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FIFTY YEARS OF STRUCTURAL SYNTHESIS: SOME MUSINGS FROM A DISCIPLE OF SCHMIT

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The purpose here is to offer a brief overview of the structural synthesis field and related developments since its inception 50 years ago. I will include three general areas which will be intermixed. First is a review of Professor Lucien Schmit's career. Second is a general overview of the development of the technology. This is not a review of the many technical contributions already reported in a multitude of references. Instead, I will focus on a more general picture of the development and include some stories not well known. Third is a more personal discussion of my career as it has been influenced by Schmit. It is a tribute to Lucien Schmit that his single paper, never published in a refereed journal, generated thousands of technical papers and hundreds of professional jobs and has now matured to the point where practical applications are routine, just at the time when the world is recognizing the importance of conserving resources.

Nomenclature

$F(X)$	=	objective function
$g(X)$	=	array containing constraint values
K	=	master stiffness matrix
m	=	number of constraints
n	=	number of design variables
P	=	vector of loads
u	=	vector of nodal displacements
X	=	vector of design variables
X^L	=	lower bounds on the design variables
X^U	=	upper bounds on the design variables

I. Introduction

THIS twenty fifth MAO conference also represents the fiftieth anniversary of Professor Lucien Schmit's classic paper which began this entire field of research.[1] In recognition of that I am offering this general, largely non-technical discussion of the field. For brevity, I will take the liberty of calling him Lucien or Schmit, as well as Professor Schmit. While many people know Lucien much better than I, I expect he has influenced my career far more than most. In this sense, it is also the story of my career as influenced by him.

A general overview of Lucien's career includes his academic and industry background, rise in academia, his SDM award, the first MAO award, the AIAA Crichlow Trust Prize, election to the National Academy of Engineering and much more. The appendix is a very brief resume of his career.

The development of engineering optimization is not limited to structures and the concepts created there have been expanded to numerous individual applications, as well as multidiscipline design optimization.

In my own case, I entered the field as a student in 1968. I and my classmates followed a series of students doing research in both finite element analysis and optimization. We called ourselves "Disciples of Schmit," hence the title of this paper. During this period, the Supersonic Transport project at Boeing was cancelled and many engineers were working in gas stations. There was little call for optimization experts with PhDs and so it was a result of a

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comedy of events, largely directed by Professor Schmit that allowed me to be the only student of that time who got a job in optimization and was able to spend his entire career in this field.

II. The Early Years

Lucien Schmit was raised in Forest Hills, NY and his father was a Cellist in the New York Philharmonic Orchestra. He graduated from MIT in 1949 with a B.S. degree and in 1950 with a M.S. in Civil Engineering. He worked as a Structures Engineer for Grumman Aircraft for two years. He then returned to MIT as a Research Engineer in the Aeroelastic and Structures Research Laboratory. In 1958 he joined the faculty of Case Institute of Technology as an Assistant Professor. In 1960, he published his classic paper on structural synthesis.[1] His 1981 AIAA paper[2] offers an overview of the genesis of the concept and credits others for early works that influenced his ideas. However, it is widely agreed that the 1960 paper, which many current researchers in the field have never read, is the key beginning of modern structural synthesis and much related work.

Figure 1. The Crichlow Trust Prize, 1999.

Figure 2 shows the classic three-bar truss used by Schmit in his original 1960 paper where he coupled finite element analysis with numerical optimization. With this example, he showed that the traditional stress ratio method gave a higher mass than optimization produced. Even though this paper offered a profound change in design methodology and led to tens of thousands of research papers and numerous commercial software offerings, it was not always helpful for academic promotion because it was not published in a refereed journal. Also, he once commented to me that a well known structures expert noted that this was a remarkably complex solution to a very simple problem. Indeed, as he recounts in his 1981 paper,[2] he presented the three-bar truss as an example to NASA in a research proposal. In response, John Hedgepath said, “Can’t you treat something that looks more like part of an airplane or spacecraft, for instance an integrally stiffened waffle plate panel?” This led to considerable research in the 1960s on waffle plates and integrally stiffened shells. Despite a somewhat slow start, the technology development progressed and I first met Lucien in 1968.

