Engagement: From Classroom to project based design, Fabrication and testing

From nearly 40 years at USNA as a Modelmaker and Shops Supervisor, I have a somewhat unique perspective from seeing and participating in what's now called Project Based Learning (PBL). Indicative of the change is that what was previously known as the TSD Model Shop in Rickover Hall's windowless ground floor is now called the "Project Support Branch".

I really don't know if Project Based Learning was a planned evolution or more likely, if it began independently and was recognized as successful, then spread to other Engineering courses. It has become a recognized "thing" here and at other schools and interestingly, is coincidental with the broader "maker movement" and perhaps, a belated recognition of the value of skill and craftsmanship as well as acknowledgement of the inherent joy in creating a physical model from the seed of an idea. From the Shop's perspective it began by individual faculty involvement, organically with no specific planning or substantial discussion between stakeholders. It has evolved to be a significant support mechanism of many courses and some are quite substantial, with some courses having students working on their projects for 4-6 hours a week in the Shops.

The significant shift from research driven, precise work to mentoring large groups of students in the Shop and accommodating many more formal Lab presentations, happened with some friction between competing interests vying for limited resources but fortunately was accompanied by a rapid modernization of the Shops equipment and digital skills. More on that later.

Background – Understanding what a model is – “Fluid Mechanics” Robert Granger – this literary gem in a rather dense book!

“Modeling is a human instinct, utterly necessary to understanding and manipulating the environment. As Children, we continually create models of the world around us, models that we can control and experiment with. We build sand castles and block towers- and learn about erosion and unstable structures. We play with dolls, toy soldiers, and stuffed animals- and fashion models of the social world we must grow into. Modeling is critical to a child’s development and allows the creative imagination to discover and expand. As adults, engineers of all persuasions still use models as professional tools to understand how and why something may, or may not work. No longer a game, when an engineer says, “let’s build a model”, or “Let’s play with that idea”, modelling is an activity that is at once serious and still tinged with magic and wonder. The ideal model is the essence of a theory or a problem, from which all trivia has been stripped. The great trick, of course, is knowing what is trivia.”

Professor Granger’s words have great meaning to me and I have carried this passage with me in my work making models with and for USNA students for nearly 40 years.

Classroom work and Shop, begin to converge

When I started here, that center section of Rickover Hall’s Lab deck, known as the Model Shops was always slightly forbidding to students and maybe faculty, with its huge red doors, loud noises coming from within and somewhat grumpy, roughly dressed denizens, highly skilled in converting raw materials into exquisite mechanical masterpieces. Work requests were submitted and finished products picked up. Occasionally students were summoned to consult on a project or attend a demonstration but it was a place of physical work, somewhat foreign but intriguing to both students and faculty alike. Today, the Shop currently has 9 employees - Welding (1) , Machine (2), CAD (2), Composites (2), Wood (1) and a Supervisor. We have had as many as 12 workers in the Shops. We serve all Engineering Departments and any other USNA support as requested. We stock an amazing assortment of materials and supplies, chosen from past experience. Work is submitted through work requests and a typical year sees nearly 500 requests completed (although each request may vary from a simple 1 hour job to a semester long project!

The Shops have, over approximately the last 20 years, transitioned to be a vital part of the Engineering students educational experience. Lab courses incorporate the building experience as an important adjunct, reinforcing the practical side of design and as "proof" of what students learn in the classroom. More importantly, the experience of hands on building in the shops is engaging and stimulating to them, especially given the general lack of building opportunity most students previously have had. Their discovery is the satisfaction and joy of creating.

