OPTIMUM EQUIPMENT START-UPS: CONQUERING THE COMMISSIONING BLUES

Steven Michael Ouellette BSMT
Staff Associate
ASQ CQE, CQA
Luftig & Warren International
2000 Town Center, Suite 2000
Southfield, MI 48075
E-mail: StevenOuellette@compuserve.com

Dr. Althea D'Souza
Staff Associate
ASQ Member
Luftig & Warren International
2000 Town Center, Suite 2000
Southfield, MI 48075

SUMMARY

The reader will attain a fundamental understanding of how advanced quality planning and a statistics-based start-up strategy has been used successfully in industry to commission over $750 million worth of new and existing equipment over the last 15 years with vast reductions in the real costs of specifying, commissioning, and operating equipment.

KEY WORDS

equipment, installation, set-up

INTRODUCTION

The "traditional" equipment start-up method and its frequent results are shown in Figure 1. Engineers involved in these start-ups have the goals of purchasing new equipment, installing it in a timely manner under projected cost, and turning it over to production as quickly as possible for full shipping runs. Although these are desirable goals, a closer examination will reveal that there are real costs if these are your *only* goals.

> **Terminology:**
> *Product* refers to the output of the purchaser's process, and can be an object or service. Product characteristics can be either in-process (may be modified in subsequent process steps) or end-of-line (as the customer sees it).
>
> *Commissioning* refers to the activities leading up to turning over new equipment for normal production.
>
> *Functional testing* refers to testing the safety and mechanical functionality of equipment.
>
> *Qualification* or *acceptance testing* are the tests that must be passed by the new equipment prior to releasing the process for normal production.

Project engineers are frequently rewarded, explicitly or implicitly, on the amount of equipment they install. Rarely are they rewarded for avoiding new equipment capital expenditures through process improvement on existing lines. Since capital project engineers do not typically perform that function this is not an important consideration for their success. However, the business as a whole would benefit from an examination of production's needs and if these needs can be met with existing equipment through process improvement or smaller capital outlays.