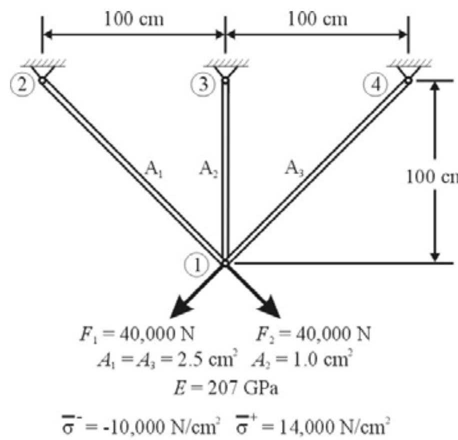

Figure 2. Three-Bar Truss.

Lucien Schmit was raised in what we can call a sophisticated, intellectual environment and he was always a high achiever. By contrast, my father was a logger in the High Sierras of California who never went to high school. I was the youngest of seven children and was a strong contender for most likely to fail upon graduation from high school. Not being qualified to attend the University of California (I later redeemed myself by becoming a Full Professor there), I attended Junior College for two and one half years (I wasted the first half year with a 1.15 grade point average). I was not able to transfer to the University of California because in needed a 2.4 grade point average and had only managed to move up to 2.37. Therefore, starting with the A’s in the library and looking at college catalogs, I found Arizona State University that only required a 2.0 grade point average to transfer and was only a one long day’s drive away. There, Professor Louis Hill (who got a PhD at Case in structural synthesis in two years) took me under his wing and helped me grow up. My senior year, he encouraged me to stay for a Master’s degree, but I wasn’t interested until he stopped me on the sidewalk in May and told me he had a fellowship for me. This meant that I could afford to stay and would no longer need to make tomato soup from catsup I “borrowed” from the cafeteria.

Professor Hill suggested a thesis in optimization and gave me Professor Schmit’s original paper along with several others. I started with Schmit’s paper, threw up my hands at the mathematical gibberish, and did my Master’s in finite element analysis under a different professor. Professor Hill didn’t give up and the following spring he stopped me on the same sidewalk, the same time of day, and told me he had gotten a three year NSF fellowship for me to attend Case Western Reserve University but I needed to send them an application. I was beginning to enjoy being a professional student and had never been to Cleveland so it seemed like a good idea. Upon arrival, Professor Schmit told me how pleased he was to have me come to study structural synthesis with him. Having just driven 2000 miles, it didn't seem politic to tell him I thought optimization was gibberish so I said how happy I was to be there. After a course on structural synthesis from him, I was hooked and it led to my career in this field.

Today, we write the optimization problem in the standard form;

Minimize $$F(X) \tag{1}$$

Subject to;

$$g_j(X) \le 0 \quad j = 1, m \tag{2}$$

$$X_i^L \le X_i \le X_i^U \quad i = 1, n \tag{3}$$

where $F(X)$ is the objective function and the $g_j(X)$ are constraints. Eq. 3 defines lower and upper bounds on the design variables, X.

While the original paper did not state the optimization task this concisely, this has become the standard form of the problem statement. This is very close to the statement of engineering design in general and perhaps if Professor Schmit had written it in this form I may have identified it as something I could understand!

During the 1960s considerable progress was made in structural synthesis. A key student of Schmit was Richard Fox whose thesis was in truss optimization. During those years, Leon Lasdon was a professor in the Operations Research Department and Professor Schmit would send his students to Professor Lasdon for theoretical courses in linear and nonlinear optimization. Professor Lasdon was on Fox's doctoral committee and folklore has it that, during his thesis defense, Fox wrote the standard finite element analysis; $Ku = P$ and noted that since we want $\frac{\partial u}{\partial X_i}$ we must calculate it by finite difference because the displacement, u, is an implicit function of the cross sectional areas contained in the design vector X. At this point, Professor Lasdon asked, "Why don't you just differentiate?" noting that

$$\frac{\partial K}{\partial X_i} u + K \frac{\partial u}{\partial X_i} = \frac{\partial P}{\partial X_i} \tag{4}$$

so

$$\frac{\partial u}{\partial X_i} = K^{-1} \left[\frac{\partial P}{\partial X_i} - \frac{\partial K}{\partial X_i} u \right] \tag{5}$$

