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Rethinking Automotive Engineering Education – Deep Orange as a Collaborative Innovation Framework for Project-Based Learning Incorporating Real-World Case Studies

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Abstract

Through the traditional education for engineering discipline, students are expected to be familiar with basics of engineering design and principles through stages of educational materials explanation and a series of assignments and/or class projects. Commonly, the knowledge flow offered to engineering students is based on a step-by-step process taught by faculty using textbooks. Real-world problems often necessitate solutions that are not obtainable from traditional textbooks, such as ideation and selection of meaningful solutions, learning to deal with trade-offs, balancing competing properties, collaborating and communicating with colleagues whose perspectives are shaped by different backgrounds, in addition to the ability to visualize solutions. This paper discusses the implementation of Project-Based Learning (PBL) within the curriculum of the automotive engineering department at Clemson University in collaboration with the transportation design department at Art Center College of Design (ACCD).

The program, called Deep Orange, is focused on developing and producing innovative new vehicle concepts and is driven entirely by graduate automotive engineering and transportation design students as part of their education in collaboration with industry partners. The paper discusses and demonstrates the methodology followed to translate PBL components within the educational context as well as the process the students need to follow. During this process, the students start with translating the grand challenge (defined by the sponsoring industry partners) into consumer needs and wants incorporating market and trend analyses. The project proceeds with general explorations, investigation of various design and vehicle architecture alternatives including selection of one concept based on carefully balancing environmental, economic, and social aspects. During this process, the faculty serves as mentors rather than knowledge dispensers. The students are empowered to make decisions and justify their concept selection to different groups, i.e. faculty members and industrial partners. The last eight months of each project comprises of building a physical prototype and validation of target achievement. Extensive marketing of the project outcomes at trade-shows with graduates involved concludes each project.

1. Introduction

The traditional education approach for engineering has struggled to provide young engineers with the necessary skills and experiences needed to succeed in today's professional practices; for the most part, the current educational methodology is generally the same as that used during the last century going back as early as the 1940s [1]. According to Wagner [2] America's last competitive advantage - its ability to innovate - is at risk because of the country's lackluster education system. Wagner identified five reasons in which America's education system is inhibiting innovation: 1) Individual achievement is the focus, 2)

Specialization is celebrated and rewarded, 3) Risk aversion is the norm, 4) Learning is profoundly passive and 5) Extrinsic incentives drive learning.

In a recent study, the American Society of Mechanical Engineers (ASME) defined aspects that the engineering education is currently lacking [3], with focus on mechanical engineering. The most absent aspects are practical experiences, an overall system perspective, an understanding of engineering codes and standards, oral and written communication skills, problem-solving skills, critical thinking skills, and project management skills. To bridge the gap between the current state and the needed changes, ASME identified the following actions for curricular change: 1) Offer more authentic practice-based engineering experiences such as the design spine or design portfolio approach (these skills should be learned in the context of a structured approach to problem solving - problem formulation, problem analysis, and solution), 2) Incorporate "Grand Challenges" into the design spine (such as energy, sustainable development, population growth, and health issues), 3) Create a curriculum that inspires innovation and creativity (professional skills such as problem solving, teamwork, leadership, entrepreneurship, innovation, and project management need to be central features of the design spine) and 4) Increase faculty expertise in professional practice.

The present engineering education requires some fundamental changes. Particularly, changes that develop dynamic educational curriculum that rapidly respond to industry requirements while in the same time adhering to the basic needs of traditional engineering. Today, the design, manufacture, and effectiveness of modern road transportation require the integrated application of concepts in disciplines ranging from engineering and information technology to business and behavioral sciences. The challenges and opportunities arise from advances in enabling technologies amid the myriad of often conflicting and ever-changing public regulations and policies. The rate of market change has dramatically increased challenging product development speed and innovation cycles. Furthermore, it is increasingly difficult to forecast and integrate future product requirements into new products and services. Our industry is in dire need of an engineering workforce that can master/lead this process.

Tomorrow's engineering leader will need to combine deep knowledge of a particular field with the breadth to place it in context. They will need to collaborate with many other industries as well as with colleagues whose perspectives are shaped by radically different experiences. They will need to understand systems, cultural, societal, and political forces. Tomorrow's engineer will also need to tackle complex problems, and be thoughtful about the lifecycles of their work and production. Wagner [4] identified core competencies that every student must master to lead the innovation process being: 1) Critical thinking and problem solving (the ability to ask the right questions), 2) Collaboration across networks and leading by influence, 3) Agility and adaptability, 4) Initiative and entrepreneurialism, 4)

Accessing and analyzing information, 5) Effective written and oral communication and 6) Curiosity and imagination.

An educational approach that is increasingly common in engineering education to meet those requirements is Project-Based Learning (PBL). It is believed that PBL can satisfy the needs of active learning to develop robust professional skills [5], which greatly depend on design and creativity, as is the case in automotive engineering.

The PBL model requires design principles that convey the learning objectives and ensures the effectiveness of the model. Barron et al. [6] discussed main four principles necessary for the success of PBL including: 1) clear learning purposes, that convey the project goals and objectives, the major questions the project will answer, and the connections between the design activities and the learning purposes the faculty are seeking; 2) learning infrastructure that supports both student and teacher learning and how each major answer to the open questions will be addressed. This infrastructure can be in the form of steps and phases the students need to follow to reach the outcome. However, the learning infrastructure is not required to state the desired results, rather it highlights the tools needed to reach them; 3) revision and assessment plans. The evaluation process can include self, peer, student to faculty, and faculty to student assessments to ensure that the learning objectives are met; 4) promoting participation and involvement through proper social organization of the students groups, faculty, and public community. The students' groups and forums should be structured to promote participation. The participation should provide structure for the necessary roles and interaction needed for project completion, which may include mentoring roles of faculty, mentoring and/or advising from industry professionals and even students groups.

Ayas and Zeniuk [7] suggested two additional elements for PBL model. Their work focused on the implementation of PBL in applied environments and showcased examples from industry that have similar needs to educational institutions. They emphasized the importance of 1) leader role models which set the attitude for learning and monitor the behavior and results, and 2) the need to build a psychologically safe learning environment, where there is an atmosphere to encourage open and honest discussion. Figure 1 summarizes the PBL model's major principles.

