topic. A summary of each breakout group's discussion follows.

4.1. Modeling and the Design Space

This group presented a number of ideas related to modeling, the design space, and the interaction between the two. The first of these related to evolving the model and problem formulation during the design process. In the conventional design optimization process, the model of the given system and the design variables are decided in the problem formulation phase, and they remain fixed throughout the optimization. Allowing the model to be changed, changing the set of design variables, or both, would allow new regions of the design space to be explored and might lead to better designs. The issue is which strategy in the evolution of the design variables, model, or both should be used to achieve this. This has been partially addressed by research on multi-fidelity optimization and variable parameterization [40,41], but more research is needed in this area to increase the flexibility in MDO methods and tools to identify truly novel solutions.

The topic of emergent behavior was also discussed extensively. Emergent behavior arises from couplings in the system that are unknown and cannot modeled effectively. Determining how to model and the unexpected coupling behavior due to emergence remains an open area of research that has many implications for complex engineered systems design. MDO was originally developed to address the couplings between disciplines [9], and it has the mathematical underpinnings to support these interactions provided they can be captured, represented, and propagated through the system.

The importance of keeping humans "in the loop" was emphasized repeatedly in the discussion. The reasons for this are the role human creativity, which has still no synthetic replacement, and the ability to eliminate unrealistic designs rapidly. For MDO, it was stressed that a team was necessary, due to the fact that people invariably specialize in a single discipline and must therefore work as a team to achieve multidisciplinary objectives. Finally, engineering systems are becoming so complex that they are beyond the comprehension of a single engineer, and design convergence can become an issue depending on how the team is organized.

Managing the design space was also discussed at length. Ways of managing all possible combinations of choices for designs are needed. It was suggested that managing the process using "smart filters" might be a possibility, but more work is needed to clarify this idea. The inclusion of humans "in the loop" would also help the process by, for example, quickly eliminating impractical design variables. Another suggestion during the question period was to include the ability to cluster the design space for designs that are qualitatively similar.

A final topic addressed the fact that sometimes one does not know exactly what the objective function should be. Inverse design of an airfoil is an example of this: the engineer knows what pressure distribution is desirable and uses numerical optimization to obtain the shape that yields that distribution, instead of maximizing the lift to drag ratio, for example. This is why Pareto fronts are often generated, e.g., there are multiple objectives that are important or design freedom should be maintained for later decisions. Echoing the importance of appropriate objective functions was the suggestion to incorporate manufacturing and system lifecycle models into MDO.

4.2. Metrics, Objectives, and Requirements

The first point addressed by this group was the need to use MDO to develop a rigorous systems engineering framework. This needs to be based on a mathematical formulation to coordinate the interaction between thousands of design groups typically involved in large-scale complex engineered systems design. The group suggested a bottom-up approach that would start with fundamentals and build up to the system level.

To describe a complex engineered system, it must be able to be quantified using, for example, axiomatic measures of complexity, flexibility, reconfigurability, and adaptability. The flexibility of reconfiguring a system could be managed to take advantage of (and accommodate for) emerging behavior. Additionally, such metrics need to undergo more rigorous testing to ensure not only their validity, but also their usefulness in MDO. Testing of metrics through research case study problems, interviews, and examination of past designs was suggested as a possible avenue of work.

Decomposing system requirements has various challenges, including handling the coupled nature of the many requirements and understanding how to allocate requirements to different disciplines. Clearly establishing what are requirements and what are objectives was considered to be very important during complex engineered systems design. In 5 to 10 years, the group would like MDO to help allocate and negotiate both requirements and objectives between subsystems and components in a complex engineered system effectively. Leveraging ideas from the companion workshop discussed in Section 3.1, the group suggested that MDO may move toward a value-based approach and be developed so that it is sufficiently robust to handle the variety of organizational structures found in companies. Ensuring that designers were effectively “in the loop” would also help determine appropriate tradeoffs at all stages of the process.

A broader view of MDO in problem formulation was also deemed necessary. The current view of an MDO problem as a large nonlinear program has become obsolete, and a more flexible model is needed that lends itself well to industry practice. To achieve this, researchers must first understand what engineers want out of MDO and what the customer needs are to ensure that they will be satisfied with the output. The process would benefit from integrating designers "in the loop" through, for example, visualization and design steering tools, which was also emphasized by the first breakout group. Having designers "in the loop" would create a paradigm shift that might enable such MDO tools to deal with emergent behaviors as they occur and result in a broader impact in engineering education.

During the ensuing question period, a participant made the point that the more coupled the problem is, the less effective a hierarchy becomes. An alternate approach would be to treat the different modules as agents, thus removing much of the complexity. Another participant suggested that aspect oriented-programming, an emerging new programming paradigm in computer science, might be able to help tackle some of these challenges. Finally, the question of whether requirements and objectives can go "beyond math" and be more qualitative in nature was raised. They can, but the issue is whether this can be done with a strong theoretical foundation. In this context, someone suggested that MDO should include psychological factors, thus broadening the scope of both the work and the researchers involved in the MDO community.