Now, noting that for static point loads $\frac{\partial P}{\partial X_i} = 0$, K has already been decomposed, and $\frac{\partial K}{\partial X_i}$ is just the element stiffness matrix with the cross sectional area set to 1.0, the analytic derivative becomes easy to calculate. Note that it took four years of research before this observation was made and became one of the tools available. This is called the Direct method for behavior sensitivity analysis and was published by Fox as a technical note in 1965.[3] In 1979, Arora and Haug published the Adjoint method[4], followed by a comment by myself showing that the two methods are equivalent and should be chosen based on the number of gradients needed.[5] Fox and Kapoor followed this in 1968 with calculation of derivatives of eigenvalues and eigenvectors[6] and Nelson provided a simpler eigenvector calculation approach in 1976.[7]

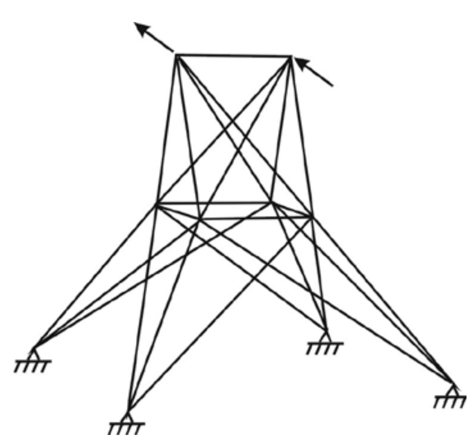

Figure 3. 25-Five Bar Tower.

Fox went on to become a professor at Case and was required to seek research funding. Another story of the time was that he (and I think Schmit) made a presentation to the Air Force seeking funding. The truss shown in Figure 3 (showing a twisting load case) was an example from his thesis and was presented as an optimization example. At that point an Air Force researcher noted that, "We are not in the business of designing trusses," and denied funding. On the next iteration the title on the figure was "Lunar Lander Superstructure," and the research received funding.

"*It was the best of times, it was the worst of times…*" Charles Dickens. This described the research environment in the late 1960s. Professors Schmit, Fox, Kicher, Moses and Goble at Case were active in the field and had a significant group of graduate students. However, the research funding environment was bleak and whenever someone received even a small grant, it resulted in major celebration. The main funding sources were NASA and the Air Force, as well as the NSF and competition for funding of any engineering research was fierce. Also, it was becoming apparent that optimization was limited to only a few design variables due to the computational cost, as well as the limited state of the art of optimization algorithms.

As for myself, just as I was beginning formal research for my thesis, Professor Schmit called me to his office to tell me that he was moving to UCLA. I asked to go with him and he pursued the possibility but advised me to stay at Case and finish under Professor Moses and that I would be in California sooner; advice which later proved to be prophetic.

III. Growing Pains of the 1970s

While there were a multitude of research contributions in structural synthesis in the 1960s, the technology never really took hold, largely because the computational cost was too great and the problems that could be solved were too small. In the late 1960s Venkayya and his associates developed discretized optimality criteria which could solve large problems, though with limited applicability.[8] The relative weakness of numerical optimization was dramatically demonstrated in a paper by Gallatly, Berke and Gibson where they called the 1960s the "Period of Triumph and Tragedy" for structural optimization.[9] They went on to suggest that structural optimization was little more than an "interesting research toy."

I graduated in 1971 during a time when virtually no industry or academic positions were available. I had done some research on an Air Force project and had a job opportunity at Wright Patterson Air Force Base with Venkayya, Berke and others. Being a native Californian, this was an interesting work opportunity but not such an interesting location. Then I, as well as my roommate Hirokazu Miura, received a call from the NASA Ames Research Center in Mountain View, California. They had visited UCLA seeking someone in optimization and Lucien gave them our names. Hirokazu had a Master's degree in Aeronautical Engineering and was doing his thesis on supersonic wing design with flutter constraints. I had a Master's degree in Civil Engineering and did my thesis in multilevel truss configuration design. NASA chose me because I was the one with U. S. citizenship, which was a requirement. It was not until eight years later when I left NASA for a teaching position that Dr. Miura was hired for the job he was best qualified for in the first place.

