**My Philosophy on**

# Machine Design, Engineering and Development

**of Prototype, one-off Machines and Production Systems**

by Ted Stroud

*During the process of designing, building and supplying a unique machine or system to a customer, there is a seemingly endless stream of decisions to be made. Each of the thousands of assessments involved has the potential to substantially impact subsequent evaluations and decisions in the chain, either positively or negatively.*

*These decisions involve safety regulations, environmental issues, legal concerns, and of course the design and engineering details, as well as the specifics of the machine's performance, its maintenance and its life cycle, including the training and effective interaction with the personnel involved.*

*Depending upon the final destination, factors to be considered also include international law, local regulations, and the politics and culture of the countries involved.*

*Large or long range projects can be subject to a turn-over of personnel during the evolution of the integrated teams. It is necessary that continuity be maintained through successive teams to ensure the smooth flow, transition and cross team collaboration during the design, development and building of a machine, as well as through the installation, commissioning and customer training.*

*As each assessment potentially effects each following decision to be made, and each conclusion is connected to, and has an effect upon other choices that follow, the reasoning for each decision and the results that are expected to be achieved, should be recorded along with subsequent changes that may be made as more data is compiled. Yes, out of these thousands of assessments and decisions there are a vast number that would seem too insignificant to record, such as those that would just be the following of good design and engineering practice. However, the decisions which relate to the uniqueness of a prototype or a one-off machine should be clearly documented. These records will serve well as a basis from which to trouble shoot and further develop the specific areas where unforeseen problems occur.*

*The wide range of detailed engineering calculations that are necessary during the creation of a machine should be meticulously recorded to facilitate an in depth examination of a particular design aspect should unexpected problems become apparent. Comprehensive records are also essential in ensuring that a continuously evolving team is able to easily see how the progressive steps of the planning, design and construction of the machine have developed to date.*

*The terms design team, design engineer, machine designer and designer as used herein, include all of the people and entities involved in the design process from the individual designer/drafter to the project engineer/manager as well as* *the corporation by whom they are employed or contracted and include all of those who share in the legal, moral and ethical responsibility for the project. The design team may consist of a group of people all working for a large corporation, or a small company which conducts a machinery design and build operation and acquires the needed additional expertise on contract.*

*The term customer, as used herein, includes all of the people and entities involved in the acquisition of the machine or system, its operation and the eventual maintenance that will follow once it is in place at its final destination.*

Pressure on industrial machinery manufacturers is increasing exponentially as competing machine builders continually reposition themselves to achieve ever decreasing costs while at the same time answering to their customers' demands for faster, safer and more versatile operator friendly and durable machinery with the flexibility to produce a wider range of products with little or no set-up or changeover time, while requiring minimal maintenance. At the same time the end users expect a lower capital cost that will provide a greater return on investment, in addition to their demand for machinery and processes that are "green".

In striving for this versatility and economy, machinery manufacturers have for some time been moving from manual controls and mechanical drives to PLC controlled servo drives with advanced motion and to mechatronics, all of which results in greater control over the manufacturing processes. Vision systems are increasingly being employed in the monitoring and the controlling of a variety of functions during the production process. The automatic detection and feedback of deviations from pre-established norms can initiate warnings while making corrections without operator intervention. The production data may well be transmitted to another global location from where an automatic response will be returned with data to update the machine's on-board control system, all of which is recorded for future reference. This of course, introduces much greater complexities, not just into the finished machine, but very much so into the art of designing, engineering and building such a machine or system.

The necessary multidisciplinary ensemble of engineering talent that is necessary to undertake a large machine/system design and build project will require: research and development management skills; familiarity with the technologies expected to be incorporated; design engineering expertise in each of the disciplines involved, 3D CAD and CAM software programming and operating proficiency; and document management systems with more than enough capacity to handle the entire project, including electrical and electronic design software with the capability to run and debug the electronic and electrical control system design before it becomes a physical reality.

The CAD files generated should be compatible with more than one suitable CAM interface.

It should be kept in mind that a one-off machine (a prototype) will probably require some modifications before it is able to reach its productive potential. Mistakes will occur, better ideas will flow and the designer needs to be flexible and adaptable and to be able to easily alter course should new data becomes available. Before building a prototype, a 3D solid model of the critical areas should be 'built', with some animation being run to accomplish the initial debugging.

A well designed machine or system will more than meet the customer's performance goals, safety standards and ease of operability as described in the design criteria established from the needs of the productive output in both quantity and quality, as well as meeting the requirements dictated by other factors, e.g. overall efficiency, savings in material costs, lower labor costs, durability, reduced impact on the environment, lower energy consumption, utilization of less floor space, minimal waste and scrap, etc.