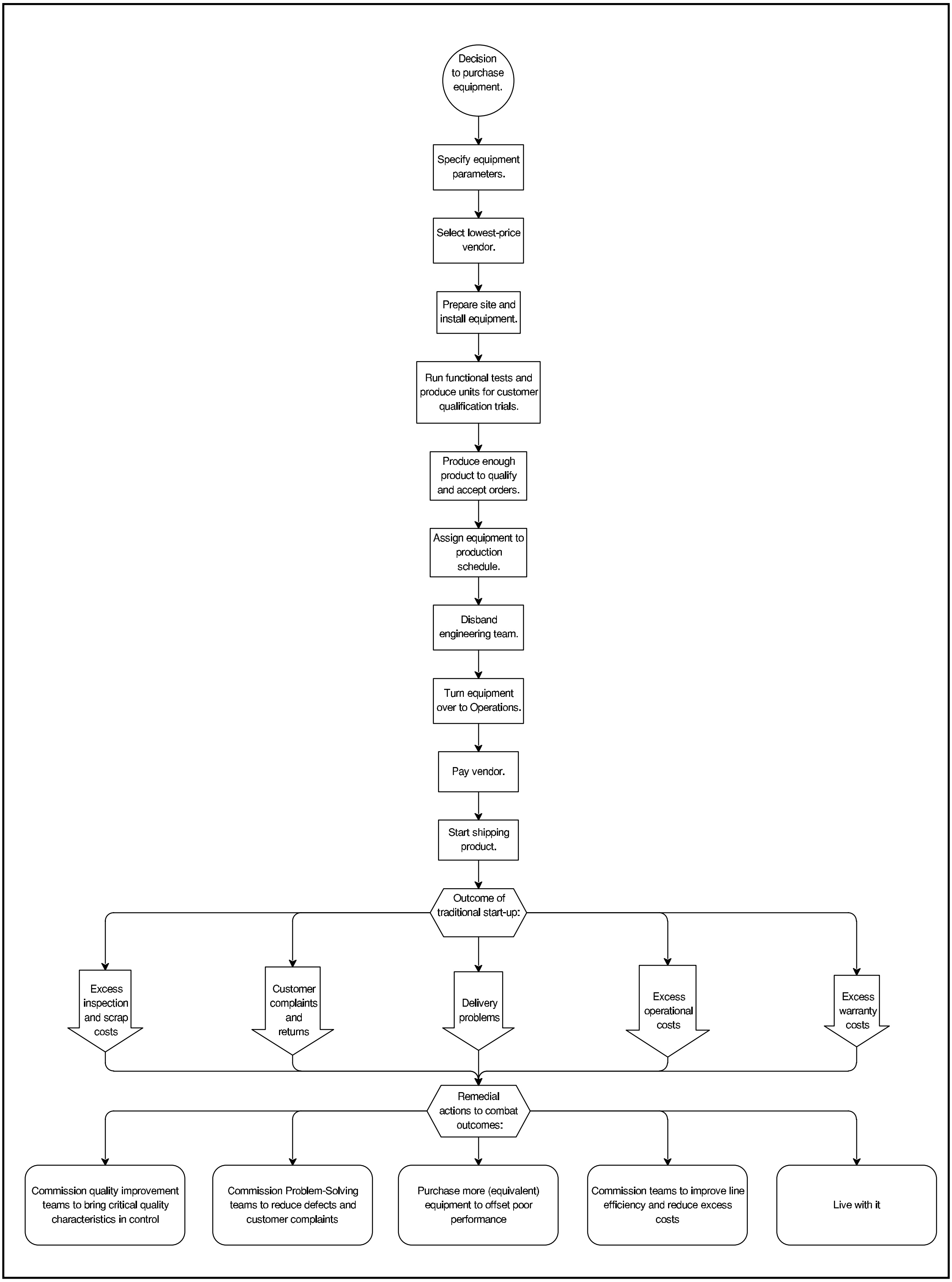

Figure 1. Traditional start-up.

Rewarding project engineers for on-time installation when an outside vendor is responsible for much of the timing is also a frequent occurrence. Typically, this is an attempt to ensure that the equipment is fully installed by a certain date when penalties for the vendor have not been written into the contract. This situation can encourage the engineer or vendor to cut some corners to meet the required date, particularly if there are no process and product performance guarantees written into the vendor's contract. Rewarding engineers for coming in under projected cost may have the effect of driving them to submit a slightly padded project cost or to bypass an unexpected but needed cost at some point in the project.

The goal of quickly turning the new process over to production drives the project engineer to spend little time on commissioning beyond functional testing. It is usually left up to the production personnel to figure out how to run the new equipment in the real world after the project engineer has moved onto the next project.

No hardworking project engineer wants any of these things to happen, but the capital improvement system that most companies use can pressure them into doing just that. Most engineers end up doing the best job they can under those conditions, and succeed in bringing their projects to conclusion. It is ironic to note that the managers they are protecting through their actions will likely be the ones pressuring them to control costs and provide a more rapid turnover to production.

We contend that a capital improvement project brought to completion in the typical way is not complete, and will almost certainly cause a net loss to your bottom-line. In the traditional start-up, there is no mechanism for the start-up engineers to make new production lines easy to run, or to make sure that the line meets production's needs beyond the trial run.

We will show how an "optimum" start-up, on the other hand, will not only result in a lower cost in the short term, it will show an improvement to your bottom-line over the long term. This strategy has been used effectively by several of our clients. You will find this strategy is unique in its practicality and efficacy in industry. By following the methodology summarized in Figure 2, you could realize savings like those shown in Table 3. We use the term "optimum" start-up not because it will be free of problems, but because when the inevitable problems occur, you will have vital information and a plan for overcoming them.

