Clemson Engineering Design – Application and Research (CEDAR) group - Clemson University, Clemson, SC, USA

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Abstract

This chapter summarizes many years of design research at Clemson University and their impact on industrial practice. It shows how various ideas percolated, were developed and eventually made their ways to become used in industry. In design research, a broad area of endeavor, design theories take the longest to develop and are the slowest to transition to industry. The development of methods, practices, and their applications to industrial problems are much quicker to transfer, however, since industry sees immediately the potential benefits or shortcomings of the methods on the issues that interest them. Finally, the training of students at all levels in design practice certainly impacts industry since many become employed and affect the practices of their companies.

1 Introduction

The CEDAR group at Clemson brought three researchers and their students together to perform design research, to design artefacts for industry, and to teach design. We have chosen to write a chapter together as the group became a single entity focusing on mechanical design at Clemson. Though we do not always work together, we do have many projects in which we collaborate, and through which our individual directions complement each other. All of our students meet weekly, and through their sharing of experiences, problems, and results, they have helped each other as well as defined both the group name and its code of ethics. We also have many projects we conduct individually with students, but typically, depending on the research topic, we serve on each other's student thesis or dissertation committee.

This chapter is organized as follows: The three faculty members describe their research projects and the impact of these projects (if any) on industry. They list one or two publications per topic. The evolution of the descriptions shows how they coalesced to address several of the multiple facets of engineering design as they describe their collaborative efforts on these projects. Next, their impact on design practice through the education of students is highlighted, and finally they describe their use of the student designers as test subjects to learn about design, and to train their students in design research. The chapter finally concludes with the overall lessons from this effort.

2 Research Contributions

2.1 Dr. Georges Fadel – Clemson, 1992-2013

Dr. Fadel's contributions have addressed theory, methods and application in support of mechanical design. They are presented roughly in chronological order, focusing on the research that improved design practice. From this presentation, the overall thrust of his and his students' work is exposed.

Dr. Fadel began work in optimization when he spent a spring semester at NASA Langley collaborating with Drs. Jarek Sobieski and Jean-Francois Barthelemy. At that time, Dr. Sobieski was laying out the foundations of multi-disciplinary optimization (MDO), and an important part of the approach was the ability to use approximations to speed up optimization and avoid long and costly analyses when possible. Dr. Fadel developed and published with Dr. Barthelemy a paper on the two point exponential approximation, (Fadel, Riley, & Barthelemy, 1990) and then later derived approaches based on the approximation to control the magnitude of change of design variables to ensure convergence during optimization. Users of structural optimization in academia and in industry, and of course NASA, have used this approach as well as others to reduce computational cost.

Upon returning to academia, Dr. Fadel laid a plan to address complex design problems using optimization. He established a goal to solve packaging or layout optimization problems, considering complex non-convex shapes, and a multiplicity of criteria. One of the first problems he attempted to address with his students was the layout of the under hood of a vehicle subject to ground clearance, the location of the centre of gravity, and accessibility. Dr. Fadel and a team of collaborators applied for and received a grant from NASA to work on this multidisciplinary problem, a facet of which entailed tasking the students involved in this effort to collaborate with others from other disciplines. Several PhD students worked on the problem over the years, defining it, developing a method to encode the CAD data and for use with an interference checker and an optimizer to locate the individual components within a non-convex allowable space subject to a multitude of constraints and criteria. To mitigate the expense of the interference calculation, in terms of computer time, the CDOM or the Configuration Design Optimization Method was adapted. It has since been used to solve problems for the Tank Army Command (TACOM), particularly in the development of hybrid vehicle configurations. It addressed objectives such as roll over prevention, survivability, ground clearance, dynamic response, and thermal considerations. The approach was also modified and tailored for the GM Corporation for use in computing the luggage packing capabilities of new vehicles. That code is still currently in use and far as we know, still outperforms other existing codes (Fadel & Fenyes, 2010; Miao, Fadel, & Gantovnik, 2008).

While addressing optimization and the tie to CAD in the layout or packaging optimization, Dr. Fadel became interested in rapid prototyping, and began applying optimization to problems in additive manufacturing. First, under his direction, his students developed a method to optimize the placement of objects on the build platform. The optimal direction of the build was next addressed, followed by an optimization of the slice thickness to reduce stair-stepping. Next a number of algorithms were developed, one of which was a code to correct STL files (Morvan & Fadel, 1996), and another for immersing users within their CAD representation in a virtual environment. Many of these codes and papers were published and some computer codes sold to companies. The experience obtained developing these approaches enabled Dr. Fadel and his colleagues to establish a consortium of companies and to train them on the use of additive manufacturing and to transfer the results of design research to the companies.