History

My recollection is that the first shift towards Project based learning at USNA started around 1990 with a Systems Engineering course, called "Introduction to Composites" which was followed by - "Smart Skins" . Interestingly, Composites can be viewed as a "system" with the interrelationship between the components (resin and fibers). I was intimately involved in the development of the Lab work supporting the classroom and developed hands on Lab experiments to illustrate the properties of the laminate samples fabricated by the students. We favored simple, difficult to quantify but clearly illustrative experiments rather than using available testing machines that give accurate data but "hide" the actual work being done (see crude Lab write ups). We pushed, pulled and sheared specimens and even devised models to show more complex interactions (like the odd cupping and twist reactions that can be introduced through asymmetrical "unbalanced" laminates with off axis fiber orientations). We also conducted Labs on processing the composites – from simple hand lay ups to processes like vacuum bagging and resin infusion that reduce resin content and compact the fibers more closely. That led to fabrication of shapes and products with more complicated geometry such as aircraft wings, boat hulls and the use of core materials both to give shape and make lighter yet stiffer structures.

Shop involvement quickly snowballed, once again led by Systems Engineering, with their "Systems Ball". These were "Battle Bot" type competitions (loosely based on a popular television show, making heroes of nerds and featuring aggressive sparking and sawing dismemberment of their opponents robots!) This mechanical "cage fight" suited Midshipman warrior mentality and there was great enthusiasm by the Systems students to build ever more aggressive fighting robots, which reached its natural conclusion when their battles began to endanger the spectators! Open saw blades, smashing hammers and even a highly electrified zapper arm resulted from this arms race! In the interest of safety and academics, more structured physical challenges were introduced, supplanting open warfare. Peace at last! All areas of the TSD Model Shop , Composites, machine , welding and sheet metal, were utilized in the construction of these robots and students were sent to the Shops to work with the technicians directly in devising solutions to robot movement, activity and structural problems.

The enthusiasm generated by the student success with building these clever devices was clear. What other course gets a room full of cheering and sweaty spectators to view their final product!? Soon, other challenges were introduced including a swimming pool, boat version involving navigational challenges and the USNA entry and support of the "FIRST" Robotics competition (a more "liberal minded" sort of battlebot competition that more involved teamwork and egalitarian support)

Class sizes for the Systems Composite courses were around 18 and the course was fully subscribed. I clearly recall the enthusiasm of the students being gloved and gowned, digging into mixing resins and cutting materials! Comments from course evaluations were favorable and many mentioned the hands on aspect as being one of their best academic experience they had found at the Academy (probably based on the looser, non- classroom environment, team aspect of construction and their product being largely non - quantifiable in a traditional sense. Also, sometimes with musical accompaniment, ranging from Simon and Garfunkle to Nicki Minaj). The lessons they carried away about making the basic practical engineering challenges understandable were valuable. Other lessons learned were less tangible yet equally as important. The opportunity to work side by side with skilled professional machinists, welders, composite fabricators and woodworkers was unique and valuable. Seeing their tool usage, pace of work, the importance of precision – and where it was or wasn't necessary – was worthwhile.

Working their way through problems – with the confidence of a professional "problem solver" mechanic at their side was invaluable. Knowing when to disagree and stand your ground - or accept a better solution was important to both the student designer/ engineer and the shop technician. (an important skill for the shop modelmaker has always been the ability to let the student learn gently through "failure" while still guiding toward success). Even the experience of being introduced to the sometimes, let's say, "elemental" language and behavior of a working Shop at times can be valuable, and not dissimilar to the life aboard ship that they might experience.

The relationship of the Shop experience to what topics, students learn in the Classroom is most relevant and ideally, should be discussed between Faculty and Shop but this is an area that could be improved upon. And I believe that it could be beneficial both ways – meaning that if time allowed, the Shop technicians might benefit by some experience in the classroom when relevant discussions are covered.

Big Projects and Competitions!

About the same time as the systems courses, we began to see several major projects that involved USNA in competitions. These were introduced as Class projects and could take place for a single semester or over the entire academic year!