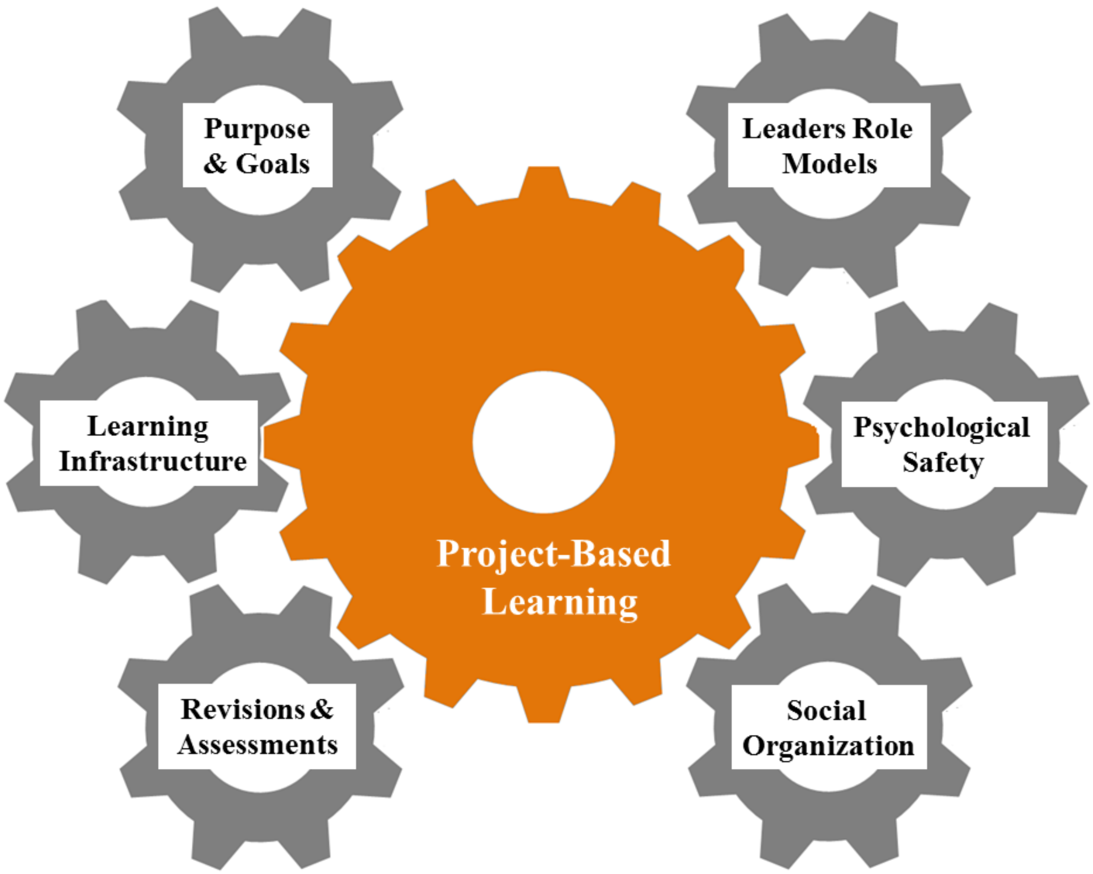


Figure 1. The major six principles of PBL model.

The Automotive Engineering Department at Clemson University-International Center for Automotive Research (CU-ICAR) initiated an educational framework that incorporated PBL within the curriculum known as Deep Orange (DO), a vehicle prototyping project. The teaching paradigm of DO satisfies the needs of engineering education to encourage active learning that can achieve the engineering education objectives as well as respond to industry needs.

2. The Deep Orange Framework

In 2009, the Deep Orange initiative was launched as a part of the curriculum for the master's program of an Automotive Engineering's department at Clemson University in partnership with the Art Center Transportation Design Department in Pasadena, California. The Automotive Engineering curriculum merges the depth (through specialization tracks) and breadth (through the interdisciplinary Deep Orange initiative) into an integrated scholastic experience. Deep Orange is a framework that immerses students into the world of a future Original Equipment Manufacturer (OEM) and/or supplier emulating an accelerated product development process of a new vehicle. Working collaboratively, students, multi-disciplinary faculty, and participating industry partners focus on producing a new vehicle concept with each cohort of students, where the industry participation and mentoring plays an essential role.

Each DO project incorporates integrating breakthrough product innovations and new processes, which provide the students with hands-on experience in multi-disciplinary areas, such as market analysis, creation of the value proposition, vehicle design, engineering concepts, product development, systems integration, prototyping, production, and quality testing from their entry into the automotive engineering program until graduation. The strategic focus of DO is to develop new automotive/mobility solutions that address a grand challenge (such as sustainability, safety, health, and wellbeing). Currently, Deep Orange is in its fifth and sixth series, the annual two-year project is divided into six main design stages illustrated in Figure 2, which include:

- Strategy and market assessment, identification of opportunities and creation of the value proposition.
- Ideation, solution formulation, and concept selection.
- Concept development (detailing engineering and design).
- Systems integration (design space, function, production).
- Prototype build and assembly.
- Product confirmation and target validation.

The development cycle of the vehicle design initiates the project with the value proposition and defining customer needs; the students are required to justify all of the generated solutions and concepts within the context of the derived customer needs. This design methodology ensures the confirmation of design specifications to the initial targets.

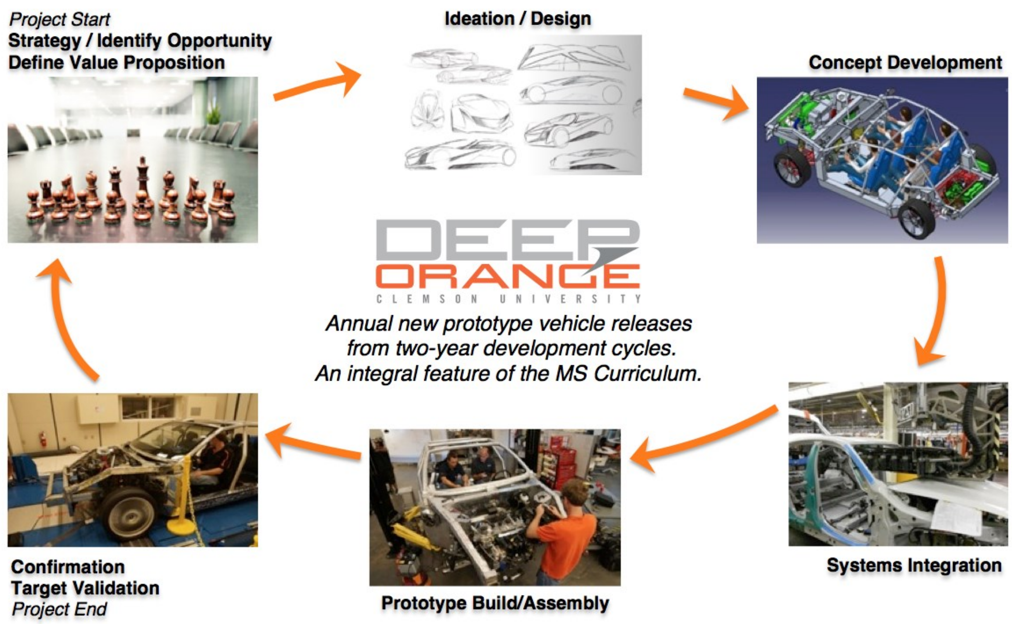


Figure 2. The 2-year Deep Orange vehicle development cycle.

3. Integration of Deep Orange in the Automotive Engineering Curriculum

The Automotive Engineering MS curriculum was designed as a two-year, post-BS degree program consisting of a minimum of 42 credit hours. The students first complete 36 credit hours of graduate coursework, which is concluded with a six-month internship (consisting of six credit hours). This internship was included to ensure students have the opportunity to incorporate industry needs within their educational experience. The internship requirement can be met through a traditional industry internship where students typically gain a great deal of experience in a single topic area (depth) or through DO where students get experience with both depth and breadth.