Besides the mechanical aspect of a machine or system, the design process will incorporate a control system which in turn will likely include programmable logic controls (PLCs), mechatronics, networking and machine/product condition monitoring (via vision systems) as well as the human/machine interfaces; but on the other hand, the control system might be much simpler.

Most automated machinery now comprise mechatronics and are controlled through PLCs or other computerized systems. However, most of the physical aspects of machinery do require mechanical systems to work the materials to create the product or a part thereof.

Unlike mass-produced machinery and equipment, custom one-off specialty machines do not warrant its manufacturer investing in expensive and unique tooling and dedicated machinery to produce just one particular machine, and then to maintain a large spare parts inventory – there is little or no economy in this, except for the very specialized components. The one-off specialty machine should be designed to take the best economic advantage of machining common materials and sizes and by using standard commercially available components wherever possible, with the result that large accessible inventories of spare parts are held by the manufacturers and suppliers of those components. Further, the companies which mass produce a standard line of machines, with few exceptions, are not interested in, nor are they set up to compete in this field with smaller companies whose specialty is innovative custom one-off machinery.

Pound for pound, (kilo for kilo) custom machinery is far more expensive to build than mass produced equipment, mainly because the engineering is amortized over just one machine. But their raison d'être is that custom special purpose machinery can do what standard commercially available machinery cannot, notwithstanding that each newer generation of custom machine must deliver its product at a higher rate of speed with lower operating costs, improved quality and increased safety over previously available custom specialty machinery, if it is going to make economic sense.

The design of a custom special purpose one-off machine or prototype should be arranged so as to allow alterations and revisions to upgrade the machine to meet the future anticipated needs at a later date. This is a judgement call and it is easy to miss the mark in anticipating the future needs and requirements of the machine or system. However, unless the predicted revisions and upgrades are obvious, one should not incur extra costs just on the off chance a particular change or modification might be required at a later date.

Before the designing begins, a study should be conducted which would include all available economic data as well as the technical information and operational expectations relating to the results or product. It is important that the marketing, sales and engineering personnel ensure that the customer fully understands the legal, and ethical ramifications of the use of whatever chemicals and dangerous materials that maybe employed, if any. It is also the responsibility of the design team to look for alternatives that will reduce the inherent risk and reduce the impact upon the environment. Likewise, it is a further responsibility of the design team to understand the legal ramifications for their organization, as a manufacturer producing such a machine where dangerous goods and chemicals are involved, and to proceed accordingly.

A detailed list of all that the machine is intended to achieve should be compiled along with data on the related pre-engineering that will give an overview of the technical hurdles to be overcome and the magnitude of the loads and stresses involved. Also included should be the machine speed or productive rate and the target efficiency as well as quantification of quality and precision of the intended productive output.

The designer must understand the effect of tolerances on not only the quality of fit, or the mating of parts, but also on the cumulative effect on the precision of the items being produced, in order to be able to design a machine of the appropriate level of quality. The utility of a component will, in a large part, dictate the tolerances to be specified for a particular application. Tolerances and finish have a direct effect on the precision and quality of the machine and resulting product.

The machine designer, more than ever, has a need to continually improve his/her development techniques and to use the latest design software and methods, use the most versatile embedded control technology and to integrate the use of these technologies into the machine. It is essential to have frequent design reviews which include the designers' and their peers, with separate reviews which would include the customer, all of which must include scheduled targets.

reword>The level of advanced technology incorporatred into a machine is critical; too much sophistication can unnecessarily increase the capital, training and operating costs, and too little can result in longer set-ups with the necessity for overruns to replace spoiled product due to inconsistent quality. Mechatronics and has been integrated into the control systems of production machines and manufacturing systems for some time now. Most manufacturing systems are now usually equipped with at least a PLC and/or other 'smart' components or systems to control the various functions, servo motors and actuators, to increase their flexibility to control conditions and to handle a broader range of products and to reduce downtime associated with product changeover. This includes the integration of mechatronics and the application of separate but interconnected mechatronics components, some of which may be designed by others on the engineering team or they may be supplied by an outside vendor. <reword

Before beginning a project to design and develop a machine or production system, a study will undoubtedly have been conducted on the criteria and economics that would dictate that a custom special purpose machine or system would be required to achieve the desired end result. It is assumed at this point that a recent market study or survey has also been done along with a feasibility study and that both offer strong support for a custom machine or production system to meet the projected needs. The study should have determined what the general criteria will be and the level of productivity and quality required in the end product, as well as the general magnitude of the costs that can be supported while still meeting the projected production targets and the expected return on investment over the life of the machine, according to the projections and predictions.

A preliminary proposal should then be developed to determine if all of the criteria can be met or what percentage can most likely be achieved. This will probably include some basic pre-engineering, which will be necessary to determine if the targets are within the achievable range. It should be confirmed at this point whether suitable standard commercially available equipment can be purchased to meet the needs, if available equipment can be suitably modified to fill the requirements or if it is indeed necessary to design and build a custom special purpose machine to meet the needs of the market. The refurbishment, modification and reconfiguration of a used machine or system might also be an alternative.