The combination of the work on layout optimization and additive manufacturing led Dr. Fadel and his students to explore the field of multi-material design and manufacturing. The approach used for the layout optimization was adapted to the layout of materials inside of a morphing shape to determine both the optimal shape and the optimal placement of materials. A flywheel was optimized for material distribution and for shape, and since Dr. Fadel's students had assisted in developing the code to drive the LENS machine developed at Sandia and commercialized by Optomec, they used this opportunity to build a flywheel made of materials optimized to increase energy storage capability without a commensurate increase in size or weight (Huang & Fadel, 2000; Morvan & Fadel, 2002). The approach was also applied to the design of moulds that are optimized to achieve rapid and uniform cooling by judiciously designing copper paths in the original mould material. This work has been of interest to industry since additive manufacturing is becoming more mainstream, and as companies are eager to increase performance while reducing weight, and therefore are more inclined to consider novel approaches.

Another effort in a different additive manufacturing process, namely ultrasonic consolidation (UC), was carried out initially with the inventors of the process, the Solidica Company. The process, which consists in ultrasonically bonding thin foils of metal by ultrasonic vibrations, has the potential of bonding dissimilar materials and embedding fibres or sensors between the foils. With support from the National Science Foundation, Dr. Fadel and his team elucidated why the process failed at some characteristic length, and then determined that past that length, there was no difficulty in consolidating additional material (Gibert, Austin, & Fadel, 2010; Gibert, Fadel, & Daqaq, 2013). Thus, using this research, Solidica resolved this difficulty and continued to advance its process. Dr. Fadel and his students are now trying to understand why the process works, an understanding which will directly affect industry. Though this UC process and the LENS process both allow multi-material manufacture, both have very different characteristics; UC is layer based and LENS is point based. Dr. Fadel and his students showed how manufacturing considerations must be considered in the design phase to generate heterogeneous objects within the constraints of current manufacturing capabilities (Hu, Fadel, Blouin, & White, 2006).

Through this research into multi-material constructs, Dr. Fadel and his students began collaboration with Dr. Summers, and the Michelin Corporation. They submitted a proposal to the National Institute of Standards and Technology (NIST) to investigate how to reduce rolling resistance when using a novel airless tire concept invented by Michelin, the TWEEL. Dr. Fadel's students developed a two-level approach in which they first identified the required material properties of the shear layer material of the TWEEL by performing analyses with models developed by his colleagues. Next, they used topology optimization approaches to design the geometry of a meta-material object (an object with material properties that differ from the bulk material properties because of specific geometries). Again, issues of manufacturability had to be considered, the results of which, though understandable, were not initially envisioned by the design team (Czech, Guarneri, & Fadel, 2012). This industry/academia initiative was of direct benefit to the automotive industry and the TWEEL is now marketed by Michelin for certain classes of vehicles.

The work on optimization in support of the US Army TACOM continued with the investigation of approaches to optimize complex system. Initially, Dr. Fadel and his colleague, Dr. Wiecek and their students applied the Analytical Target Cascading

(ATC) approach, developed by Dr. Papalambros' group at the University of Michigan, to various vehicle design problems for the Army. Issues of convergence were studied, and a two-level approach based on ATC along with geometric considerations was then performed. In one application of interest to the Army and to one of its civilian suppliers, the cell configuration inside a battery was optimized to reduce hot spots while its outer geometry and placement under the hood were simultaneously determined, considering the geometric and functional constraints (Dandurand, Guarneri, Fadel, & Wiecek, 2013). In the last few years, the NTC or Network Target Coordination has been under development by the Clemson team to optimize non-hierarchical and multi-disciplinary systems. NTC is currently being applied to solve problems in army vehicle design.