The Automotive Engineering MS curriculum is divided into four content areas including core courses, technical electives, business courses, and the industrial or DO internship. Figure 3 illustrates the program's courses. The core courses are 15 credit hours (five courses), or 18 credit hours (six courses) if a student participated in DO. The content and objectives of the core courses focus on engineering topics that convey the fundamental technical concepts including automotive design, project management, automotive systems overview, systems integration concepts and methods, applied systems integration, automotive systems manufacturing, and automotive electronics. These topics are the backbone of the DO program. The rest of classes are designed to provide more detailed technical knowledge, which are based on the vehicle system designated to one of four specializations tracks: 1) advanced powertrains and drivelines, 2) vehicle manufacturing and materials, 3) vehicle performance, or 4) vehicle electronics/electrical systems. In addition, the curriculum includes business classes to prepare students to lead technological change as an independent entrepreneur within a complex organization. Figure 4 illustrates the time domain of the curriculum and the integration of DO within the MS program. The designed classes are essential components for the DO project, where each class covers the basic engineering knowledge for each vehicle system.

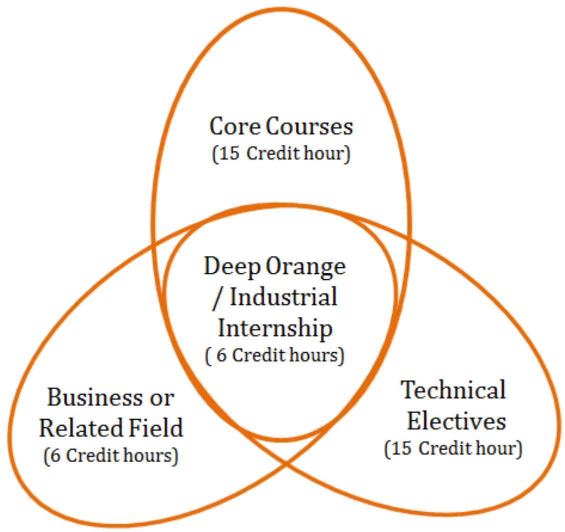


Figure 3. The courses are designed to support the DO project for the master program.

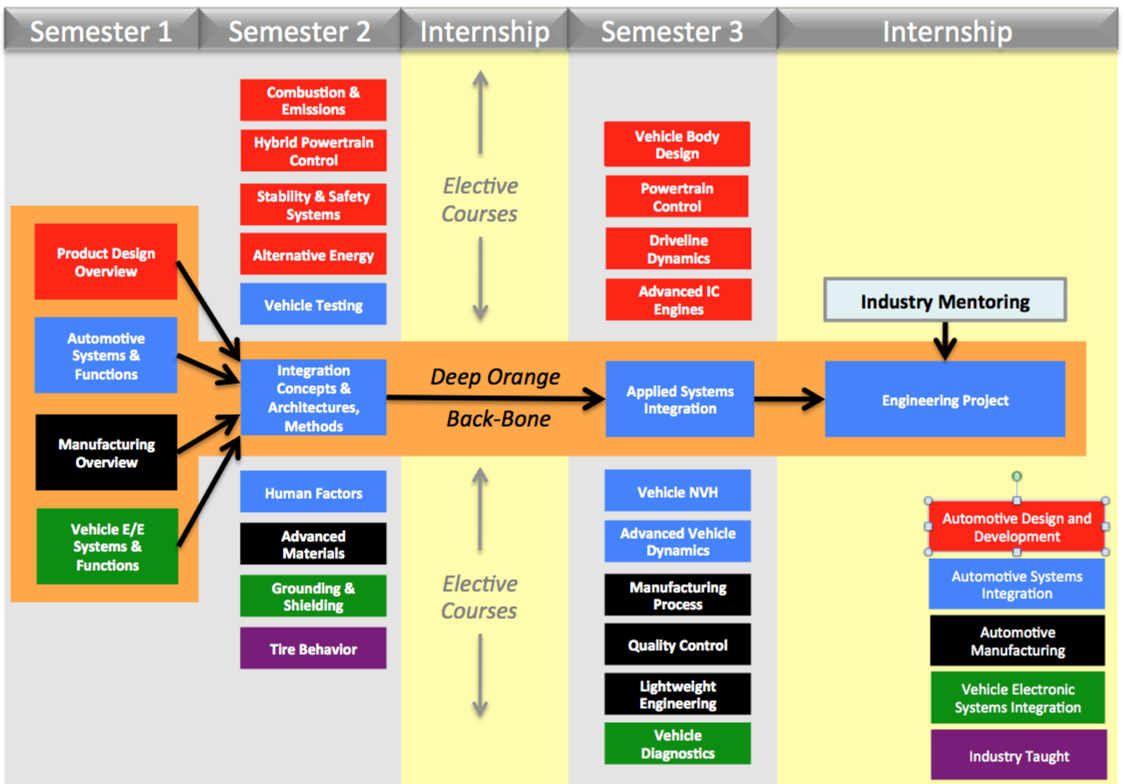


Figure 4. The engineering curriculum includes core courses offered in the first semester as will as four specialization areas: automotive design and development (in red), automotive systems integration courses (in blue), automotive manufacturing courses (in black) and vehicle electronics courses (in green), industry taught courses (in purple).

4. Deep Orange Educational Elements

In order to achieve the robust and effective PBL approach, DO utilizes the following educational elements:

- **Strategic Thinking.** All of the major design activities are driven by engineering principles derived from content standards and the needs of customers. At the first stage of DO, the students are engaged in a strategic phase consisting of trend and market analysis including data mining vehicle owner surveys. This stage is incorporated to develop the students' ability to identify an opportunity/need and to connect "pure" engineering design concepts with (real-world) customer wants/needs. The challenge consists of translating these non-technical customer responses into engineering targets for the vehicle to be developed. The students support the strategy process by benchmarking competitors' vehicles that are available in the market and evaluate them based on to the technical requirements they derived from customers' needs. The faculty role is to mentor, provide feedback and direction rather than defining the problem statement and project boundaries.

- **Ideation and Candidate Solution Formulation.** The design of vehicle prototype, which should be able to compete in the future market, is an open-ended design problem that requires the students to explore and search for different design alternatives on both the system and component level. The DO students learn in an opposite order compared to the traditional educational approaches, where the students search for answers, derive conclusions, make decisions, and should be able to justify their design choices within managerial, economic, social, and engineering contexts. At this phase, the students are divided into different team including but not limited to major vehicle subsystems such as interior, chassis, powertrain, vehicle body, vehicle electronics, and project management.