> **Terminology:**
> An *optimum start-up of new equipment* refers to a process by which advanced statistical methods are applied in a strategic and disciplined fashion to critical product performance, quality, and defect requirements, as well as critical equipment performance requirements. The purpose of this effort is to achieve statistical qualification or optimization for all of the critical elements prior to the initiation of full-scale production (Luftig 1997).
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> An *optimum start-up of existing equipment* refers to a process by which advanced statistical methods are applied in a strategic and disciplined fashion to critical product performance, quality, and defect requirements, as well as critical equipment performance requirements. The purpose of this effort is to achieve statistical qualification or optimization for all of the targeted elements during the partial or complete suspension of the 100% dedication to production requirements (Luftig 1997).

THE SITUATION

At some point, your company will believe it has a gap, and believe that they need new equipment to fill that gap. Usually, it will be a need for more capacity, better product quality, and, less frequently, newer technology. The preliminary step is to fully explore and document the need, not the equipment that is needed. It is important to try to describe the need in terms of product and process results and quantify the impact of fulfilling these needs in monetary terms. Technological upgrade should not by itself be a justifiable reason for expenditures.

Many companies will require an estimated return on investment, or payback time; consequently impact quantification is the first step in justifying capital expenditures. We suggest working with an accountant in this phase, to make sure that the numbers are valid and that the full impact is counted. For example, if you need more production, you may be increasing speeds, decreasing maintenance downtime, or running the machine longer, and all of these have effects beyond that machine itself. If you increase speeds, you should ask whether you would be able to transport and pack quickly enough. If you decrease maintenance downtime, will you be freeing up mechanics for essential work elsewhere? If you are able to run the machine longer, will you need more crew members? Once management is provided with an accurate accounting of the need, they can in turn support the decision to proceed with confidence that there will

