<u>**The ART of**</u> Edited May 10 /25

<u>Machine Design, Engineering and Development</u>

of Prototype and One-off Machines or Production Systems

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There is a seemingly endless stream of decisions to be made during the innovative process of designing, developing, building and supplying a unique, one-off machine or system to a customer. These decisions involve safety, environmental and legal concerns, and of course the design and engineering details, the ingenuity, the specifics of the machine's performance, the maintenance and its life cycle, including the training and effective interaction of the personnel involved.

Depending upon the final destination, international law as well as the politics and culture of the countries involved are all factors to be considered. Each of the thousands of assessments involved has the potential to substantially impact subsequent evaluations and decisions in the chain, either positively or negatively.

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 and commissioning.

The following is an outline of my approach to the 'Art' as applied to this decision making process and, attempts to illustrate that a common general approach to all of the (technical) decisions may yield the most predictable of outcomes, while at the same time promoting continuity through successive teams.

As each assessment potentially effects each subsequent decision to be made, and to which each is connected to, has an effect upon other choices that follow. The reasoning for each decision, and the result that is expected to be achieved, should be recorded along with subsequent changes that have been made as more data is compiled. Yes, out of these thousands of choices and decisions there are a vast number that would seem too insignificant to record, such as those that would be just the following of good design and engineering practice. However, those decisions which relate to the uniqueness of the prototype or 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 unusual problems may 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.

There are numerous engineering handbooks and texts available that cover all aspects of engineering details very thoroughly. However, this article concentrates on the approach to the thousands of decisions that must be made in the process of designing a machine or production system, from those required in designing just a simple component, through the attention that must be paid to the coordination of every facet involved in the development of a complex automated production system and the environment and ambient conditions where the machine will operate.

*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 including the corporation by whom they are employed or contracted and all of those who share in the legal, moral and ethical responsibility for the project. The design team may be a large group of many dozens of people or may comprise a single designer who has undertaken a design contract or who operates a one person machinery design and build operation and purchases the needed additional expertise on contract.*

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

Regardless of the rapid and ever changing advanced control systems which are the 'brains' of the machine or system, the mechanical components required to form, alter and handle the materials being processed are still the 'heart and muscle' of a manufacturing machine. This article is intended as a guide for the designer or design team responsible for the creation of the mechanics of the machine or system.

Pressure on industrial machinery manufacturers is increasing exponentially as competing machine builders continually reposition themselves to ever decrease costs while at the same time answer to the customers' demands for faster, safer, more versatile operator friendly quality machinery with the flexibility to produce a wider range of products with little or no set-up or changeover time – all of this with durable machinery and equipment that requires little or no maintenance. At the same time the customers expect a lower capital cost that will provide a greater return on investment in addition to machinery and processes that are 'green'.

In striving for this versatility and economy, over the decades machinery manufacturers have moved from manual controls and mechanical drives to servo drives with advanced motion controls. This often includes the use of vision systems in monitoring and controlling a variety of functions as well as the recording of events during the production process. The automatic detection of deviations from pre-established norms can initiate warnings while making corrections without operator intervention using IIoT. 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 systems. 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.

Machine to machine communication (M2M), wired or wireless, can include sensors, vision systems and instrumentation to adjust the settings or controls on a production machine to affect changes on a separate materials preparation machine, even when the production of the materials occurs in another location but will be consumed on the final production machine or system. The data emitted from some of the sensors could well be used to monitor environmental compliance, and control the appropriate adjustments to take corrective action.

The necessary multidisciplinary assemblage of engineering talent will require: research and development management skills; familiarity with the technologies expected to be incorporated; and the design engineer's skills and experience to guide the decisions to be made by the designer, accompanied by 3D CAD and CAM software operating skills and document management systems with more than enough capacity to handle the entire project, including the electrical and electronic design software which has the capability to run and debug the electrical and control design before it becomes a physical reality. It is important that the CAD files be compatible with a suitable CAM interface.

To reduce the total time elapsed, from concept to satisfaction on the customer's plant floor, the design, engineering and development in all disciplines in the various critical areas, and those not so critical, must occur concurrently wherever it can and as much as possible.