4.3. Coupling in Complex Engineered Systems

This group challenged the audience to envision a system capable of full-scale MDO for a large-scale complex engineered system in the next 5-10 years. The MDO system would be flexible so as to be capable of creating new computation sequences and connections between computational modules. It would also be developed so that both the modules and framework managing the modules are reusable in different applications. A component-based approach seems to be essential to address these challenges. Components must be developed from the start with interactions in mind. One of the keys for this to happen is a programming culture where multidisciplinary considerations are the default. Hence, emphasizing MDO as part of engineering education would help. In order to implement this component-based approach, a formal interface design with well-defined and well-designed input and output objects that adhere to certain standards is necessary, as well as thorough documentation. The design of the interfaces between the modules was deemed extremely important and several examples of failures and successes due to this issue were discussed.

Well-designed interfaces between components in an appropriate framework have the potential to fulfill the vision of a system capable of performing MDO of complex engineered systems through next-generation MDO architectures. This would be possible if the connections between components were easily restructured and also allowed for the nested structuring that might be required for multi-level, multi-fidelity MDO of complex engineered systems. This point was previously alluded to by other focus groups as well. Inherent in this is the importance of significant computational power. In spite of the ever-increasing power of computing platforms, the complexity of engineered systems has also increased dramatically [42], and the expectation of what MDO should do for complex engineered systems design requires efficient computation via high performance computing and massive parallel machines. Many emphasized this as an important area of future research.

Finally, some more specific needs for component interactions were discussed. For example, in the case of engineering systems that required a geometric model, the need for a consistent geometric description that can be accessed by any other component that depends on it was emphasized. The geometric representation for models of differing fidelity is particularly challenging. For the near term, the group suggested that engineers need a more explicit education on interdisciplinary interaction and well-designed interfaces between computational components. A solid basis in interfacing already exists in the computer science community, which some MDO researchers are starting to leverage.

4.4. Dealing with Uncertainty

Uncertainty is inherent in complex engineered systems and there is no way to avoid it. Thus, researchers have confronted uncertainty by developing the mathematical foundations to quantify it and optimize systems subject to uncertainty. During the design of complex engineered systems, uncertainty is present in the models, the interdisciplinary interfaces, the requirements, and the operating conditions. The fact that multiple designers and engineering disciplines are involved in the process further adds to the overall uncertainty. A participant noted that the design process itself is uncertain, not just the inputs and outputs of a model, and there is a need to look at these uncertainties as well. Uncertainty also evolves over time, as requirements change and constraints are relaxed or tightened. Ultimately, to make a design decision, one must first decide what is “better” in the context of uncertainty, and a number of ideas were discussed: robustness, reliability, safety, and durability. Risk reduction was suggested as another alternative, i.e., by dealing with uncertainty, one is reducing the risk in the system. All of these objectives depend strongly on uncertainty.

The design problem formulation for a complex engineered system is particularly challenging. There are often multiple objectives that are important, and priorities for each objective will shift within a design hierarchy. Problem formulations also evolve as new insights are gained or new information becomes available. Hence, there is a need for a rigorous, self-consistent theory that underpins the formulation of the decision process for problems subject to uncertainty. Dealing with requirements and constraints in such situations remains a challenge, especially when uncertainty is being taken into consideration. There are many open research questions to develop a theory that is general enough for widespread use and adoption. Finding a way of assessing the different modules in a complex engineered system and then studying the implications of using decomposition-based approaches to design the system was offered as an initial path of investigation.

The recurring issue of education was raised, namely, the need for a widespread education of industry, practitioners, and students (both at the undergraduate and graduate levels). As an example of this need, engineers in industry often talk about uncertainty without translating it into mathematical quantities. In order to manage uncertainty, metrics to quantify uncertainty in a meaningful way for engineers are needed. .

Estimating reliability accurately is another challenge in this field. Sampling to estimate probabilities is computationally demanding, but it has in some cases been addressed with the use of high-performance parallel computing. New algorithms are still needed to take better advantage of high-performance parallel computing. The Department of Energy has made progress in this area, and our community would benefit from engaging more extensively with the computer science community. A related issue is the fact that when estimating reliability, predictive models are often pushed to the edge of their applicability and beyond. Thus, there is a need for decision methods that are robust to uncertain estimates of reliability. The group was split, however, as to whether optimization was the "only way" to deal with decision-making under uncertainty or just part of the decision-making process.

4.5. People and Workflow

This group argued that the future of MDO is not MDO; rather, the future lies in "Multidisciplinary Collaborative Human Decision Making". They stated that MDO needs to change the design process at a fundamental level while adhering to a core set of principles and values. In particular, MDO should support human decision-making, encourage teamwork, and facilitate collaboration (via networking). MDO should not only facilitate innovation but also help engineers gain insight into their design and the design process. The use of MDO should be transparent to the team and help people feel like a team. Finally, MDO should be able to deal with change (e.g., the uncertainties discussed in Section 4.4.), and ultimately it should change the environment, and how people perform design for the better.