While performing mostly optimization-based approaches and applying them to a multitude of problems, Dr. Fadel and his students investigated design methods and theories. They initially researched Function Based Design, and established the first grammar used to describe functions for a mechanical system (Kirschman & Fadel, 1998). Though they favoured the concept of Function for describing transformational processes and as an abstract concept to generate possible solutions during innovative design, they also deemed it necessary to create another paradigm to handle non-transformative aspects of the design. They adapted the concept of Affordances from perceptual psychology, (what a system affords the user, either for good or for ill) and developed a number of methods to support Affordance Based Design (ABD) (Maier & Fadel, 2008, 2009). They collaborated with Dr. Mocko and his students to determine the aspect of situatedness of the design and how to consider this aspect during the design. Using the perspective of interactions or affordances, Dr. Fadel and his students showed that a system consisting of a user, artefact and designer behaves like a complex adaptive system and can be studied as a complex system. This approach was applied to various examples, and is currently being tied to an optimizer to show that designers typically increase positive affordances, and remove negative ones as design evolves in a variant design problem. This approach has gained significant momentum in the last few years, and is only starting to impact Industry as evidenced by the comments from the readers of a book on ABD published by one of Dr. Fadel's students, Dr. Maier. Current research is showing how affordances can be coupled to an optimizer to improve variant design during the conceptual stages, research that has been shown to various companies. Several other collaborative efforts with Drs Mocko, Summers and their students are described in the subsequent paragraphs.

Bringing all these aspects together, dealing with the complexity of the various problems has been the central focus of Dr. Fadel's research. It has evolved over many years, in which the computational capabilities and the approaches have been configured to manage the increased complexity of the multiplicity of interactions in a design. Dr. Fadel believes that optimization, focus on interactions, and prototyping are critical to this continual evolution. Now, applying complexity theory to these various problems may allow design researchers to develop new theories, methods and tools. These are certain to further improve industry and enhance the knowledge students are taught at various levels in their education.

2.2 Dr. Joshua Summers – Clemson, 2002-2013

There are three main research strategies that have emerged with regard to the types of research that Dr. Summers directs. The first is the development of new design enablers to support different engineering design activities. This area of research is typically supported through the development and testing of new tools, both manual and automated. The second is centered on trying to develop a more fundamental understanding of the engineering design process. This research direction is supported with empirical research strategies of case study analysis and protocol study research. The final research strategy is focused on application design and development. While the first strategy seeks to provide justified and tested support for engineers, the second strategy seeks to understand the processes in which they engage and the final strategy provides the research lab with experiences in practicing engineering design from a first person perspective. In the past decade of graduate researcher training, several projects have provided students with opportunities to grow as researchers, engineers, and professionals. Several of these projects are illustrated below to offer evidence of a major mechanism for design research transfer to industry via the trained students on industry sponsored projects.

One of the first projects that Dr. Summers established was the development of a "Lamelle Query Systems" for Michelin in 2005-2006. In this project, students used the design exemplar as a software prototyping tool to define geometric algorithms that could be used to match repeated line-arc-line patterns for tire tread inserts within bounding tolerances. This was the first industry sponsored project that employed the principles of the design exemplar (Summers, Bettig, & Shah, 2004). The design exemplars, a basis for a CAD Query Language (Summers, Divekar, & Anandan, 2006), were then recast into a dedicated system that was delivered to Michelin to support tire designers in reusing stamping tooling to make the lamelles, the tire inserts, thereby saving an estimated several hundred thousand dollars annually (Anandan, Srirangam, & Summers, 2008).

The success of this industry sponsored design automation project led to two other industry sponsored projects. The first, a collaborative project with Dr. Mocko, was sponsored by Hartness International and resulted in a detailed method for capturing the design rules for configuration and manufacturing management (Chavali, Sen, Mocko, & Summers, 2008) that is still employed at the company. The second project, initiated in 2006, was sponsored by Wright Metal Products, a company that produces the metal frames for shipping riding lawnmowers and water jetskis to distributors. In this project, the company was challenged with upcoming retirements of key frame designers and wanted to develop tools that could help mitigate this future knowledge loss. Dr. Summers collaborated with Dr. Biggers and graduate students to develop a tool that allowed the frame designers to quickly, in real time, configure frames and run basic load analysis to determine deflection while providing costing estimation for the materials and weld times. This tool (Kayyar, Ameri, & Summers, 2012), while initially anticipated as a design tool, has been most frequently employed by the sales team in providing quick project cost estimates to the customers.