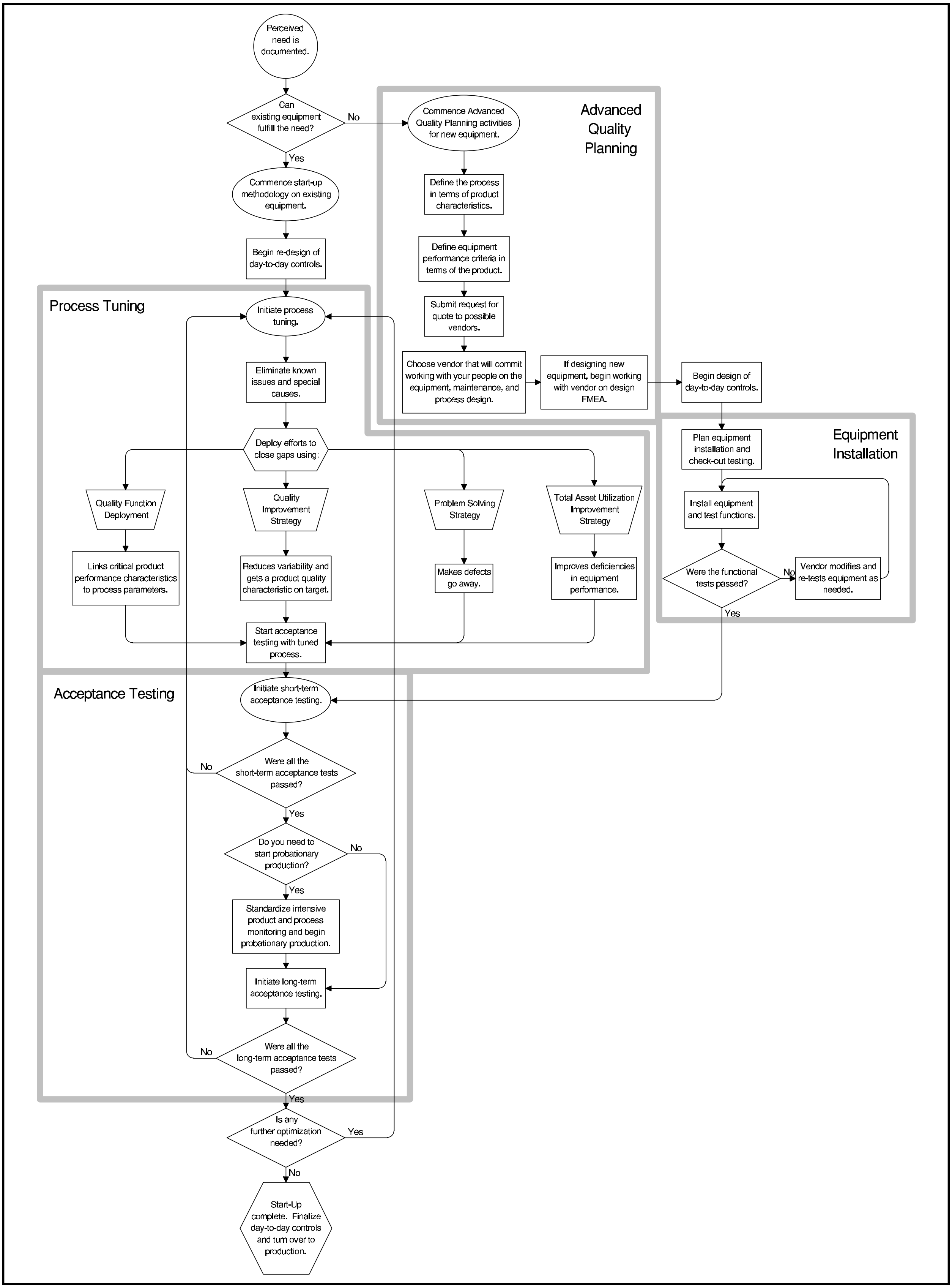

Figure 2. Optimum start-up.

be a bottom-line benefit realized as a result. As soon as you have decided that there is a need and that it makes sense for the business to fulfill that need, you are ready to begin the optimum start-up methodology. The following steps give the details behind the flowchart in Figure 2.

FIRST STEP—DO YOU REALLY NEED NEW EQUIPMENT OR CAN YOU GET WHAT YOU WANT FROM EXISTING EQUIPMENT?

Although this is not the primary thrust of this paper, we need to emphasize how important this step is, and how frequently it is not done. Project engineers have, at one time or another, become involved with equipment that should never have been purchased. In one of many cases of this in an author's experience, the needed capacity improvement was achieved on other similar equipment without any major capital investment. The tragedy was that new equipment had already been purchased before the improvement efforts had begun since everyone "knew" that process improvement alone could not close the gap. The start-up technique that we will outline later can be applied to an existing line just as it can be to a new line (except for advanced quality planning). It does, however, require that you to be willing to devote line time and personnel to its improvement. Listed are some common techniques in the literature that we have found useful in improving existing processes, short of major capital improvements.

- Improving maintenance metrics
- Operator training
- Mistake proofing
- Autonomous control
- Standard Operating Procedures (SOPs)
- Supplier Quality Assurance (SQA)
- Experimental design
- Smaller equipment additions or changes such as:
  - Controllers
  - Measuring devices
  - Feedback and feedforward controls
  - Climate controls
- Robust process design
- Statistical and engineering process control
  - Improving stability (Shewhart SPC charts)
  - Adjustment charts to improve output (different than Shewhart SPC charts)

SECOND STEP—ADVANCED QUALITY PLANNING

Define vendor requirements in terms of end-of-line product characteristics.

Consider what you are really purchasing when you buy new equipment. For example, are you purchasing a machine that will deliver a certain temperature, or are you really purchasing a machine that will make a product with a given strength by controlling the temperature?

Too often, we define the process or equipment variables without the involvement and commitment required from the equipment vendor to meet the product requirements. Specifying end-of-line product performance actually benefits your vendor since it gives them more flexibility in design as well as clearly defining what will make their customer happy. An unhappy client who received exactly what they ordered often unfairly berates the vendor when the vendor was not told their customer's product needs.

In order to define vendor requirements in product characteristics, you begin by **defining the process output in terms of customer-delivered characteristics**. For many mature industries, these characteristics can be written right into the vendor's contract. For example, if you are purchasing a new mill for rolling steel sheet, you will write into the contract the control you need over thickness. The vendor has installed enough mills to feel comfortable (based, hopefully, on data) guaranteeing thickness control in the product.