In the early 1970s, research continued in both formal optimization and optimality criteria. It was a friendly competition and we always remained friends. Venkayya often encouraged me and others to study both methods more closely but that didn't happen. Fleury and Sander did listen and in 1978 reconciled the two methods by showing that optimality criteria is actually a dual formulation if viewed as a formal optimization method.[10]

On the optimization algorithm side, we continued to use the three-bar truss as a standard test case until the mid-1970s. In time it became almost comical to listen to ourselves debate whose optimization algorithm could solve this two variable (symmetric) problem with the fewest function evaluations. Finally, this was replaced with the ten-bar truss in the mid-1970s and that standard test case was used into the 1990s. Only in the last 20 years of this 50 year history have we begun to solve problems of realistic engineering size and complexity.

IV. New Life for Structural Synthesis

Schmit's second major development was approximation concepts in the mid-1970s. This is not to suggest that he didn't recognize the need sooner. Indeed, he was encouraging his students at Case, including myself, to seek efficient approximations to reduce computational cost. The only result was a Master's thesis by Shelangoskie, which while a valiant attempt, did not produce the needed breakthrough.[11] Although sequential linear programming had been published by Kelly in the 1960s, in 1974 Schmit and Farshi created approximations based on physics.[12] This included the concepts of intermediate variables and intermediate responses. Now, structural optimization required about ten detailed finite element analyses instead of hundreds and this breathed new life into the field.

As already noted, Lucien and I had become good friends and I followed his work closely. At this time, I was dabbling in airfoil optimization and took his approximation concepts idea there. At that time, we didn't have gradients or the understanding to create physics based approximations. Therefore, I simply used the concept of sequential linear programming but expanded it to use quadratic approximations.[13] This was possible because we had a small number of design variables but the function evaluations were very expensive. I called it an approximation method. Today, we call it response surface approximations. John Swanson read this paper and immediately added the technique to his ANSYS program to provide a commercial structural synthesis capability. Also, at that time, Picket, Rubinstein and Nelson introduced the basis vector concept.[14] While it was not all that useful (in my opinion) for sizing optimization (although it's great for shape optimization), it was ideally suited for airfoil optimization (also shape optimization).[15] Also, once the approximation concepts approach was understood, Bofang in China[16] and I and my students[17] extended it to approximate forces (from which stresses are calculated) rather than stresses directly. This is actually a one order higher approximation. Bob Canfield created an approximation to eigenvalues based on the Reyleigh quotient.[18] Thus, it is seen that, with the approximations concepts seed planted by Schmit, these and numerous other advanced approximations have evolved.

The mid-1970s were an exciting time for structural synthesis, as well as general purpose optimization because we were now confident that the technology had a future. Lucien and I maintained a good relationship and usually found an evening at each SDM Conference to have dinner together. Often his wonderful wife, Eleanor, was there also and occasionally my wonderful wife, Ginny, was able to travel and attend with me. Also, on another occasion, he visited me at NASA Ames and we went to lunch, together with a Post-Doctoral Fellow who was working with me. During lunch, the Post-Doc said words to the effect, "Professor Schmit please suggest a research topic for me. Something really simple like the three-bar truss that will make me famous." It is a tribute to Lucien's class that he didn't hit the fellow (who later moved on to become an Optometrist).

V. Multidiscipline Design Optimization

By 1980, structural synthesis methods were becoming established and applications had begun to spread into other areas. In 1982, Sobieszczanski-Sobieski published a linear decomposition method for multidiscipline design optimization that he called a blueprint for development.[19] This led to a considerable amount of research, funded by NASA, in the development of MDO techniques. However, MDO did not begin in 1982. Indeed, Schmit and Thornton presented the design of a supersonic aircraft wing including aerodynamics and structures in 1965.[20] Lee, et al published a paper on computerized aircraft synthesis in 1967 which included multiple disciplines.[21] In 1968, Thornton and Schmit published a multidiscipline paper on an ablating thermostructural panel.[22] In my own experience, we developed the ACSYNT aircraft synthesis program at NASA Ames where we performed conceptual design and optimization of aircraft considering several disciplines simultaneously.[23] These early works are seldom referenced as they considered several disciplines simultaneously (although ACSYNT did some sub-optimizations). While not mathematically sophisticated, these methods worked well and generally model traditional design with the addition of optimization. This general concept is contained in the EMDO method.[24]