Additionally, in 2006, Drs. Summers, Fadel, and Mocko initiated a project with BMW to explore the association of the mass with vehicle sub-system requirements (Mocko, Summers, Fadel, Teegavarapu, & others, 2007). While this project, as explained above, was a catalyst for Drs. Mocko and Fadel to explore requirements allocation and management for the US Army, it led to additional design method development projects for Dr. Summers. These included the development of a lazy parts identification method for BMW with Dr. Mocko (E. Namouz et al., 2011) which is currently being integrated as a design process best practice within the BMW development teams. One of the lazy part indicators, duplicate geometry, served as the motivation for a feature recognition design enabler (Shanthakumar & Summers, 2013). The success of these BMW design method development projects also led to subsequent product-process modeling and support projects for BMW with Drs. Mocko, Mears, and Kurz (Miller, Mathieson, Summers, & Mocko, 2012). This project served as a motivation for the development of computational tools to estimate assembly times from assembly models absent of installation instructions (Namouz & Summers, 2013; Owensby, Namouz, Shanthakumar, Summers, & Owensby, 2012). These latter tools are informed by prior fundamental research on complexity (Ameri & Summers, 2008; Sen, Ameri, & Summers, 2010; Summers & Shah, 2010).

The efforts in these projects led to the identification of the challenges associated with conceptual design level automation, namely issues associated with sematic information modeling. These more fundamental issues have been addressed in an NSF funded project with Dr. Bettig of West Virginia University and an NSF workshop organized with Dr. Rosen of Georgia Tech. These pragmatic industry projects provide a unique opportunity to motivate the fundamental research that is more typical in academic environs.

While the initial research direction for Dr. Summers was a continuation of his dissertation work on design enablers and automation, he and his research group exploited additional opportunities to work with industry through the form of development projects. One of the first of these was in 2005 when BMW introduced the first three development projects funded through Clemson University, of which Dr. Summers was a collaborator on two projects the lightweight engineering redesign of car seats and of headlights. In these projects, executed collaboratively with Drs. Grujicic and Thompson, graduate and undergraduate students reverse engineered multiple competitors to establish benchmark best practices in an effort to reduce the weight of the two systems. Though a formalized reverse engineering tool was developed to support this activity (Snider, Teegavarapu, Hesser, & Summers, 2006), the primary objective involved identifying concepts that could be explored for mass reduction. Dr. Thompson worked on a follow-on project on seat design while Dr. Summers led the subsequent development project on LED headlight design (Morkos et al., 2009). The LED headlight design project led to Dr. Summers initiating a new undergraduate Creative Inquiry team that explored metal-foams (Hess, Bowman, Morkos, & Summers, 2011) which is now evolving into a collaborative graduate research thesis on metal foam manufacturing, jointly advised by Dr. Summers and Dr. Choi.

Other development projects that supported graduate students and provided motivation and demonstration platforms for graduate research include the development of an integrated trash and recycling truck for Environmental America, Incorporated (Smith, Johnston, & Summers, 2007), the development of a tire tread sample mud debarrage device for Michelin with Dr. Mears (Maier, Mears, & Summers, 2012), the development of a cryogenic temperature non-pneumatic tire endurance “road wheel” for the Jet Propulsion Laboratory (Morkos, Mathieson, Summers, & Matthews, 2010), and the development of a tent ballast resistance testing system for the Industrial Fabrics Association International with Dr. Blouin. These projects are critical opportunities to provide students with relevant design and development practice while in graduate school. Moreover, they have been used for case study exploration of information exchange during the projects (Miller & Summers, 2010) and as experimental elements in understanding how the presence of proposed controls influence students’ ability to estimate project success (Thimmaiah & Summers, 2013).

A different development opportunity in 2006 led to an expansive collaborative research effort in design and analysis of meso-structures. This opportunity was initiated with a short three-week visit by Dr. Summers at NASA’s Jet Propulsion Laboratory funded by Michelin to explore possible material replacement for the polyurethane based non-pneumatic tire to support future manned missions to the moon and Mars. This project led to a jointly sponsored capstone design project, in the framework discussed in the next section, through which several undergraduate student teams designed, built, and tested the first generation of lunar Tweel concepts (Stowe et al., 2008). These successful concepts led to two major federally funded and industry collaborative projects from NASA and NIST to develop non-pneumatic tires through meso-structures. These projects, executed collaboratively with Drs. Joseph, Blouin, Cole, Fadel, Mears, Ziegert, and Kurfess, resulted in case study opportunities (Stowe, Thoe, & Summers, 2010), new design methods (Berglind, Ju, & Summers, 2010; Ju, Summers, Ziegert, & Fadel, 2010), and four patent applications. Dr. Summers has advised subsequent student research efforts based on the meso-structure experience development as part of these projects and side sponsored project. These include acoustic-vibration attenuation (Griese, 2012), energy absorption and crushing (Schultz et al., 2012), and meso-structure design method development (Berglind & Summers, 2010; Fazelpour & Summers, 2013).