If the equipment is not the last process that affects any of these characteristics, you will need to cascade product characteristics back through the process until you get to output of the new line (in-process product characteristics). For example, if your final characteristic is how many cookies fit in your package, you will need to link size back through baking variables to variables for the new dough extruder you are buying.

Compile a list of the in-process and/or end-of-line product characteristic specifications and capabilities.

Define your needed process averages and specifications or defect and defective rates and assign desired capabilities to the characteristics defined in the previous step. Remember that you usually don't sell "averages" so define capability in terms of individuals.

In some industries where the purchaser is the expert, an additional step of **translating the product characteristics to process parameters** will need to be performed. *Resist this impulse* unless absolutely necessary. This puts the burden of process engineering on the purchaser and reduces the vendor's responsibility for actual end-of-line product output. If the vendor doesn't know what product output you want, she may provide you with something that meets your process specifications but had she been asked would have known it could not do what you wanted to the product. If you do have to specify process parameters, make sure you clearly communicate with the vendors what your design intents are, ideally through a design failure mode effects analysis (FMEA) (Krausch et al. 1994, 14).

There are still some process parameters that you may have to specify like sizes, weights, depths, and range of motions. The key is to leave as much of the process design that affects the product as possible to the vendor.

Note that part of what you are actually buying is the safety, productivity, maintainability, and quality output of the machine. These should also be defined with specifications for the vendor to meet. An efficient way to do this is by using safety and Total Asset Utilization (TAU) metrics (Medlin 1992).

Clearly define your performance criteria and put them in the request for quote and in the final contract.

Once you have defined the in-process and end-of-line product characteristics, write them into your request for quote along with the potential penalties if they are not attained. A typical payment plan would be one-third before starting, one-third after on-time equipment installation, and one-third after it has passed all of the performance criteria. Some vendors who promise that their equipment will do whatever you need become very defensive when you tell them that part of their fee will be dependant on product performance guarantees. It is very reasonable that you ask that their faith in their equipment be backed up with actual performance data at your location and enforced in the contract. Be sure to define your performance criteria as being of a given sample size, in statistical control, and with a given capability. Be fair to your vendor, though. Use the limits you really need for your criteria, and pick what capability you really need for each based on the risks. Clearly define what penalties will be incurred if the equipment is installed late or does not meet some or all of your criteria. There is a real consequence to your end customer, and it is fair that the cost be passed back to the vendor. Consider a reward for exceeding performance criteria that affects the bottom line. For example, just as a vendor should be penalized if the equipment requires more maintenance downtime than planned, so should they be rewarded if the maintenance needs are lower, since this improves the purchaser's bottom line. Also give some thought to confidentiality agreements. If it is a custom-designed piece of equipment, do you want others to be able to see the design? If it is acceptable for competitors to see it, and for the vendor to sell it to them, perhaps they can give you a price reduction for your aid in design. Another possibility is that you and the vendor learn how to get better performance from off-the-shelf equipment during the start-up tuning activities. The vendor will want to use this information with future customers, so perhaps you can license the settings or work out a discount based on the performance improvement.

Pick a vendor that will commit to working with your people in equipment, maintenance, and process design (as appropriate).

Part of your request for quote should include the requirement that vendor personnel will work with you to:

- **Design the equipment (design FMEA) if the equipment is custom made**. If it is "off the shelf," you should require that a copy of the vendor's design FMEA accompany the quote so that you can make sure that your product criteria were accounted for in the design. If the vendor did not design the equipment with the aid of a tool such as a design FMEA, it is an invitation to you to propose creating one together.
- **Design the maintenance schedules (equipment FMEA)**. If it is "off the shelf," you should require that a copy of the vendor's equipment FMEA accompany the quote along with reliability data from actual installations.
- **Design the process (process FMEA)**. If it is "off the shelf," you should require that a copy of the vendor's process FMEA and SOP's accompany the quote.
- **Resolve any occurrence if the equipment fails to meet the acceptance criteria**. The system for this point will be outlined later in Acceptance Testing and Process Tuning.