- **Visualization and Demonstration.** Initializing the design with the customer wants/needs in mind, the DO framework requires the students to visualize the final vehicle prototype by mapping the relationship between customer requirements and design solution. The DO design stages include building mock-ups and prototypes that enhance the visualization of the final system and component. This also allows exploring if the various sub-systems will work together as anticipated. It is helpful for the students to see a physical structure rather than the digital visualization of the solution on a computer screen. Component packaging is one example of a challenging task that requires the students to be aware of the component location, interaction with other subsystems, safety aspects, mounting concept, assembly sequence, and serviceability.

- **Decision Making.** During DO, the students are the main drivers of the design. This high level of engagement empowers them to make design decisions as well as decide when ideal characteristics must be cut due to time, budget, or other constraints. The students are taught to make their ideas transparent and translate them into final vehicle systems and concepts that relate back to the target customers and project objectives. They are taught to make decision matrices that incorporate and balance competing properties (such as cost, weight, design space, functional properties, component availability) and learn how to deal with trade-offs. With that, the students own the designs' solutions because they make the decisions as individuals and as a team, which in turn increases their ownership.

- **Feedback Loop.** The DO has preset design reviews on increasing levels of design completion, which include faculty, industry partners, and eventually the public. Hence, the students learn to critique their own work as well as provide and receive feedback. This is an essential element of DO that ensures the quality of the vehicle's final execution. It also enables the students to think holistically, particularly about the impact of their component or system design on the final vehicle's overall concept.

- **Documentation and Presentations Skills:** During the entire DO project, the students are responsible for documenting their work (including decisions/mistakes made and rejected solutions) in an evidence book. In addition, they need to present their progress and the final design to various types of audiences (such as target consumers, faculty, and industry sponsors) and go to industry trade shows to sell their project outcomes. This is very motivating for the students and provides them with real-world experience of having to justify their ideas and decisions to the public.

5. The Role of Collaboration

- **Industry Partnerships.** Deep Orange would simply not make sense without multiple industry partners. Partners range from OEMs to aftermarket suppliers to small, local businesses owners and entrepreneurs. The industry partnerships (on average 20-25 partners participate in each vehicle project) contribute to the development of the DO program for both short-term (e.g., what are the pros and cons between options A and B) and long-term aspects (e.g. the type and target market of a vehicle). Their role includes providing realistic examples of problems encountered in industry that convey engineering challenges and future design requirements to provide the students with concrete examples of trade-off which are constantly made in industry. In addition, the industrial collaborators mentor the students and offer feedback during each stage of the project. The students are frequently involved with 1:1 meetings to resolve technical issues that arise. These interactions between students and mentors are of great benefit since the feedback is given from a pragmatic industrial viewpoint; the industry partners frequently provide tips that generate alternate approaches to achieve the design targets. The partnerships offer access to technological tools and innovative processes / materials that are currently used by OEMs, in addition to the funding of the program. The partners also get to interact with students whom they may hire in the future.

- **Interdisciplinary Collaboration.** The interior and exterior design of the DO vehicle is achieved through a 42-week collaboration (across three terms and 2 semesters) between the engineering and design faculty and students. The team synchronizes the design milestones where in the ideation phase a small team of automotive engineering students is assigned to one transportation design student to jointly generate a vehicle concept. This is the phase where the left-brain (engineering world) collides with the right brain (artistic world) and is a critical project phase where both worlds need to create an understanding for each other's (rational/emotional) drive and motivation. The partnership allows the students to explore creative options and develop unique vehicle concepts that are both feasible (engineering input) and desirable (designer input). The partnering between two educational institutes has created challenges due to the fact that students must collaborate from separate geographic locations with different classroom schedules and a 3-hour time difference (SC and CA). It also requires the students of both institutions to translate and convey the (artistic/customer/engineering) requirements into a mutual (graphics-based) language to discuss the desirability and feasibility of the ideas and concepts developed. At the end of the ideation phase, the industry partners and faculty from both educational institutions evaluate and rate the concepts and select a winning idea to move forward with for the DO concept development and realization phase. Figure 5 shows a design student during the final presentation of his design.

Figure 5. A transportation design student presenting his urban mobility solution.

- **Research Innovation.** DO projects focus on the establishment of existing and new innovative solutions in the design and manufacturing of a concept vehicle. As the program continues to grow, one goal is to incorporate more PhD students to use DO vehicles into their research projects or incorporate new research innovations into DO. This opportunity can enable the definition of future trends in the design and manufacturing of vehicles and explore new innovative trends. One example of a PhD research project, which was incorporated into a DO vehicle, includes doctoral work examining the design analysis for origami folded sheet metal [8], which was implemented in the third DO vehicle.

6. Deep Orange Project Outcomes

To date, 5 Deep Orange projects have been initiated:

- **DO1 "Future Electric Mobility"** (completed in 2010, BMW Sponsored). DO1 focused on the integration of powertrain, energy storage, seating concept, and infotainment elements in one vehicle [9]. A baseline vehicle was converted into a range-extended, plug-in hybrid-electric vehicle with a unique seat attachment architecture that mounts the seats backrest to both the roof and floor of the vehicle. In addition, the vehicle interior relied solely on a portable Smartphone device, in combination with a cloud-storage concept (Figure 6).

Figure 6. Deep Orange 1 at the 2010 SEMA Show.

- **DO2 "Future Digital Cockpit Experience"** (completed in 2011, BMW Sponsored). DO2 focused on the development and implementation of a digital reconfigurable vehicle cockpit for the DO1 vehicle. It demonstrated a new Human Machine Interface (HMI) and center stack design that allowed for personalized, intergenerational driver interaction with various vehicle, infotainment, and climate controls. Multiple usability tests were conducted including students from the automotive engineering, computer science, design, and human factors programs [10] (Figure 7).

Figure 7. Deep Orange 2 at the 2011 SEMA Show.

- **DO3 "The Next BIG Thing"** (completed in 2012, Mazda Sponsored). DO3 is a fully functional hybrid mainstream sports car concept targeted towards Generation Y, Figure 8. The vehicle concept developed was given the name "Next BIG Thing" with a target start-of-production in 2015 and was the first project vehicle built from scratch. The vehicle has a through-the-road parallel hybrid powertrain concept with a manual transmission [11]. The concept design has 6-seater interior concept [12] and body structure made of origami folded sheet metal [13].

Figure 8. Deep Orange 3 at the 2013 LA Auto Show.

- **DO4 “Transformative Activity Vehicle”** (completed in 2014, BMW Sponsored). DO4 focuses on the transformation of a baseline luxury Sport Utility Vehicle (SUV) into a pick-up style truck. A sliding glass roof transforms the hatch compartment from an enclosed area into an open-bed configuration. The interior is designed to seal the passengers’ cabin in addition to rear seats new design to accommodate the storage requirements

- **DO5 “Personal Emotional Urban Mobility for Generation Y/Z”** (completed in 2014, Chevrolet Sponsored). DO5 is about creating a better value proposition for young adults that have little money to spare, that have less interest in vehicle ownership, need a personal mobility solution for commuting and shopping at the lowest cost of ownership, and have the desire for extra space, and performance for leisure activities. In addition, the project is about creating a solution where social networking and mobility go hand-in-hand ultimately creating an emotional connection with the vehicle, which leads to the creation of a mobility lifestyle.