In addition to this specific meso-structure research, a new endeavor from their projects involves the modeling of sand-tire interaction and the development of traction concepts. These additional efforts have been supported by the US Army through an Automotive Research Center project with Drs. Joseph and Biggers and have been formalized in a six year Creative Inquiry project for undergraduate students. Modeling the sand-tire interaction computationally has provided numerous intellectual challenges to motivate graduate research (Reeves, Biggers, Joseph, Summers, & Ma, 2010). The undergraduate teams have produced results that have been archived in various publications (Satterfield et al., 2013). More significantly, the undergraduate approach to physical testing of sand-tire interaction has resulted in design-build-testing opportunities for students, enabling Dr. Summers to recruit several graduate students with experience in the CEDAR lab.

As evident by these three research themes of design method and tool development, design solution projects, and meso-structure development, Dr. Summers collaborates extensively with colleagues, uses the industry sponsored projects to initiate new research themes, exploits the sponsored projects as motivating and demonstrating cases for other graduate research, and continuously seeks opportunities for graduate and undergraduate student engineering skill development. This philosophy of highly coupled industry-driven, informed, and enhanced research has guided Dr. Summers in advising over four dozen graduate students over the decade of his experience at Clemson University (Summers, 2013).

2.3 Dr. Gregory Mocko – Clemson, 2006-2013

Dr. Mocko's research is focused two primary themes: (1) the development & formalization of knowledge to support mechanical engineering design and manufacturing and the application of tools to mechanical engineering design practice, and (2) the study of tools used in conceptual design to support the ideation process and generation of innovations. Several government and industry sponsored research projects, presented in chronological order, demonstrate the fundamental contributions to engineering design research and the application to industry practice.

Dr. Mocko began work in the area of automotive design and requirements and testing analysis with BMW AG. In this project, he collaborated with Dr. Fadel and Dr. Summers to develop methods and a computational tool to identify, manage, and mitigate changes in engineering requirements. In particular, a graduate student and post-doctoral researcher leveraged existing techniques from the Design Structure Matrix (DSM) and Design Mapping Matrix (DMM) to enable changes in engineering requirements, systems architecture, and validation and verification tests to be evaluated (Mocko Gregory et al., 2007). The research project resulted in an MS thesis under the supervision of Dr. Fadel and several papers presented at national and international academic conferences as well as at the BMW Research and Development Center (FIZ) in Munich, Germany. The contributions from this research were applied to several automotive systems to help identify key engineering requirements and tests during conceptual product development and generational redesign. In addition, the techniques developed were further explored by Dr. Mocko and his graduate students to address concepts of manufacturing flexibility and change management. An approach was developed to guide designers during system changes to understand the impacts of requirements on the manufacturing processes. This approach was subsequently applied to the evaluation and redesign of a vehicle headliner and design of innovative automotive seating structures for a first tier automotive supplier.

Dr. Mocko and Dr. Fadel continued to collaborate through the integration of affordance-based design approaches and existing function-based design. In this research, sponsored by the U.S. National Science Foundation, the situated context of engineered products was explored as both [active] function and passive functions [affordances]. Situatedness is defined as how a product is used, the users of the product, and the interactions between the product and the user, other products, and the environment. Situatedness provides a larger scope and context that must be considered when designing a product over the traditional view of engineering function modelling. The goal of this research is to provide formal tools for product design that integrate functional and non-functional approaches. Dr. Mocko’s graduate students formalized a model and a method for capturing active product functions, product-product interactions, product-environment interactions, and product-user interactions. The different types of interactions as well as the activities performed by the user are modelled. A graphical modelling technique and template are developed to aid in the documentation, modelling, archival, and communication of situatedness for a product. Further, they validated and verified the approaches through several user and empirical studies. The model of situatedness was then applied to the development of automotive seating structures in which the functionality of the seating structure and the interaction of the seat with the vehicle occupant and vehicle is of primary importance. In addition, a focused research topic in the area of modelling and analysis of engineering requirements using advance text and language processing techniques was identified. A graduate student identified and developed formal models of engineering requirements using computational linguistics and natural language processing approaches and tools (Caldwell & Mocko, 2009, 2011; Caldwell, Ramachandran, & Mocko, 2012; Caldwell, Sen, Mocko, & Summers, 2010; Caldwell, Thomas, Sen, Mocko, & Summers, 2012; Ramachandran, Caldwell, & Mocko, 2011).