Regardless of the conclusions of the foregoing, the next step would be to develop a full-scale proposal for either the required custom equipment or for the standard commercially available machine, complete with cost estimates and firm pricing for any modifications that may be required along with documentation for the rationalization. To avoid gray areas, it would be necessary to document the thinking in arriving at each: the conclusions, the expectations, the costs, and the risks.

Regular interim reviews should be conducted throughout the process of developing a full proposal so that corrections in the course can be made early, with minimal cost.

Whether the machine or system is for an outside customer or whether it is an internal project and the customer is your employer, these steps should be taken equally seriously.

After it has been demonstrated that the project is both economically and physically feasible, and the proposal submitted to, and approved by the customer, the machine design engineer can now turn his/her main attention to the preliminary design of the machine or system. There should be customer input throughout the design process and it should always be considered valuable. There will be times when the designer, or design team, will feel that some of the input is not appropriate or necessary, but it should all be considered for what it was intended to offer to the project.

During the proposal phase it will be necessary to determine the amount of space required to accommodate: the machinery or system, the necessary support equipment, the storage of raw materials, and the finished product; and whether indoor or outdoor. Besides the physical dimensions of the machine or system, locations of openings such as doorways, windows, ventilation, etc., and services such as heating system, electrical power, overhead power line clearance and location of buried power cables, natural gas supply, propane gas storage and supply, water supply, telephone cables, radio transmission towers, shipping and receiving areas, unloading capabilities, highway and roadway capacities and access points, railway sidings, possible airport services and plant security, either existing or planned should be included.

Even though the civil and architectural engineering teams will be responsible for determining the geological conditions and researching the history of the site to determine if there are any previous land fills, excavations, foundations, cavities such as disused sewers or other types of tunnels used for a previous industry, buried toxic wastes or forgotten cemeteries, the designer should be aware of this data which these engineers will have uncovered. In some locales there is the possibility of archaeological finds, which may impact the time line for the construction of foundations, etc. The depth of soil over rock, water table or other underground conditions should be determined, and if any pits or underground services may be required. Factors introduced by wind, seasonal conditions, humidity, altitude and other variable climatic and environmental conditions should also be noted.

Besides the essentials of machine design, a very important point that a machine designer must keep in mind is that of the dimensions of the sea-going shipping containers, or other conveyance, their weight capacities and the configurations that are available. If roads over which the containers will be transported include switch-backs in mountainous areas, or if the unloading space at the final destination is limited, then it may be necessary to use only 20 foot containers. The machine sections or subassemblies must fit into or onto the selected transportation containers or equipment.

It is not unusual for something unforeseen to happen where local machine shops and/or other services are urgently needed to keep the installation on schedule. Contingency plans should be developed during the design phase to address these unique needs. These plans should include the names of the organizations and/or individuals, and there proximity to the installation and the names of those who may be called upon in case of these eventualities. It would be prudent to make arrangements for their services ahead of time.

It would also be wise to determine, in the event that unions are involved, the ground rules for a good relationship with the unions.

Designing prototype or one-off production machinery, that will function as expected from the start-up/commissioning through the intended working life of the machine or system, requires a great deal of thoughtful research and development and careful planning. The design engineer and his/her team only get one shot at this machine or system and it must achieve the intended results, with no retries – a bit like a moon shot, in fact for some projects it may be just that. This can be very challenging but can also be very rewarding in financial terms for both the customer and the company creating the machinery or system. A successful project can also be very inspirational for the machine manufacturer’s team and can be very satisfying for all those involved and who will contribute greatly to the success of subsequent projects.

In beginning a comprehensive machine design project, one should first develop a list of the required parameters, in detail, with a sub list of additional features and/or parameters that would be desired by the customer, but which would not necessarily be included in the finished piece of equipment, the inclusion of which would have the potential to positively influence the thinking of the design team.

An essential aspect, which requires serious consideration, is the expected quality of the product to be produced, the quality of the material to be processed and how the accuracy and quality of these affect the production process. Through necessity, this will also include the accuracy of the monitoring/testing equipment which would be incorporated into the production machine or system and embedded into the control system. In addition, the life and total anticipated number of product units or the number of cycles must be included in the calculations to ensure that the machine will remain efficient and reliable throughout its intended life and will yield the expected return on investment. Even though an efficiency rate of in excess of 90% for an automatic machine might be projected, considering that this would be a custom one-off machine, basically a prototype, a conservative efficiency rate of 75% should be applied to the calculations for the expected output to take into account such eventualities as a lower production rate due to inferior raw materials or other unforeseen factors. There will probably be shifts when the average efficiency will exceed 90%, but there also may be periods with less than 50% efficiency. Training

Even though not functional, the aesthetics and ergonomics of the machine are important. If the machine or system is pleasing to the eye and easy to operate, then the operators/crew will have more respect for the equipment than if it were an ugly difficult beast, and the owners will also have more confidence in the machine. And the appearance of the machine can impress the customers, either positively or negatively. It should also be kept in mind that operators or crew who are dissatisfied with a machine, or system, will not be as productive as they would be otherwise and therefore the machine will probably not perform as intended. They will not work with dedication to overcome even small difficulties. Conversely, if the operators do like the machine or system, then it may very well perform better than expected due in large part to the operating crew's dedication in working to overcome all of the problems that arise.