7. Project Framework

Succeeding in the future job market means equipping the current engineering students with skills that enable them to cope with rapid changes in technological and cultural aspects [14]. The nature of the DO design stages and activities require the students to learn and master multidimensional skills and do much more than remembering information presented in a classroom setting. The students explore the spectrum of design alternatives, learn to compromise between teams, and reach feasible solutions that satisfy competing objectives. DO starts with a market analysis, where the students investigate the target segments and derive the customer needs and wants in the vehicle design. The major design stages are listed in Figure 9. For each stage, the faculty set the team responsibilities, the deliverables, and milestones. Through the different vehicle development stages, the students learn skills such as solution development, analytical reasoning, and application of mathematical and engineering concepts to size components and validate system performance. The DO product development activities also require the students to develop skills such as communication (selling ideas/concept to faculty and industry sponsors), multicultural awareness (many student come from different nations), management skills, teamwork, and creativity.

The DO educational paradigm concentrates on three levels comprising support, education skills, and attributes skills (Figure 10). Important element of the three levels include:

- **Curriculum and instructions.** The faculty set the overall deadlines and initial scope of work to ensure the students have the skills needed for each step of the DO process in conjunction with their courses (Figure 4). Students are selected for a DO team through a formal application process after their first semester in MS program. The selection criteria include academic performance during the first semester, prior experience in vehicles engineering and build, a statement of interest and the area of specialty selected (i.e., management, powertrain, chassis, interior, or body structure).

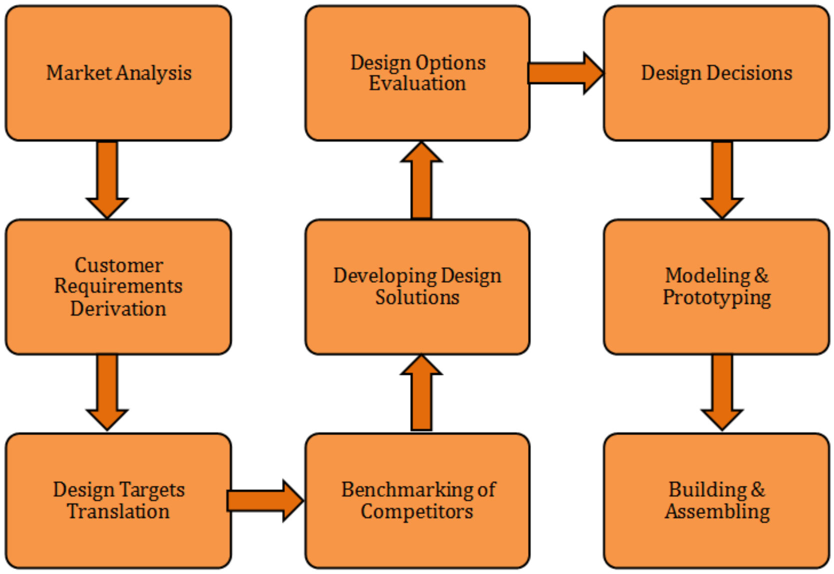


Figure 9. Major tasks within the Deep Orange product development process.

- **Establishing the learning environment.** The nature of designing activities requires an environment that is not of a traditional classroom nature. Deep Orange requires students to collaborate and interact with each other and with faculty on a regular basis in a permanent collaborative space (resembling a studio). The students work on workstations grouped by their team membership as well as team white boards in the Systems Integration Laboratory (SIL), which is divided into two sections; one is an office like area, and the second is a workshop to build and assemble the concept vehicle. The SIL is equipped with computers and software licenses for vehicle design analysis such as occupant comfort analysis, finite element analysis, and vehicle dynamics simulation. It also contains necessary tools and equipment for the vehicle assembly and build.

- **Determining the Standards and Timeline.** This includes providing standard templates for exchanged documents such as a target specification catalog, engineering convergence, outline of the design review presentations, etc. In addition, the faculty set the major milestones and due dates for design maturity, see Section 8.

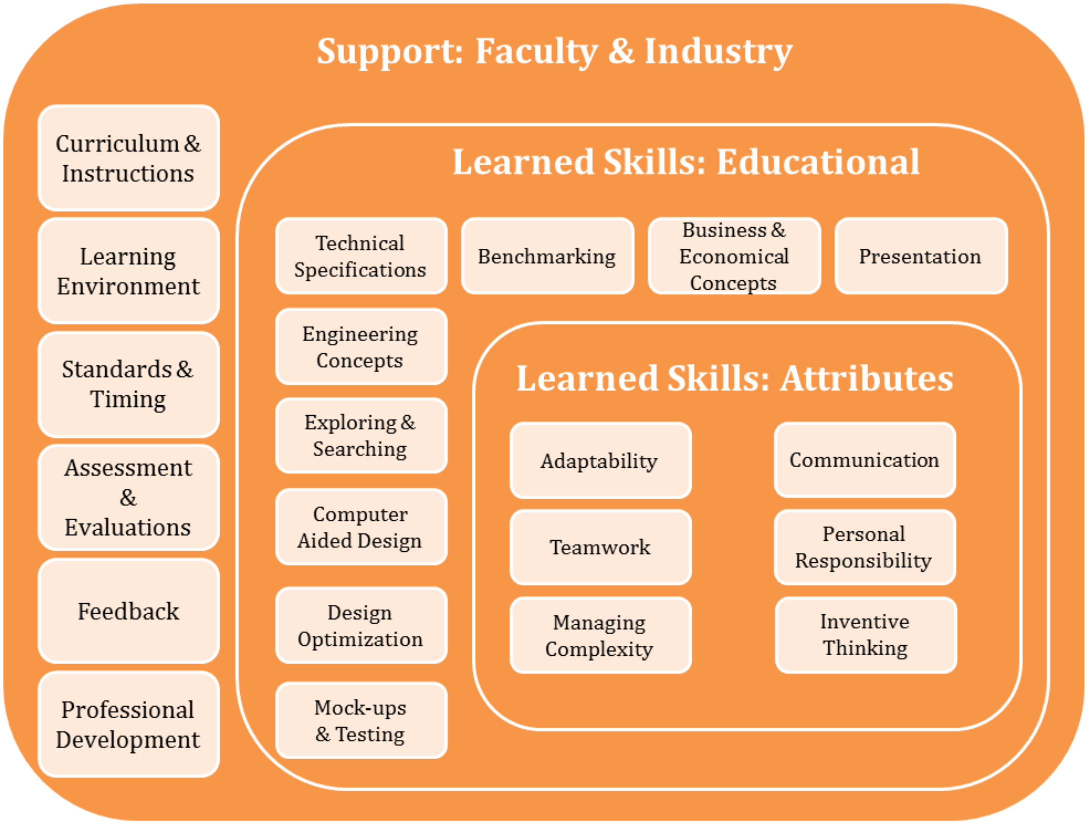


Figure 10. DO educational Framework.