Dr. Mocko and Dr. Summers, and two graduate students worked with an international packaging and machine design company to assess, develop, and integrate rule-based CAD design systems into their product design process. In this project, students worked closely with engineers, developers, and sales engineers to identify the business and design rules associated with their products, documented the rules in a formal manner, and implemented the rules in commercial CAD and rule-based systems. Using the results from this research i) the industry sponsor captured and recorded their business rules, ii) the rules and parametric CAD models were developed for use by the industry sponsor, and iii) the rule based approach, what was learned about rules helped to integrate the rule-based application into Solidworks. This project was a great example of closely collaboration with industry on both a practical design problem and a research opportunity (Chavali et al., 2008)

Dr. Mocko, Dr. Fadel, Dr. Maier (a former student of Dr. Fadel), and a graduate student worked with the Automotive Research Center (ARC) at the University of Michigan and the ARMY TACOM to develop methods for mass reduction in military vehicles to increase safety, material costs, transportation, cost, and fuel consumption to name a few. A requirements method was developed and exercised in the conceptual stages of design to identify requirements that impact significant amounts of mass. Engineering requirements are linked to mass through the creation of a standard requirement statement using pre-processing rules and syntax rules. These rules and guidelines are applicable for authoring new requirements and analysing existing requirements documentation. The processed engineering requirements are linked to physical components and assemblies based on how the requirements affect the components. These relationships are captured in Design Structure Matrices (DSMs) and Domain Mapping Matrices (DMMs). These DMMs and DSMs are used to attain the amount of mass each requirement affects and the level of coupling of each requirement. The method is demonstrated on three subsystems of Family of Medium Tactical Vehicle (FMTV) truck (Maier, McLellan, Mocko, & Fadel, 2009; McLellan, Maier, Fadel, & Mocko, 2009a, 2009b).

Dr. Mocko collaborated with Dr. Ziegert (University of North Carolina-Charlotte) and Dr. Summers with several engineer and product designers to develop (1) innovative and lightweight seating concepts, and (2) a method to support design space exploration and concept development. Several graduate students and researchers from Clemson University worked directly with design engineers to explore innovative manufacturing methods, new technology developments, analysis of seating requirements, and mechanism design with the goal of radical design and innovation. During the development of innovative seating concepts, Dr. Mocko and the students developed a conceptual design method to support distributed conceptual design space exploration. The process and information was developed in collaboration with industry partners and has resulted in an Options Exploration method currently in use at Johnson Controls Incorporated (George, Renu, & Mocko, 2013).

Dr. Mocko and Dr. Summers worked with researchers at BMW AG and BMW MC to develop methods to analyse existing vehicle designs and future concepts to reduce mass. As part of a two-year project, several graduate students developed methods and computational tools to support the analysis of vehicle to reduce mass, and thereby improve performance, from the perspective of both design and manufacturing. The methods and tools developed were applied to a conceptual vehicle design workshop attended by several vehicle designers and manufacturing engineering, and a Clemson University student. In this workshop, and existing vehicle was reverse engineered, benchmarked against other vehicles, and the Lazy Parts Identification Method was applied to identify areas for mass reduction. The approach is currently being used by BMW associates and has led to several new research projects.