My own view (and bias) is that multidiscipline design optimization remains an unsettled technology today. While the EMDO and related methods generally model traditional design methods, decomposition and related methods are mathematically elegant. However, it has yet to be demonstrated that decomposition and similar methods actually work on a routine basis. The argument for these sophisticated approaches is that, if we consider an aircraft wing, the aerodynamicist and the structural engineer will produce quite different designs. However, the counter argument to this is to note that neither of these people have the authority to define the wing planform. That is done by the chief engineer and the variables can be considered system level variables. If we perform a system level optimization to define the aircraft for a given mission, the structures, aerodynamics, propulsion and other groups can still use optimization for each proposed configuration. This allows us to use optimization in a traditional framework. While it may not produce the absolute, optimal, best design, it will improve the design and dramatically reduce design time.

VI. Going Commercial

In the 1980s optimization began to find its way into commercial finite element software. This included software from SDRC, ANSYS, RASNA and MSC among others. In the late 1980s MSC funded my company to add optimization to MSC/Nastran and this became known as solution 200. During this time frame, Lucien said to me words to the effect, "I know optimization has a future because people have figured out they can make money from it." In 1991, we released our own structural optimization program called GENESIS that makes full use of the latest generation approximation techniques.

Today, we can solve structural optimization problems with hundreds of thousands of design variables and millions of constraints. Design variables can include almost any input to the finite element analysis and objective and responses can include almost any calculated response. In addition to member sizing, topology and shape optimization are now commonplace. This ability to solve very large-scale problems has generated a new and largely unexpected issue. That is the calculation and storage of hundreds of thousands of gradients. I am reminded that in the 1970s we were bragging that we could calculate analytic gradients to greatly reduce optimization time. Roy Levi at the JPL commented to the effect, "Wait until you need over a hundred gradients." Since direct gradient calculations were essentially equivalent to added load cases, the cost of large numbers of gradients was clear. However, it didn't seem to be a problem because Schmit presented the concept of constraint deletion where we retained only needed gradients. However, now we require many thousands of stress gradients and cannot afford to either calculate them or store them when there are also many thousands of variables. This has resulted in development of approximate gradients based on some proprietary insights. The resulting software called STRDOT (Stress DOT), together with BIGDOT (capable of dealing with many thousands of variables and stress, displacement, frequency, etc. constraints) now allows us to solve extremely large structural synthesis problems.

Figure 4 shows a typical (though relatively small) topology optimization example. The model has 737,836 elements and 2.48 million displacement degrees of freedom. There are ten separate load cases and the optimization problem has 368,918 design variables (due to symmetry).

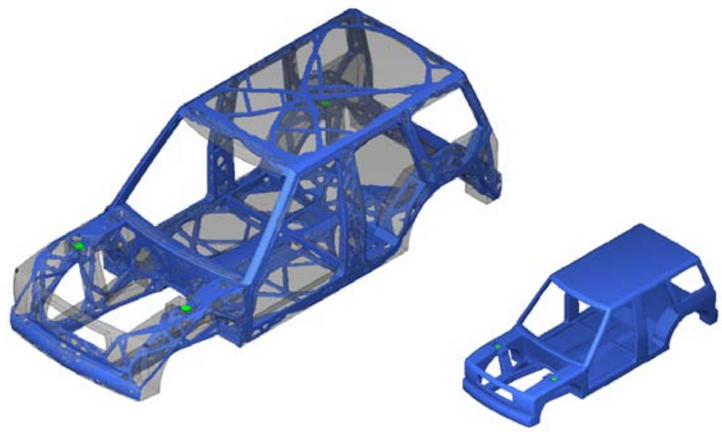

Figure 4. Body in White Topology Optimization.