If the vendor can supply you with data of any sort (from bench tests to data gathered at other installation sites), use these data to perform a potential capability study. Vendors who can supply data should be ranked ahead of those that cannot, even if they are not capable. At least you know how close they are likely to be and the vendor can plan for any required performance improvements in the quote.

ADVANCED QUALITY PLANNING CONCLUSION

Note that performing these steps may not lead to the lowest *price* vendor, but it will certainly lead to the lowest *total cost* vendor. Oddly, people seem willing to "save" capital purchase money (which is capitalized and depreciated) and end up losing money from the bottom line due to continual losses in safety, productivity, maintainability, and quality (which is not depreciable). Advanced quality planning attempts to minimize these ongoing costs through initial preparation.

THIRD STEP—DESIGN OF DAY-TO-DAY CONTROLS

This step establishes the daily controls on the process to ensure that it will continue working after acceptance testing. Many of these activities can be done prior to and during installation while some must be done after the equipment is running. During the traditional start-up, the day-to-day running of the process is rarely given much consideration since the people who are usually involved in the start-up are not the people who will be running it once it is turned over to production. The activities and information you need to design a daily control system nicely overlap with what you need to be doing anyway for the start-up itself. The scope of this activity is beyond this paper. A list of activities to help design a comprehensive day-to-day process control system includes:

- Gage capability studies
- Process flow diagram
- Supplier-Input-Process-Output-Customer (SIPOC) diagram
- Process FMEA
- Process control plans
- Quality Function Deployment (QFD) tables
- Standard Operating Procedures (SOPs)
- Defining and monitoring critical process metrics
- Reaction and containment plans
- Audit system
- Operator training system and materials

These activities can be spread out and accomplished before, during, and after installation. They should be complete, however, before turning the process over to production for unrestricted production.

FOURTH STEP—EQUIPMENT INSTALLATION AND CHECK-OUT TESTING

There is a well-defined discipline to preparing the site, installing equipment on time, making sure everything fits together and functions safely, providing operator training, and more. An optimum start-up includes this planning as well as contingency planning. Check-out testing is frequently done by the vendor, but we suggest that you have operators and engineers watch what they do very closely and take notes on anything that is not already documented. This is one area, though, that most businesses do quite well, so we will not dwell on it. Prior to and during installation, much pre-work can be done. This includes the following:

- Acceptance testing sample size (based on α and β risks)
- Failure mode effects analyses (FMEAs)
- Some gauge capability studies

- First-draft standard operating procedures
- Equipment and process training
- Product and process control plans

FIFTH STEP—ACCEPTANCE TESTING

A traditional start-up would require only enough units produced to allow for customer testing. The danger in this is that a non-statistically designed production run may appear to be acceptable, but in reality provide unacceptable long-term results. Here is an example (Luftig 1996) of how this worked on a coil plating line. Table 1 shows the data and decisions made based on traditional acceptance testing (sample size of 10), followed by the production line data after the line had been in full-scale production for three months.

The results are dramatically different after the optimum start-up strategy was used on the plating line as shown in Table 2.

An optimum start-up should have two phases to the acceptance testing. The first phase would be a short-term capability study (Petrovich 1997; Luftig 1996) to tentatively qualify the process for production. This would involve examining an appropriate sample of the output over a relatively short time period to analyze whether the process is potentially able to satisfy the performance criteria. This will likely not catch long-term effects like tool wear, maintenance, and seasonality, among others. Depending on the industry and equipment, you may make the decision to begin using the equipment for probationary production after a successful short-term capability study if you were to very closely monitor the output and process variables.