The first of these, in 1989 was the fascinating challenge of designing, building, testing and eventually racing a Human Powered Submarine! (and yes there IS actually such a thing as a submarine race!) . The goal was to build a fast and maneuverable flooded, 2 man submarine that could be raced in the ocean over a curvilinear race course. Both submariners would be breathing through SCUBA and one would drive while the other would propel (and work really hard at it!). Both Naval Architecture and Ocean Engineering students participated in the course. Challenges were not only design and building but environmental aspects such as underwater work limits, control systems, safety, communication, planning and support. The educational and experiential value of a big project like this is huge. A "gant chart" of progress is developed (and regularly modified!) to keep on schedule. Materials must be identified and ordered after a budget was established. The design is drawn and evaluated and discussed with the Shop as to building feasibility and length of time to build. Even the logistics of travel to the event, what tools to bring and ensuring that it could be safely done within Navy dive regulations came into play. The lessons learned in a large multi faceted project are invaluable! Not just to the course work but as life and career lessons.

Perhaps one of the most important lessons to be taken away from any "building project" course and especially the ambitious "big project" ones is that it ALWAYS takes longer to build something than one expects. The other corollary to this (and most neglected!) is that it is always better to keep in mind simplicity as a means to complete a project early enough to refine it! In USNA student projects, this is a common failing – the busy lives the Midshipmen lead and their natural affinity towards complex and advanced solutions collide with the realities of Time and interaction with a busy Shop – with many other demands and priorities!

In the end, USNA won 1st place overall in the World's first Human Powered Submarine contest! Judging involved not only speed over a course but innovation, cost effectiveness, and performance. The competition was held in the ocean off Jupiter beach in Florida. We were fortunate in having a very strong Marine candidate for a propulser and a skilled driver, both completely fearless in operating a very “cozy” and unique underwater vehicle in open water. USNA’s “Squid” as it was called, excelled in being a very controllable little sub. It had unique counter rotating propellers housed in a nozzle for efficiency. It had a complicated and well manufactured “water cooled”, right angle gearbox to convert the pedaling motion to the rotating drive shaft. Quite an advanced concept that, unusual for such a project, worked reliably and efficiently. USNA completed all races and set a record for human powered underwater vehicle speed. We also won a nice prize from Dupont for best use of Composite materials.

The success of this particular project was largely due to the commitment of the students and Shop staff to the project. I recall working all night with the students (at great risk to them accumulating demerits) several times to meet deadlines. We did manage several weeks testing the device in the USNA towing tank before shipping it to Florida which I feel was an essential part of its success. The “Squid” earned its place in the Guinness book of World Records.

A personal beneficial carry over from this is that I remained in contact and friends with the team leaders for many years as they carried on their careers. This has been the case for quite a few projects I’ve worked on and I value the relationships I’ve been lucky enough to keep with the fine officers, husbands and fathers they become. Modelmaker personal contact with students is quite different from that of Faculty (who grade them!)

Subsequently USNA competed in 5 more Human Powered Submarine events and a few years ago, after a long hiatus, we again won the World Championships with a novel and fast propulsion system based on the flipper system found in Hobie kayaks. The advantage of this propulsion is that both occupants can propel the vessel, independent of each other. It also drives the boat straighter, without the torque of a propeller. This little sub occasionally reached a speed of 7 knots and set a record for 2 man, non- propeller driven underwater craft, which still stands. To show how things advance, the record setting speed of the original "Squid" was under 4 knots.

Seeing the success of these projects and the enthusiastic buzz from students, other departments included closer coordination with the Shops and their classroom work. In particular we began a series that still continues, of building Formula SAE (Society of Automotive Engineers) race cars. These are spectacularly impressive and complex projects with class size being in the 2 dozen student range. To design, build and race a complete open wheel vehicle is a school year is a very difficult and in my opinion, an overly ambitious undertaking. The scale of a project is important. Too slight and it won't engage students properly. On the other hand, a manageable project can be well and thoroughly engineered and completed in time for testing, which inevitably points out and resolves design and fabrication problems. Too ambitious a project can lead to it simply being a "get it built" project and lead to frustrations resulting from rushed engineering solutions. Once again, it is a given that things will take longer to build than you would expect. I can give you a dozen reasons for this but suffice to say, it's necessary to take into account when planning a project.