Dr. Mocko has been specifically working with Dr. Summers towards the development of next-generation knowledge representations for manufacturing enterprises. Dr. Mocko's students in collaboration with Dr. Funk and Dr. Schulte at BMW AG have identified and formalized the knowledge associated with assembly line process descriptions and relationships with other sources of engineering knowledge including CAD representations, logistics models, and work place models. These knowledge representations have been developed to support a closer integration of existing databases and tasks that are performed in the extended supply and manufacturing network. In addition, Dr. Mocko has collaborated with Dr. Mayorga (now at NC State), Dr. Mears, and Dr. Kurz to support mixed assembly line balancing algorithms. Dr. Mocko's students have developed several tools, including web-based and local tools to support line balancing. During this three-year project, they developed a formalized language for the representation of assembly instructions. The project has directly enhanced the development of next generation tools and approaches for modelling, managing, and analysing assembly instructions in the automotive field with potential applications in consumer product and aerospace (Peterson, Mocko, & Summers, 2012; Renu, Peterson, Mocko, & Summers, 2013).

The common themes across the sample of research and development projects are summarized as follows:

- Close collaboration with industry. This includes several site visits, teleconferences, meetings, and workshops during the projects to have a true impact on industry. Academic research can quickly veer off course. During the completion of these projects, the PIs and students have been intimately involved with industry - often through interns or extended work periods
- The research themes continue from project to project with a particular focus on information and knowledge representation and methods to support conceptual design
- Research must be both demonstrated and validated with real problems.
- There must be a value proposition for industry.

3 Design Education and its Impact on Industry

Being an education institution, our biggest impact on industry is certainly our education of engineers who join the work force and bring some of our methods and tools to industry and transfer that knowledge to their companies. One fundamental component of the education of design happens at the undergraduate level. Though undergraduate education can be deemed as separate from the results of our design research, it is indeed affects and is affected by that research. At the graduate level, the research is directly incorporated into courses and the knowledge is therefore readily transmitted to students who pursue advanced degrees. We will first describe the undergraduate and then the graduate experience.

3.1 Undergraduate Design

At Clemson University, capstone students are expected to have completed their introductory and secondary technical engineering courses. This capstone course provides students an opportunity to apply the knowledge gained from their previous courses while adapting design techniques to execute technical tasks. Capstone is a three credit hour course given during a single semester in which each student is grouped into a team of three to four students. This encourages the student to work on his or her own social skills alongside their technical knowledge. The student teams are provided with an industry sponsored design project. Teams must apply their knowledge of the design process to complete the project successfully.

The capstone design program in the Department of Mechanical Engineering at Clemson University has been a critical part of the curriculum for over forty years. Industry partners sponsor all projects and three to five teams of four to five students are assigned to each project. The expectation of each student is ten to fifteen hours of work per week so that for a team of five, the final deliverable is well over 600 man-hours throughout the semester.

The capstone course occurs during a normal Fall or Spring semester. During those fifteen-weeks, students are expected to work in their assigned teams to design, build and test a solution to their design problem. A summary of available projects is distributed amongst the capstone students and each student must submit a resume form to ascertain each student's experience level in design and fields of interest. The form also requires students to select one negative and two positive choices for their preferences in terms of projects or teammates. These forms are then used to assign students to teams.

Each design problem is assigned to three teams of at least four Students. The teams work independently to solve the same industry problem. Each student team is presented with the problem simultaneously by the sponsor on the Clemson campus and provided the same information regarding the project. Each team is expected to design, prototype and test their proposed solutions. They must also document their solutions and any findings from testing. Assigning multiple teams to the same problem allows for three to four distinct developed, prototyped, and tested solutions.

Industry sponsors provide the teams with a presentation of the problem to be solved. This presentation is succeeded by a plant tour and student verification and clarification of the proposed problem. Student teams provide the sponsor with an official progress report in their midterm presentation. They must then present their understanding of the problem during the midterm presentation. The sponsor is expected to be available to answer questions periodically throughout the semester. At the conclusion of the semester, teams present their final design and recommendations to the sponsor.

On campus, students have access to multiple forms of technical aides. The student machine shop is available during normal business hours where students can use machining tools such as mills, lathes, and other power and hand tools to prototype their designs. They also have access to a computational lab for the creation of computer models and analysis as well as a meeting and discussion room reserved solely for the capstone design teams. Students are encouraged to use this room to meet weekly to collaborate on their team-based designs.

Two faculty members and a graduate coach are assigned to each project as an advisory committee. Weekly design reviews are conducted to provide feedback to the student design teams. Teams prepare a fifteen minute presentation to summarize the work completed over the past week and to propose a schedule of tasks for the upcoming week. Approximately eight weeks into the semester, teams are required to give a mid-term presentation to the sponsor, including the understanding of the problem and their proposed solution ideas. During the second half of the semester, the teams must choose, build and test a prototype solution. The results of the testing must be included in their final presentation and design report. Final deliverables include a prototype, fully detailed solution, and final design report complete with any necessary drawings and information for implementing the chosen solution.