- **Students Evaluations.** An important aspect of the student evaluations is the grading scheme and procedure. The students are graded based on the design maturity and meeting the target specifications of the concept vehicle by each milestone date. Furthermore, a part of the students' grade is based on performance and peer evaluations, where each student's performance is rated based on nine elements: quality of work, timeliness of work, task support, interaction with teammates, attendance, responsibility, involvement, leadership, and overall performance using a 1-5 scale with 5 being excellent. Table 1 provides an example of the performance evaluation template. Moreover, the students evaluate each other's performance via a confidential peer evaluation that uses the same template. Students are also required to include a strength and weakness of each team member. While faculty evaluates all students, team members only evaluate a subset of the team based upon regular interaction.

- **Provide Feedback Loop.** The students demonstrate their work, design ideas, solutions, and engineering analysis such as simulation prototypes and models. The role of faculty and industry partners is to give systematic feedback on feasibility, suitability of the design solution to the customer needs, and the confirmation to the targeted specifications. In addition, the faculty encourages the students to assess their solutions with respect to manufacturability, assembly, packaging, and serviceability, which all can influence the solution space and selection. One key role of this feedback is to ensure systems integration, compatibility, and the alignment to the overall project theme and technical specifications. The feedback is also provided systematically, i.e., weekly, upon each milestone, and upon major design decisions.

Table 1 Performance evaluation template.

Faculty Rating													
Group Members Names	***Attendance (# of Abscense)***	**Quality of work**	**Timeliness of work**	**Task support**	**Interaction**	**Attendance**	**Responsibility**	**Involvement**	**Leadership**	**Overall Performance**	**Sum**	**Duties**	**Remarks**
Max.		***4.0***	***4.0***	***4.0***	***4.0***	***4.0***	***4.0***	***4.0***	***4.0***	***4.0***	***36.0***		
Student X	1	3.3	3	3.5	3.8	4	4	3.8	3.4	3.8	32.4	Responsibilities - Project Manager, timing, target catalog, BOM	
Student Y	0	3.3	3	3	3.3	4	4	3.7	3.3	3.7	31.05	Responsibilities - Chassis , overall integration, steering, target catalog, BOM, full vehicle SimPack analysis	
Student Z	2	3	3	2.8	2.8	3.5	3.9	2.8	3	3.4	28.05	Responsibilities - Powertrain, BOM, Target Catalogue, Energy Management	
Student E	0	3.3	3	3.3	3.5	4	4	3.5	3	3.8	31.2	Responsibilities - Interior , Reconfigurable Interior, Comfort Assessment, Positioning of HMI, Target Catalog	

- **Professional Development.** In addition to the educational objectives, the DO framework support students' professional development to prepare them for their future work environment. The students are encouraged to identify, select and contact project partners as well as working directly with those suppliers in case a match was established. The students are required to attend academic guest lectures as well as career development workshops offered by the university's Career Center.
- **Multidimensional Skills**. DO focuses on educational and attributes skills through the design activities.

– Benchmarking. The design activities start exploration of available vehicle and concepts on the market, their specifications, and design solutions. The students assess the vehicles based on the technical target specifications and their potential to meet customer requirements and needs. This is an important feature of the project where the students learn to critique the engineering design and assess its practicability from a customer's point view (role playing). Figure 11 shows benchmarking notes completed by students for a vehicle interior to show the strengths and weaknesses from a customer's perspective.

- Business Concepts. The vehicle development stages include cost estimating, budgeting, and procurement. A project budget will be allocated to complete the prototype vehicle and the students are in charge of maintaining the project costs and propose where to spend the resources on. Furthermore, the student will need to show that a targeted Manufacturer's Suggested Retail Price (MSRP) for their vehicle concept (build as a series production vehicle) is achievable with the technology solutions proposed and capital investments required based on an assumed production volume/location.

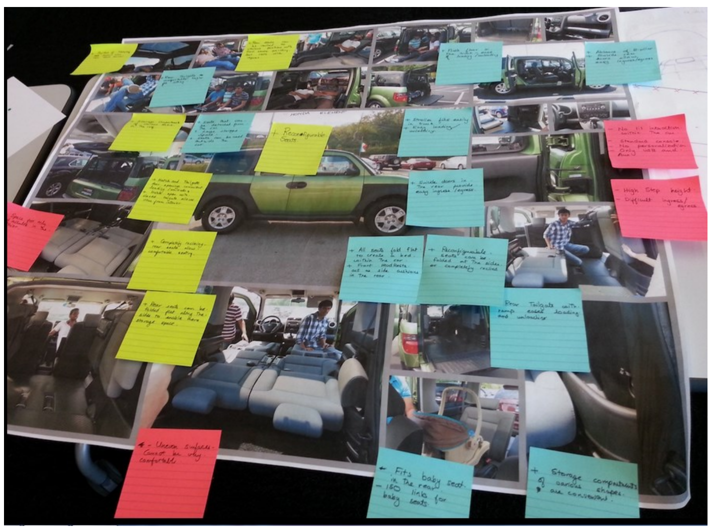
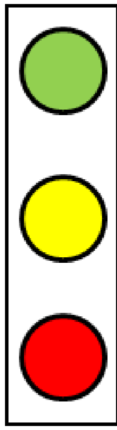


Figure 11. Benchmarking notes for a vehicle interior.

- Technical Specifications. This engineering skill includes applying a systems engineering approach to translating the (often intangible) customer's needs/wants into (measurable) technical specifications. A 3-level project target catalog is used throughout the project development process to track the project status and maturity. The first level consists of customer relevant full-vehicle level targets that are classified into program, functional, and geometric categories. The second level consists of sub-system requirements (a typical subsystem is a powertrain or a chassis) that represent specifications of these subsystems to achieve the overall desired vehicle targets. The third level represent to component specifications (such as an engine, gearbox or wheel). The overall status of each DO project (at any instance) can be assessed based on achievement of the level 1, 2 and 3 targets using traffic lights. Table 2 provides the criterion of such a traffic light based on the target specification and the deviation of the status from that specific target.

Table 2. Traffic lights symbols and their technical translation.



Target	Deviation
Target ok No Impact/ Issues All Systems are GO	< 5%
Close to Target Minor Impact/Issues Work in Progress	5 – 10%
Far from Target Major Impact/ Issues Recovery Plan Required	> 10%

Figure 12 illustrates the cascading targets for one of a crashworthiness related metric (frontal impact of the vehicle against a rigid barrier). The figure shows the dependencies of achieving a customer relevant target (passing a crash test) on the engineering requirement of a subsystem (maximum allowable vehicle deceleration) and specification of a component (structural deformation such as fire wall intrusion).

The project maturity is determined by the sum of all traffic lights (one for each target/requirement/specification) according to an example given in Table 3. At each major design review, the status is determined and compared with the required project maturity for that phase. The student grading will depend on the deviation of the project maturity. In the example shown in Table 3, the target maturity was 70% so the student team was slightly behind on the progress. This approach guarantees that the student teams strive to achieve a green status over the two years of vehicle development process.

Table 3. Assessment table for full vehicle targets level.