The SAE car evolved from an earlier “Baja Vehicle” which was a very ambitious project. It not only had to deal with extreme terrain but also had to float and propel itself in water! The SAE car, though limited to a flat racecourse with many turns and a higher speed has evolved into an extremely fine technological showcase of Shop and Classroom interaction. In some cases, the project itself has led and driven Shop capabilities. The SAE car projects have been extremely well managed and ambitious projects that have pushed technology and performance advances such as the use of aerodynamics (in producing downward forces, increasing road holding ability) and advanced composite structures in a very lightweight and torsionally rigid monocoque body, constructed in aerospace quality pre preg fabric, honeycomb cores and cured in an autoclave. Often I have seen Shop personnel learning from the students, who are relatively fearless about advancing technology!

The Aero Department has also had many years of tasking students to Design, Build and Fly (known as DBF), very interesting small and not so small, drone type unmanned aircraft. The largest has had a 12’ wingspan. Small electric motors have become amazingly powerful and the “missions” assigned to these small flying machines have been fascinating, ranging from aerial infrared spotting of buried IEDs (improvised explosive devices) to the ability to fly in sub artic conditions with a payload that must be kept warm, to a quad copter with an air-gun that fires medicine filled darts at cattle! Generally, the use of Composite materials is involved in making lightweight objects and the students begin their project with some elemental composites fabrication Lab classes. They advance to building practice components, primarily wing structures using more advanced techniques and materials. They test these structures to verify the design and calculations made as classroom work. The correlation is generally surprisingly good and their confidence in both the design calculus and building skills increases quickly.

CAD and CAM and CNC – the digital Shop revolution

Of course, with the more advanced projects, and in fact nearly all projects, are based on student application of CAD (Computer Aided Design). CAD, especially when followed by Computer Aided Manufacturing (CAM) deliver accuracy, symmetry and speed of build, impossible in the prior days of hand drawn plans and more manual manufacturing techniques.

Nothing in my 40 years here has been more significant than the introduction of CNC (computer Numerically Controlled) technology in the Shop. We literally are able to produce 10 times , more advanced projects with a smaller staff than we could 30 years ago when CNC manufacturing really came to the Shops. When I came here in 1980, there was a single CNC milling machine and it was quite limited to what it could do. There was also a single digitally trained machinist who struggled with the single computer in the Shop. Then, there were two. And 3 or more…Then even measurements on manually operated machine tools were taken using digital means (glass scales) giving greater accuracy (and far easier on the machinists eyes who previously had to read fine denominations on Vernier scales!) . Around the year 2,000 at the turn of the century (appropriately) , the Shop, experienced some employee turnover to a few younger, more digitally (1.s and 0's – not fingers) experienced employees. Through training, (mostly the machine Shop staff) and purchasing several more CNC mills, lathes and later new technologies such as a digitally programmed, wire EDM machining (like a hot wire through foam, an EDM (electronic Discharge Machining) wire can digitally "cut" – actually vaporize-conductive materials of nearly any thickness, and a digitally programmable water jet (which cuts metal and plastics of a surprisingly great thickness) with an abrasive filled high pressure jet of water, Shop capabilities expanded greatly. In the Composites shop, a relatively inexpensive 3 axis milling machine can cut the dense foam we use for models (instead of wood) to amazing accuracy, delivering ship hull models and wing sections, needing only some finish sanding and coating before testing! Instead of new tools there, advances in Composites came because of new processes to manufacture light and strong projects, and new materials that give great strength in nearly any geometry imaginable (shape is the bugaboo of any manufacturing process – but for composites, it is easily obtained and actually increases strength.

All these new process, materials and tools were adapted relatively quickly, fortuitously, at just about the same rate as the emphasis on Project based leaning began to flourish. Our capabilities grew at about the same rate as the intensity and complexity of student projects. Notably, our staffing in the Shops stayed constant or even slightly diminished.