The graduate coach, known as the gradvisor, is a graduate student specializing in design. The gradvisor must have taken graduate design methodology courses, and properly advise the students to ensure they apply the design process properly, understand the design tools they were taught for applying this process, and support their decision making with analysis, reasoning, and experiments. The gradvisors also provide feedback on oral and written communication. This gradvisors participation is rather unique, and several have used the opportunity to coach teams to also conduct research on the design process. They observe how students work, run experiments with them, and produce results that have been published. Naturally, IRB approval is sought, and the students must agree to be observed and used in the experiments. We have used much of this research to improve the process, which has also been invaluable to our graduates who have taken this knowledge and their respective employers upon graduation.

3.2 Graduate education

We have designed an evolving list of courses offered to our students, starting with technical electives that senior undergraduate students and entering graduate students may select (4xxx/6xxx courses) and ending with much more in-depth courses for Masters and PhD students (8xxx courses). These course descriptions are provided below. Note that occasionally, engineers working in industry enrol in these courses. Several were precursors to research and others were the results of design research. The Rapid prototyping, and the Integration through Optimization courses are the results of sponsored research identifying new methods and tools and transitioning them to classroom for eventual use with future employers.

ME 4550/6550: Design for Manufacturing. Concepts of product and process design for automated manufacturing are discussed. Topics include product design for automated manufacturing, inspection and assembly using automation, industrial robots, knowledge-based systems, and concepts of flexible product manufacture.
ME 4710/6710: Computer-Aided Engineering Analysis and Design. Students are exposed to geometric and solid modeling, finite elements, optimization, and rapid-prototyping. Students design an artifact, represent it on the computer, analyze it using FEA and optimize before prototyping it.
ME4930/6930: Rapid Prototyping. Students are introduced to the additive and subtractive manufacturing and associated technologies that affect the contemporary design for manufacture (DFM) practices. The course includes CAD issues for rapid prototyping (RP), reverse engineering (RE) for model reconstruction from existing physical parts through digitizing, and an understanding of the several layer-based and "rapid" manufacturing technologies. Theory and methodology are supplemented with examples and case studies.
ME 8700: Advanced Design Methodologies. Nurturing or creativity; decision-making processes for design, in-depth study of the mechanical design process and tools; quality function deployment, concurrent design, systemic design, robust design, design for assembly, and axiomatic design.
ME 8710: Engineering Optimization. Optimization in the context of engineering design; nonlinear and linear, static and dynamic, constrained and unconstrained formulation and solution of practical problems; structural optimization; multi-objective optimization; genetic algorithms; simulated annealing.
ME 8720: Design Automation for Mechanical Engineers. Students are exposed to data structures, search algorithms, geometric algorithms, geometric modeling, and software engineering for mechanical engineers. Students design and implement mechanical CAD software packages. The use of software development tools, algorithm design, and their interfaces in mechanical engineering is emphasized.

ME 8730: Research Methods in Collaborative Design. Topics include research methods for studying collaborative design, influencing factor of collaboration, computer issues in collaboration, and mechanical engineering as facilitated by collaboration. Technical writing and experimentation are emphasized.

ME 8740: Integration Through Optimization. Theory, methodology and applications of decomposition, integration and coordination for large-scale or complex optimization problems encountered in engineering design. Topics include conventional and non-conventional engineering optimization algorithms, analysis models and methods, multidisciplinary optimization, and multi-criteria optimization. Case studies are included.

ME8930: Design Informatics. Students learn database management development and implementation, software engineering, knowledge representation and reasoning, search and retrieval to support engineering design and manufacturing enterprises. Students are introduced to current issues associated with information management systems in engineering, technologies and tools to address these issues, and systematic methods to design and develop solutions. Students design, develop specifications, and implement engineering information management software packages.

4 Conclusions

This chapter summarizes some of the research topics conducted by the faculty and students in the CEDAR group at Clemson University. The close collaboration with industry shows that the work they undertook has enhanced industrial manufacturing practice. Continued support by industry and government, and the transition of this fundamental research supported by the US National Science Foundation for use in both the industrial environment and the classroom indeed shows both the success and effectiveness of our model.

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