A scope of work, with as much detail as can be developed at this early stage in the planning, should be included for each of the phases of the project. A target completion date should be established first, with the projected necessary steps to get there being developed in afterward. If the accumulation of the various sequential steps is allowed to determine the completion date, there is greater risk that the project will be late and therefore likely to be over budget. Even though there is often great uncertainty and risk in designing and building custom, one-off machinery or systems, custom designed and built equipment can be created and be up and running on schedule and on budget. However, the time-line and the budget must be very tightly managed.

The project should be divided into sections or areas of responsibility where the responsibilities for each section or area are assigned to the different members of the team, whose efforts will be coordinated by the project manager, or team leader.

The areas of the most uncertainty, and which therefore carry the greatest risk, must be confronted first. Often secondary steps cannot even be contemplated until some basic answers or solutions have been found. This may well require some research and development.

The individual design engineer should have a thorough knowledge of the various machining processes and be quite familiar with assembly procedures as well as the operational characteristics of manufacturing machines in the target industry. Knowledge of the capabilities of additive manufacturing would also be an asset.

Where the results would be suitable, all custom components should be designed to be machined with the available tooling on the company premises, with the company's standard fleet of machine tools and with the processes normally used within the company. Additive manufacturing (3D printing) should be considered for some intricate parts; in fact to achieve the necessary geometry for a part's required function, additive manufacturing may be the only viable option.

The machine design engineer should always remember to make sure that contours and special shapes that are chosen should be achievable with the available tooling, where it is feasible. It is also important to design the components to be machined from standard size and readily available materials where possible. Special processes that require long lead times should be avoided unless the desired results would not otherwise be achievable.

When a machine is designed and engineered for mass production, it is necessary to calculate the strengths and lives of most, if not all, of its components to ensure against designing more capacity, life or attributes into the piece of equipment, than necessary which would thereby add to the final costs. At the same time the design must produce a safe and predictable piece of equipment with a life range that meets the decided criteria.

This is also important with custom one-off machines or systems. However, it should be kept in mind that when manufacturing single parts or low quantities, it is easy for the designer to use up potential cost savings, and more, through intensive design effort while attempting to reduce the cost of one, or just a few components to achieve a point just above the minimum specified performance requirements. It must also be kept in mind that cost overruns on an accumulation of individual minor components can easily destroy a budget. With prototype machinery there is a fine balance between minimum design and engineering effort and high quality productive results.

Thorough calculations should be performed for all critical features and/or elements within each component, sub-assembly or assembly. Even though a design engineer may be experienced enough to select the appropriate sizes through visualization, the criteria and rationale should be recorded in notes no matter how limited, either on a computer or hand written, for future reference in case that particular item or area should fall into question. An experienced designer will have developed a feel for the relationship of the magnitudes of the components and the forces involved. It would be apparent that in some instances the decisions would be obvious before performing the calculations, while in other areas the calculations (or FEA) would be the only method to ensure adequate life, rigidity and safety.

It would be prudent to use a calculation software program to create a permanent record for all of the complex calculations, notes and observations so that if problems arise in the final design, or even worse, in the completed machine, the error can then be located and the appropriate remedial action taken.

For very simple calculations, which are done just on a calculator or just mentally, written notes should be kept, with a sketch where appropriate, showing the procedure and the results. It is easy for anyone to make a simple mistake, and which may be very difficult to find, but if the error has made its way into the finished machine it also becomes very expensive to correct. Keeping adequate records will help ensure that errors and problems will be easier to locate and remedy.

An important part of a machine design engineer's education is to experience or to observe first hand: the circuitous route of the materials chase of the buyer; the problems encountered by the machinists during the manufacture of the machine components; the difficulties experienced by the millwrights in assembling a machine; the crating and logistical nightmares of the shipper; the communications hurdles and local resource hurdles faced by the field engineers and finally the travails of the maintenance crews.

It is folly to release drawings for manufacturing before all of the drawings have been completed and checked. If the timeline is such that it is found that the drawings for some complete assemblies must be released for manufacture before the others have been completed, the designer must be cognizant of the risks that, without the utmost care, this could lead to great difficulties.