I'd like to point out that there is an assumption that Midshipmen know CAD software before coming to USNA. There is little in the way of design software course offerings unless you are able to take them as an elective (or are naturally adept in that sort of thing!). One suggestion might be to offer more course work, earlier, in a design software – particularly *Solidworks*, so that more students can deliver more finished CAD designs to the Shop. The Shop staff has only really expanded, in its members who can turn rather crude student attempts at digital design into accurate machinable files and parts. This take a fair bit of time at the front end though it speeds up production at the other end.

And then, suddenly, on the morning of Sept 19, 2003, we were wiped out! A hurricane named “Isabelle” brushed the Chesapeake but it’s timing and unfortunate path brought a huge influx of water into the Bay and we arrived at work to see an 8’ rise of evil, turgid, swirling water turning Rickover Hall and other buildings at low elevation into islands. Our Shop had 35” of water everywhere. Computers and tools carefully placed on top of desks the night before, caused them to capsize as water flooded the shop. Chemicals were mixed with waste, tow tank models flowed over into the Aero Lab and wind tunnel models washed into the Hydro Lab. In 6 hours, a single tidal cycle, the storm blew through and the water receded. But the damage was done. Little was salvaged. Our larger two CNC mills were later rebuilt but most other machines were replaced. Manual machines were also refurbished and are still operating . The silver lining to this (one has to have a sense of humor and an eye to the future), is that it gave us an opportunity to upgrade our capabilities and improve our layout to better accommodate the new digital age that had worked its way into the Shops. Even workbenches, hand tools and materials were replaced. We are eternally grateful to Management who readily saw the importance of quickly rebuilding the TSD Shops branch and funded us completely in our great rebuilding effort.

Meanwhile, what of the students? It turned out that this was a great experiment in seeing what things might be like if time reversed itself and they were faced with a year of only classroom studies and no project based support to their studies. Of course, it takes little imagination to see that the graduating class of 2003-4 had a greatly reduced experience. I doubt that there are any statistics on the varied educational outcomes targeting the time of Hurricane Isabelle but I suspect the student course evaluations would tell the story.

So What does it take to do Projects ?

A shift to using projects as an effective learning tool, supporting classroom teaching requires a substantial investment. The materials required to build stuff, the support staff to safely manage students in a new and potentially hazardous environment and the space to do it is are all expensive investments. The up - front costs for starting a fully equipped and staffed shop is significant. Schools are generally able to handle worthy funding. The real challenge is not funding but time. Carving out time for students to experiment and build things is difficult to do with an already loaded schedule. Generally, the time in the shops is designated as Lab time. I suspect that reshuffling existing course work to include time devoted to project development is generally possible and there can be great paybacks offsetting the lost classroom time, in the increased enthusiasm from newly found relevance of classroom studies to the hands on work. In fact, the real problem may be that student's primary focus shifts towards building things!

Time in the project spaces must be found in blocks long enough to allow for work to be done, including set up and clean up at either end. Generally, classes that utilize the USNA Project Support branch devote 2, 45 minute periods back to back on Lab days. A respectable demonstration in the Shops can be done in that time and it can include hands on work. Later, after the introductory "skill building" Labs, the actual project is assigned and larger amounts of class time can be devoted to studying the problem and considering solutions. Here is where the skilled craftsman can be very valuable, if included at this stage. It is an extremely important lesson for students to lean that the “How to” of building MUST accompany design. Designing in a vacuum will lead to overly complex or potentially impractical solutions. More likely, the students, who have little experience in building structures can be gently led towards best practice by craftsmen who have encountered similar building problems. Joining elements, achieving structural stiffness, choosing materials and planning work are all difficult issues for a young engineer and can lead to a period of “analysis paralysis”. A few suggestions, examples of other similar solutions to problems and offering different pathways to follow can break this roadblock and allow the students to leapfrog difficult but tedious situations. For example. To build a wing structure, the Classroom work can easily bring the students to design solutions of loading, area required, planform and wing section. But exactly how many layers of composite material are actually needed in the main spar? Can the wing be built around a core material or with ribs, stringers and a covering? How can it be joined to the other wing or fuselage? These can be highly complex questions and overly specific, beyond student’s general knowledge. But if working with an adviser or technical craftsman who has built similar structures, he may confidently suggest the path forward based on either knowledge or precedent.