As already noted, today we can solve problems with over one million design variables using finite element models with several million degrees of freedom. Design variables include sizing, shape, topology, topography and topometry. The materials can be isotropic, composites, etc. and we can even design for the optimum stacking sequence of layered composites. Responses can include mass, stress, deflection, frequencies, mode shapes, dynamic responses, random responses, temperature, noise, etc. Almost any calculated response can be an objective or can be constrained and we can even include manufacturing constraints to insure that cast parts can be built. In the case of nonlinear responses (such as crash) we use the Equivalent Static Load Technique developed by G. J. Park and his associates.[25] In short, while research and development continues, we are now able to solve a very wide range of real structural synthesis problems.

VII. Summary

Commercial applications are now growing rapidly, largely driven by the need to conserve resources and a growing understanding in industry of the power of optimization. In addition to the well developed state of the art in structural synthesis, Schmit's contributions have led to a remarkable breadth of applications in other disciplines such as fluid mechanics, nonlinear structures, electromagnetics and many more.

All of this has taken fifty years of concentrated effort by a large number of people. The resulting influence on society is hard to quantify but is becoming increasingly clear as we recognize the importance of using limited resources wisely. All of this began in 1960 with a single paper presented at a relatively unknown conference by a visionary named Lucien Schmit. Few people have had the profound influence in their field that can equal Professor Lucien Schmit's.

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Appendix

Brief Resume of Lucien Schmit

Figure 5. Lucien and Eleanor, 1999.

Rockwell Professor of Aerospace Engineering, Emeritus
School of Engineering and Applied Science, UCLA
Born: May 5, 1928, New York, NY
B.S. Civil Engineering, MIT 1949
M.S. Civil Engineering, MIT 1950

Employment:

Grumman Aircraft Engineering Corporation, Bethpage, NY
1951-1953 Structures Engineer
Aeroelastic and Structures Research Laboratory (MIT), Cambridge, MA
1953-1958 Research Engineer
Case Institute of Technology, Cleveland, OH
1958-1961 Assistant Professor
1961-1964 Associate Professor
1964-1966 Professor
1966-1969 Professor & Head, Division of Solid Mechanics, Structures & Mechanical Design
1969-1970 Wilbert J. Austin Distinguished Professor of Engineering and Head, Division of Solid Mechanics, Structures & Mechanical Design
University of California at Los Angeles
1970-1991 Professor of Engineering and Applied Science
1976-1979 Professor of Engineering and Applied Science & Chairman, Mechanics and Structures Department
1991- Rockwell Professor of Aerospace Engineering, Emeritus

Affiliations:

Fellow, American Society of Civil Engineers, 1969-present
Member, National Academy of Engineering, 1985-present
Fellow, American Institute of Aeronautics and Astronautics, 1986-present
Member, USAF Scientific Advisory Board, 1977-1984
Member, Special Ad Hoc Committee to the Federal Aviation Administration for Investigation of the DC 10 Pylon Structure, 1979-1980
Chairman, Selection Committee 1980 USAF Research and Development Awards
Chairman, Peer Review Committee for Assessment of Multidisciplinary Optimization & Analysis Program at the NASA Langley Research Center, 1982
Chairman, ASME Spirit of St. Louis Metal Committee 1999-2005

Awards and Honors:

Walter L. Huber Civil Engineering Research Prize, 1970
AIAA Structures Design Lecture Award, 1977
AIAA Structures, Structural Dynamics and Materials Award, 1979
Author of invited paper in AIAA Journal, “History of Key Technologies Series” entitled “Structural Synthesis – Its Genesis and Development,” AIAA J., October 1981
USAF Meritorious Civilian Service Award, 1984
Elected to National Academy of Engineering, 1985 “for Pioneering work in structural synthesis, combining finite element analysis and nonlinear programming algorithms to create a powerful class of modern structural design methods”
AIAA Multidisciplinary Design Optimization Award, 1994
AIAA Crichlow Trust Prize, 1999 for “pioneering seminal contributions to the initiation of structural optimization and multidisciplinary design and their evolution from abstract concepts to widely used practical tools”

Publications:

Author or co-author of more than 100 publications dealing with analysis and synthesis of structural systems, finite element analysis, optimization of fiber composite structures and multidisciplinary design.