Traffic Lights	Program	Functional	Geometric	Score
Green (100 Point)	2	25	18	450
Yellow (90 Points)	0	5	5	50
Red (0 Points)	2	18	4	24
Exempt (0 Points)	13	69	1	0
Total Targets	17	117	28	524
Design Maturity [%]				66%

As in the "real world", challenges may arise when meeting the project targets and deadlines. Some challenges may arise from the supply chain side (non-availability of desired components for educational institutions), others may result from a financial aspect (not enough resources available to realize the ideal concept). The faculty's role is to identify such challenges early on, have students work on backup plan, and if needed, adjust project targets to guarantee a successful completion of the project at graduation...

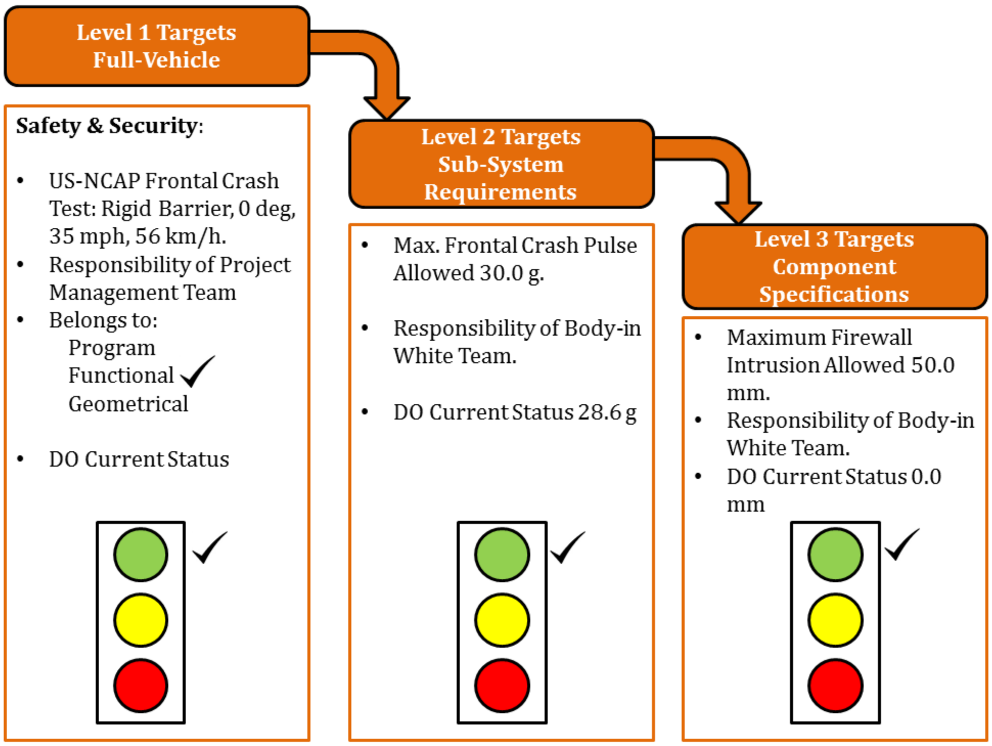


Figure 12. Cascading targets for concept vehicle design.

– Exploring Innovative Engineering Solutions. During the design analysis, the students are encouraged to explore new manufacturing process and fabrications techniques, evaluate their feasibility for the vehicle prototype, and search for possible suppliers. Examples of innovative manufacturing processes the students employed are rapid 3D prototyping, composite molding, and origami sheet metal folding. During DO3, the students built a vehicle body structure of origami folded sheet metal, while in DO4 the students designed new roof rails and cross members by 3D printing. Figure 13 shows two students from DO4 installing the 3D printed components.

Figure 13. Two students from DO4 installing the 3D printed components.

- Computer Aided Design. The students perform the engineering analysis using computer-aided design. The challenge of this stage is to master the engineering basics and the software skills at the same time. Most students have a preliminary knowledge in generic engineering software packages for computer drawings and modeling. However, programs that are more sophisticated require the students to complete online tutorials or attend workshops. In general the students conduct occupant comfort analysis (example in Figure 14), interior and exterior packaging analysis, crash performance estimation, and finite element analysis with industry standard software such as CATIA, SoildWorks, RAMSIS, HyperWorks and Simpack.

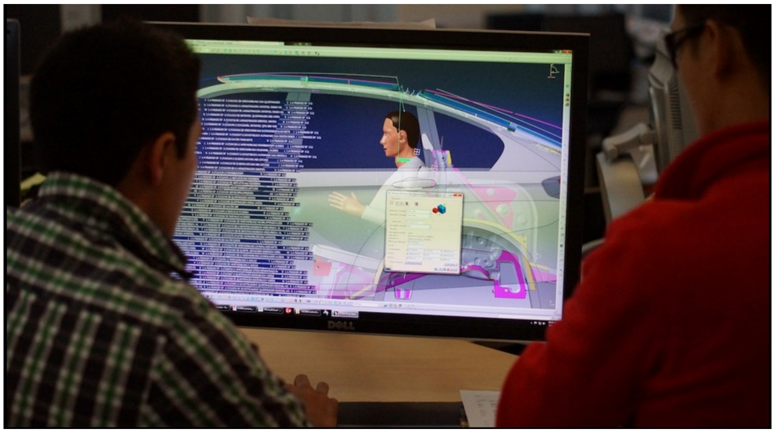


Figure 14.1 Students conducting occupant comfort and packaging analyses.

- Design Optimization. The design process takes place in iterations, so the students experience how to improve their design and how to compromise between competing objectives and packaging requirements. This stage is challenging for them but improves their problem solving skills because it requires them to adapt to constant changes in the design. For example, when designing an electric vehicle the location and number of battery packs influences the interior space and the body structure and vice versa.

– Mock-ups and Testing. During the DO process, the students have the opportunity to analyze their design by prototyping and building mock-ups. Figure 15 shows a 1:1 mock-up for DO3 concept vehicle where the vehicle body is made out of cardboard. This is an essential stage in teaching engineering since it enables the students to evaluate their solutions and adjust them if needed. This is one of the most important stages of the students' learning process because often they experience that the perfect solution that they developed using computer based tools may not be what they expect in the real world. These mock-ups also allow for heuristic evaluation feedback from the Human Factors team members. Finally, the students have the opportunity to validate their final design in the lab using the engine/vehicle dynamometer and circuit testing for vehicle wiring and electronics.

– Technical Writing. To record the design specifications, solution space and the design process, the students document and illustrate their finding and proposals in a standard document template, referred to as the Evidence Book. This is a major program requirement and it is included in the grading and performance assessment for each student. This is where the students learn how to convey their engineering designs in a globally accepted format and provide a design manual for the concept vehicle by the end of the project.

Figure 15. Mock-up built by students for DO3 vehicle body structure.

– Interpersonal Skills. The students' interpersonal and attribute skills are developed throughout the DO process. The students simply "grow-up" during this process and learn how to compromise. They often realize that their personal interests must come second to the group's goals. Working in groups enhances the student's teamwork skills and enriches their written and oral communication skills by the constant interaction with other team members, faculty, industrial partners, and suppliers. The students are required to manage complex problems and learn to prioritize the design tasks. Working on real world problems encourages out-of-the-box thinking and the need to explore other possible design alternatives. While learning to work in a team, each student also has ownership on a specific part of the project giving each student a sense of personal responsibility.