The role of a skilled and experienced Modelmaker advisor to projects is invaluable. More than a “builder” of things, he must also appreciate that this is a learning experience over a building one. He must lead students to solutions – not simply tell them shortcuts. He must know when to strongly advise and when to respect the students ideas. Above all he must be tolerant and willing to share tools and work in a somewhat chaotic “rushed” situation where students are under the gun to accomplish as much as they can in a limited time. He cannot ever let expediency and urgency get in the way of safety though! It has to be a primary function of this individual to be ever watchful and firm in the need for all safety gear and procedures. Safety glasses, hearing protection and respiratory protection are paramount. Students, not knowing, will sometimes do incredibly unexpected and unsafe things! The Modelmaker instructor will seem to grow eyes in the back of his head and be acutely sensitive to sounds and smells of tools being used improperly. A 6th sense for danger as it were…

Working with students.

Motivation – If they enjoy the experience they are amazingly motivated. Most have little hesitation in attempting difficult tasks but little realization of the limits because of a lack of skill. We try to start them off with skill building tasks.

Failure – they are so limited in time that “failure” (learning) experiences can be hard on them. Luckily they have plenty of energy.

What they want vs what they get…- They generally have a goal in mind of a pristine product “like the pictures”. They must realize that most products they are making are prototypes and therefore “rougher”.

Satellite Shops – Many Departments have set up satellite shops to give students a place to fabricate “on their own”. This can be a learning experience and shortcut the inevitable Shop work system but what is missing is the expertise of Shop craftsmen and they guidance.

Stoppage – as with all course work we see a change after service selection. We are lucky to have the end, physical product as a goal (rather than a grade). We find a significant number of students are motivated by wanting to see the thing they are building actually "work" (float, move, fly, etc). When it's clear that the goal can't be reached, I feel that they still have a take away of the joy of the process (although sometimes they just want to be done…)

Milestones – build things in small bites. Keep building and it rather quickly comes together at the end. In the Shop unlike in Class, progress or lack of it can be physically seen! Quite often, the design has to be modified to accommodate the remaining time. Time is always a factor!

Gender – I have noticed a difference between levels of enthusiasm between men and woman students in the Shops – speaking in generalities. The guys can be "too cool for school" thinking that they should know how to build stuff - because they are "guys". The girls seem to have an extra motivation because it is new to them and want to try harder. Always risky generalizing about gender but it's an observation.

Is it Worth it?

The sense of achievement having designed, built and then tested some invention of your own is invaluable. It can literally be a life changing experience. When a student will go to bed thinking about his project – turning over in his head, how he will resolve that problem and wake up with a burning desire to get to the Shop and fabricate a solution, he is hooked. To be able to apply the knowledge he picks up in the classroom and then model it as a physical example, is priceless. And so is a student remembering the experience when you see him after several decades…but you all, as teachers already know that!

Some feedback

Better communication between faculty and shop staff should be encouraged. A lot of time is spent in the Shops and we have a pretty good idea of their efforts and talents.

It is a given that the more we in the Shops know about projects, the more helpful we can be.

Funding for Capstone projects is largely based on gift funds! Shop funding has dropped dramatically and becomes “hostage” to delays in gift funding purchases and ordering.

Similar to the Writing Center, there should be a “CAD Help Center” as most students NEED to know how to design using CAD software and even Faculty can often be a doubtful level of expert help. The Shop has some very qualified CAD and CAM experts and as time allows could offer help.

The purchasing system is terrible and tasking a skilled Craftsman to do purchasing is very unproductive. Purchasing responsibilities are significant and time consuming and not a trivial “added duty”

Feedback from “after action” (end of project) might help improve Shop help

Having faculty more involved in project construction through visits or status reports would be beneficial.