A well designed machine will meet or exceed the customer's performance goals, safety standards and operability as described in the design criteria established by the need of productive output in both quantity and quality and other factors. Some of these criteria would likely be: efficiency, lower material costs, savings in labor cost, durability, reduced impact on the environment, lower energy consumption, utilization of less floor space, etc.

Design for manufacture with the lowest cost machinery.

It should be kept in mind that a one-off machine (a prototype) will probably require modifications before it is able to reach its productive potential. Mistakes will occur, better ideas will flow and the designer needs to be in a position to be able to shift direction as early and as easily as possible. Before building a prototype, a 3D solid model of at least the critical areas should be ‘built’ by CAD, with some animation being run to accomplish the initial debugging.

Besides the mechanical aspect of a machine or system, the design process will incorporate a control system which in turn may include programmable logic controls (PLCs), networking, machine/product condition monitoring (product monitoring via vision systems) as well as the human/machine interfaces - but the control system may also be much simpler.

Most automated machinery is now electronically controlled via PLCs and in many cases, in conjunction with an HMI 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. This article addresses an approach to the design of the physical aspects of the mechanical systems involved with only general references to the control systems that would be required. It does not include engineering data, formulae, tables and other information that can be found in numerous reputable handbooks and references, but rather describes a philosophy in regard to custom machine design.

Unlike mass-produced machinery and equipment, custom one-off specialty machines do not warrant a company/employer (the manufacturer) investing in expensive and unique tooling and dedicated machinery to produce just one or a few parts for particular machine – there is little or no economy in this, except for the very specialized components. The custom 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 of large accessible inventories of spare parts being held by the manufacturers and suppliers of these components. Further, the companies which mass produce 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 they 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 all the other specified attributes) over their predecessors if the custom machine is going to make economic sense.

The design of a special purpose machine should be arranged to facilitate revisions and modifications to the machine to meet future anticipated needs. This is a judgement call and it is easy to miss the mark and, unless predicted revisions and upgrades are obvious, one should not incur extra costs just on the off chance that a particular change or modification might be required at a later date.

Before the design process begins, a study should be conducted which would include all available economic data as well as the technical information and operational expectations. 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 may be 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 description of all that the machine is intended to achieve should be compiled, along with a description of the expected pre-engineering that will be necessary to provide an overview of the type and magnitude of the loads and stresses involved. The machine speed or productive rate and the target efficiency should be included as well as quantification of quality and precision including that of the materials to be processed.

Before the design process begins, a study should have been conducted which would include all available economic data, as well as the technical information and operational expectations. It is important that the marketing, sales and engineering personnel ensure that the customer and their representatives fully understand the legal and ethical ramifications of the use of whatever chemicals and dangerous materials that may be employed, if any.

It is also the responsibility of the design team to ensure that the customer and their operating crew understand any risks, liabilities and responsibilities involved with any of the materials and chemicals involved in the operation and/or during maintenance of this new machine or system. The design team should investigate alternatives that will reduce any inherent risk or the impact upon the environment. 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.

Tolerances and finish have a direct effect on precision and quality, of not only the machine, but also on the product being produced. The designer must understand the effect of tolerances on the quality of the resulting fit of the mating of parts, as well as the tolerances of the materials to be processed. The utility of each component will, in a large part, dictate the tolerances to be specified for a particular application. Unnecessarily tight tolerances are expensive and add no value.

The machine designer, more than ever, has a need to: use the latest in development techniques, employ the latest design systems and methods, apply the most versatile imbedded control technology and to integrate the use of these technologies with each other as well as into the machine. It is essential to have frequent design reviews which include the designers' peers, with separate reviews that would include the customer; all of which must include scheduled targets to be met, where the integrated team would be able to make the coordinated decisions which would lead to a smoothly integrated design, where any design changes would be implemented as early as possible.

It does not necessarily follow, but the machines now being produced will probably be equipped with PLC's, HMIs and/or other systems allowing the crew to control and adjust the various functions, servo motors and actuators, to increase their flexibility to handle a broader range of products and reduce downtime associated with product changeover. The machine designer, in designing a machine, will in many cases, be designing an intricate unit or system that will employ a multitude of interrelated and interconnected mechatronics components, some of which may be designed by others on the engineering team or they may be supplied by an outside vendor.