MDO should strive to change the mindset of engineers (e.g., help them achieve the MDO "state of mind" discussed by Cramer). This necessitates a critical evaluation of the limitations of the current state of theory and practice of MDO. This can be accomplished by showcasing successful examples of MDO in industry, and creating learning communities that can share best practices while involving people in industry, academia, and government agencies. The group emphasized the importance of learning from failures that may occur when using MDO. Inherent in the discussion was the notion that current MDO practices do not embrace failure enough. Current incentive structures discourage failures and risk taking, which might lead to dramatic improvements, and this needs to be addressed given the potential for new insights that might occur. The issue of hierarchical versus democratic design processes was also raised in light of Collopy's comments on requirements flow-down (see Section 3.1). Understanding the advantages and disadvantages of each approach remains an open research question.

Finally, the group also talked about how best to manage design freedom and ensure flexibility in the design process. This relates back to the uncertainty discussion in that as design decisions are made, more things become certain, yet each decision reduces the team's design freedom. How to effectively support human designers' exploration of the design space, manage design freedom and the associated uncertainties remains an open research question. Likewise, the process of developing customized workflows that can be adapted to the organization and complex engineered system at hand was considered critical. Furthermore, adapting workflows to different cultures and regions will become increasingly important as organizations continue to expand their global operations and supply chains.

5. RECOMMENDATIONS AND CLOSING REMARKS

MDO has unparallel potential to play a significant role in the design of complex engineered systems. It offers rigorous approaches founded on sound mathematical principles that can help avoid the pitfalls that plague systems engineering today. In order to capitalize on these opportunities, however, the MDO community must embrace a broader perspective. Designing complex engineered systems invariably includes multiple people working across multiple organizations spanning multiple regions around the world. Devising the best way to integrate disciplinary analyses (e.g., FEA and CFD for the design of an aircraft) is no longer enough. The MDO community must broaden its view on what MDO entails and how it is performed, so that it can help transform industry practices and overcome the schedule and cost overruns that plague the many complex engineered systems projects today.

In addition to the specific research topics discussed by the breakout groups and summarized in Section 4, several over-arching themes emerged from the workshop. These over-arching themes constitute the primary recommendations from the workshop to advance MDO tools and methods to support the design of complex engineered systems.

First, MDO researchers need to engage more disciplines outside of engineering and target opportunities outside of their traditional application areas, such as aerospace and automotive engineering. Much like MDO borrowed from numerical methods and operations research at its inception, there is much to learn much from computer science, cognitive science, psychology, decision theory, economics, and other fields that can help us solve the challenges raised during the workshop. The MDO community needs to identify lines of communication with these research communities and devise ways to engage with them that are mutually beneficial.

Second, MDO problem formulations must evolve to encompass a wider range of design criteria as we have already started to see (e.g., supportability, noise, and environmental concerns in the aerospace industry). As the MDO community engages other disciplines, new criteria will emerge. Some of these criteria will be easy to quantify and others will not. Complex engineered systems are inherently coupled, difficult to model, and often exhibit emergent behavior that is unexpected. Integrating human behavior and social context into MDO problems will create additional challenges for modeling and simulation.

Third, effective strategies are needed to put designers "back in the loop", so that they can explore design spaces, broaden or shrink and redefine the design spaces as the design process moves along, filter out ineffective system architecture, manage design freedom, and handle uncertainties. Industry panelists, in particular, emphasized the importance of human feedback in the MDO process, stressing that MDO was "just a tool" to help people make better decisions. While MDO can help integrate and automate engineering analyses, no one advocated removing humans from the process. In fact, many argued that humans were better than computers in many aspects of the design and development process. Consequently, understanding how MDO can best augment and enhance the designers' capability to make good decisions is a critical component of this effort.

Fourth, the MDO community needs to do a better job of publicizing its successes so that it can improve the "buy in" that is needed to advance MDO research and practice in academia, industry, and government agencies.

There is no better way to showcase the impact of one's research than to clearly show how it has helped others solve their complex problems, save money, reduce time to market, etc. The community needs to capitalize better on the successes of MDO tools and methods.

Finally, students and practitioners need to be better educated on design from a systems perspective, optimization, and MDO, including their benefits and drawbacks. This entails making people more aware of the algorithms and MDO frameworks that are available, as well as their strengths and weakness, so that they know how to interpret solutions correctly (versus blindly accepting the results). While it is already a challenge to cover all the important material in engineering curricula, faculty need to find creative ways to bring MDO into the classroom. For instance, using "inverse problems" in textbooks and assignments provides opportunities for students to work from the desired output to the input instead of the reverse (i.e., given the input, find the output). This will shift the focus to synthesis instead of analysis. Also, using solvers in Matlab, Excel, and Mathematica as part of assignments and course projects is an easy way to get students to start using optimization. This will foster the "state of mind" that seems to enable MDO to pervade corporate culture.

The presentations and suggestions summarized in this paper are part of a larger discussion that is starting to take shape around the nation. Regardless of whether you consider yourself a "conductor" or a member of the "orchestra", your input is needed to help transform current practice, which is not working well. Faculty and researchers in MDO must continue to engage researchers in other fields as well as industry practitioners and government personnel, as the problems are too large for any one community to solve alone.

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