8. Major Program Milestones

Each DO project is divided into milestones that are incorporated into courses, where faculty set the overall objectives of the design activities and evaluate the results at each milestone along with the key industry partners. The major milestones for the DO project are established over 85 weeks that are divided over the academic semesters of approximately two years. The milestones are:

- **Automotive Systems and Functions Course (Fall Semester of First Year, Weeks 1-16).** The focus of this course is to analyze the target market (demographics, psychographics) and current vehicles purchased by the target market, understanding purchase behavior, understanding the target market's vehicle usage and activities, defining the design brief and personas. Key elements are:
  - *Market Analyses (**Week 10**).* The final deliverable of this phase is a student presentation of market research, which includes analysis of the concept vehicle and those of competitors, to determine the strengths (S) and weaknesses (W). The presentation should also identify the needs, wants, and/or problems that drive the target market, in addition to determine the Opportunities (O) and Threats (T).
  - *Project Start Brief, Personas (**Week 12**).* Project start brief and personas are completed.

- **Systems Integration Concepts and Methods Course (Spring Semester of First Year, Weeks 17-32).** The focus of this class is benchmarking, capturing full-vehicle targets; decomposition of full-vehicle targets in subsystem requirements; architecture selection and trade-off analyses. In addition to ideation of the desired functionalities/experiences, deriving the unique selling propositions, identifying enabling technologies, and defining the overall value proposition (why buy this vehicle?). The class of approximately 30 students is divided into groups, which collaborate with design students from ACCD to complete the assignments. The milestones are:
  - *Research, Research Analyses, Competitive Benchmarking, Start Concept generation (**Week 20**).* PowerPoint presentation. Students provide an overview of their vehicle concepts already realized. Create a wall in the classroom that includes all benchmarking materials, referred to as the benchmarking wall. Start collaborative teamwork to generate new ideas.
  - *Candidate Solution Formulation and Selection, Formulation of Unique Value Proposition (**Week 24**).* PowerPoint presentation. Students provide their first draft of their chosen candidate solution. This presentation must demonstrate understanding of the user

experience, vehicle and hardware opportunities, identification of general characteristics of the vehicle architecture and operating parameters as well as their first draft of the unique selling propositions.
  - *Target Catalog and Solution Development (**Week 26**).* Initial definition of the vehicle target catalog which must capture the basic vehicle level performance requirements and systems requirements, the start of solution detailing, and initial component sizing.
  - *Final Presentation / Virtual Design Review 0 (maturity level 20%, **Week 32**).* Presentations of approximately 15 alternative concepts. The presentations each include an initial functional (weight, performance), geometric (vehicle packaging) and cost status as well as an initial CAD model. Students start to develop an evidence book, which will document the entire design and build process by the conclusion of the project. The CU-ICAR and ACCD faculty and industry partners select the winning vehicle concept as well as reformulate the project based on the design and engineering outcome.

- ***Sixth Term Interior/Exterior Design Ideation (Spring of First Year @ the design school).*** These activities takes place with the design students at ACCD the same time as the activities describes in the proceeding section.
  - **(Week 18)**: Kick-Off. Presentation of market research and design brief.
  - **(Week 21)**: Research & development review. Market research (studying trends, demography, psychographics) and how the Art Center students translate this information into the design foundation, ideation sketches, and initial vehicle concepts.
  - **(Week 24)**: Midterm, design direction and packaging proposal.
  - **(Week 32)**: Final presentation, which includes a 1/5 scale model or ALIAS model. The faculty from both institutions along with the industry partners select the winning vehicle concept as well as reformulate the project based on the design and engineering outcome.

- **Deep Orange Internship, Part 1 (Summer of First Year).** The student work full time over the summer to complete the following: Architecture detailing, subsystem integration, performance layout, virtual integration and validation, and design-engineering convergence.
  - *Virtual Design Review 1 (maturity level 40%; **Week 37**)* PowerPoint presentation of the functional, geometrical, design and production status with back-up materials commonly used in industry including traffic lights (documents in each stage of the project is on track or not), build of materials (BOM), target catalog, weight catalog, CAD/CAE models/results, etc. along with an updated evidence book which documents all tasks to date.
  - *Virtual Design Review 2 (maturity level 60%; **Week 42**)* PowerPoint presentation to the faculty and industry partners. All materials are updated to reflect current status.

- **Applied Systems Integration Course (Fall Semester of Second Year).** Focus: Component design, interface design and virtual integration and validation.

- *Virtual Design Review 3 (maturity level 70%; **Week 50**).* Presentation of results in PowerPoint. Functional, geometrical, design and production status with traffic lights. BOM, target catalog, weight catalog, CAD/CAE models/results. Evidence book update.
- *Virtual Design Review 4 (maturity level 90%; **Week 58**)* Presentation of results in PowerPoint. Functional, geometrical, design and production status with traffic lights. BOM, target catalog, weight catalog, CAD/CAE models/results. Evidence book update.

- **AuE890 Deep Orange Internship, Part 2 (Spring and Summer of Second Year).** Focus: Design release, part release, component built, assembly, initial operation, and total vehicle validation.
  - *Virtual Design Review 5, Concept Freeze and Part Release (maturity level 100%)(**Week 66**).* Presentation of results in PowerPoint. Functional, geometrical, design and production status with traffic lights. BOM, target catalog, weight catalog, CAD/CAE models/results. Evidence book update.
  - *Vehicle Rolling Chassis Assembly (**Week 77**).* Vehicle prototype assembled. Safety inspection. Weight measurement.
  - *Initial Operation (software tuning) (**Week 80**).* Drivable rolling chassis completed. Software running reliably.
  - *Total Vehicle Validation (**Week 83**)* Presentation of results in PowerPoint. Total vehicle validation completed (ergonomics, BiW stiffness, performance, and fuel economy on chassis dyno and test track). Reconciliation of full-vehicle level targets.
  - *Final Design Review, Reporting (**Week 85**).* Presentation of results in PowerPoint. Evidence Book completed. Graduation.

9. Conclusion

The Deep Orange framework has quickly moved from concept to reality in preparing automotive engineering students for the rigors of industry. It gives them hands-on experience in designing, producing and validating a vehicle and gives them exposure to all aspects of engineering and manufacturing. Deep Orange provides a test bed for pioneering new technologies and methods in vehicle manufacture and feed the knowledge gained back to both industry and academia. In this manner, Deep Orange can bring new concepts and innovations "from promise to practice". The studio-learning atmosphere and use of industry-relevant teaching and mentoring methods provide a closer alignment of academic and industry practices. Students quickly learn to assume responsibility and to embrace new team roles and challenges. Ultimately, it prepares the engineers of tomorrow to address the challenges that the automotive industry will face in the years to come. Future efforts will focus on the assessment of the program from both institutions.

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