Before beginning a project in designing and developing 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 will also have 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 what sort of productivity will be required along with the general magnitude of the costs that can be supported while still meeting the projected production targets and the ROI over the period covered by any available 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 determined by 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.

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 will be necessary to document the thinking in arriving at each of the conclusions, the expectations, the costs and the risks. During the process of compiling this documentation, it may be necessary to do some additional pre-engineering reduce as much uncertainty as possible.

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 their 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 may 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 exact amount of space required to accommodate the machinery or system being designed, as well as 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 including overhead power line clearance and location of buried power supply, natural gas supply, propane gas storage and system of 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 also 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 whether any pits or underground services are to be required. Factors introduced by wind, seasonal conditions, humidity, altitude and other variable climatic and environmental conditions may also need to be taken into account.

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 or individuals, and there proximity to the installation, who may be called upon in case of these eventualities. It would be prudent to make arrangements for their services ahead of time. Keep in mind that anything that can go wrong may well go wrong – paraphrasing Murphy.

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

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 their 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, 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 the 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 will have the potential to positively influence the thinking of the design team.

An important aspect, which requires serious consideration, is the quality of the product to be produced, the quality of the material to be processed and the accuracy and quality of these during the production process. Through necessity, this will also include the accuracy of the monitoring/testing equipment incorporated into the production machine or system and imbedded control technology. 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 the final results may predict an efficiency rate well in excess of 90%, in general a rate of 75% should be used in the calculations for the target output of an automatic machine, i.e. 6 hours production at expected running speed for an 8 hour shift. There will probably be shifts when the average efficiency will exceed 90%, but there will also be periods with less than 50% due to problems with, among other things, the quality of the materials.

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 beast. The same is true with the owners – they 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 crews 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 a 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 required steps to get there being filled 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 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 responsibilities for each section or area are assigned to the different members of the team, all of whom 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 could require some research and development.

It is of great advantage for the individual design engineer to be familiar with the machining and the assembly processes as well as with the operational characteristics of the processes for which a machine is being designed. Some familiarity with ergonomics is an asset as well as.

Where the results would well be satisfactory, 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.

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 add to the cost. At the same time, the designer strives to keep production costs down while producing a safe and predictable piece of equipment with a life range that meets the criteria set by marketing.

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 stay down to 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. There is a fine balance between minimum design and engineering effort and high quality results.

Appropriate 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 the computer or hand written, for future reference in case that particular item or area should fall into question – do not try to rely on memory. With experience, a designer will develop 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.

A shareable engineering calculation software should be used to create a permanent record for all of the involved calculations 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. A suitable engineering calculation software will allow notes, observations and comments to be included with the calculations.

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, 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 components; the difficulties experienced by the millwrights in assembling a machine; the crating and logistical nightmares of the shipper including the delivery problems encountered with difficult roads and terrain; the communications obstacles and local resource hurdles faced by the field engineers; and the travails of the maintenance crews – all of which will help ensure that some seemingly minor, but important, details will be considered during the design process.

It is necessary that the design of each component allows sufficient area for holding during machining or other processing.

It is also necessary to ensure that each assembled section of machinery will fit into or onto whatever shipping conveyance will be used.

It is important to ensure that no patents are being infringed upon. It is possible, or perhaps quite probable that a patentable feature will be developed during the creation of this new machine. This becomes more valuable if this development, or feature, can be used elsewhere in industry.

The decision whether to patent is another subject. Inventions can be inspired by unrelated technologies. As an example, look at the Nike shoe history and its ‘waffle’ sole.

Copied from “Smithsonian site – National Museum of American History: *In 1972, Bill Bowerman applied for a patent on “an athletic shoe suitable for use on artificial turf . . . the sole has short multi-sided polygon shaped studs. . . which provide gripping edges that give greatly improved traction.” The sole’s design was inspired by his wife’s waffle iron which Bill subsequently ruined while using it to form his experimental rubber soles. Bowerman received his shoe patent number 3,793,750 on February 26, 1974 and Nike began producing the “waffle” trainers the same year.*