If the short-term capability study shows the process might be capable, then you would move onto the second phase. This second phase is the long-term capability study (Luftig 1996), which tests to see if the output conforms to your requirements after giving everything that can go wrong a reasonable chance to occur. If, for example, your process were likely to be affected by the low humidity and temperatures during winter, you would not want to say with finality that the process is capable without having to work under those conditions. This also gives you a chance to observe the effect of maintenance cycles, raw material fluctuations, operator differences, motor burn-in, and other time-dependent occurrences. When the long-term study shows that the process is in control and capable of producing the product characteristics you want, the start-up is officially concluded and can be turned over to production and the vendor paid their last installment. The intensive monitoring that you have been doing of product and process variables can now be reduced to a sampling frequency calculated from your data and the risks involved, and the transfer to unrestricted production will go smoothly.

Table 1. Acceptance testing results and outcome after three months production.

Quality Category	***Requirements/ Specifications***	***Observed Outcomes (and Decision) after Acceptance Testing***	***Observed Outcomes (and Decision) after Three Months of Production***
Product quality	0.1025 ± 0.0025	0.10211, 0.10492, 0.10371, 0.10416, 0.10156, 0.10370, 0.10400, 0.10272, 0.10244, 0.10325 *(acceptable)*	4.73% Defective *(unacceptable)*
Product defects	No more than 2 voids per coil	1, 0, 2, 1, 1, 2, 2, 2, 1, 2 *(acceptable)*	17% of coils with > 2 voids *(unacceptable)*
Product Performance	2% Units per coil maximum	2, 0, 1, 0, 0, 2, 2, 1, 1, 2 *(acceptable)*	9.86% of all coils > 2 % defective rate *(unacceptable)*
Equipment performance	MTBF ≥ 2 Hours	MTBF = 2.35 Hrs *(acceptable)*	MTBF = 1.75 Hrs *(unacceptable)*

Table 2. Results on plating line three months after optimum start-up and tuning.

Quality Category	*Requirements/ Specifications*	*Observed Outcomes (and Decision) after Statistical Qualification*	*Observed Outcomes (and Decision) after Optimization*
Product quality	0.1025 ± 0.0025	99.994% In Specification with $\mu = 0.1025$ *(acceptable)*	≈ 100% In specification with $\mu = 0.1025$ (More than minimally acceptable)
Product defects	No more than 2 voids per coil	99.865% of coils with ≤ 2 voids *(acceptable)*	≈ 100% of coils with 0 or 1 void (Lower costs due to higher yield, lower internal rejection rates and low/no customer returns and complaints)
Product performance	2% Units per coil maximum	99.997% of all coils less than 2% defective rate *(acceptable)*	≈ 100% of all coils < 1 % defective rate
Equipment performance	MTBF ≥ 2 hours	MTBF = 2.35 Hrs *(acceptable)*	MTBF in control at 6.25 hours (More than minimally acceptable; lower costs due to higher levels of asset utilization)

SIXTH STEP—PROCESS TUNING

Unfortunately, it is has been our experience that the ideal start-up you were aiming for with advanced quality planning rarely materializes. When it does, it is usually a mature industry and an application of well-tested technology. In either case, the advanced quality planning done at the beginning will help you out either by preventing problems or by giving you the information to find a path out of the crisis. It is important to note that you probably only know you are in a crisis because you are using the optimum start-up methodology. The traditional start-up would already have turned the equipment over to production with a full schedule planned for the next year, as in the examples in Table 1 and Table 2. The problem would eventually be detected and still needs to be fixed, but you have to do it without the equipment experts and while maintaining a full production schedule.

Start off by **eliminating known issues and special causes**. If common sense tells you to fix something, and it is easy and inexpensive to do, take care of it. Since you are analyzing the process statistically, you may be able to identify sources of special cause variation with Shewhart charts and eliminate those as well.

It may be obvious what to do, but if the problem remains, or if it is not obvious where to start, **deploy efforts to close performance gaps using the appropriate methodology**.

- Quality function deployment (QFD) (Cohen 1995)
- Quality improvement strategy (Luftig 1989)
- Problem solving (Petrovich 1996)
- TAU improvement for equipment gaps (Medlin 1992)

These efforts can be teams working in parallel, or even be a single multitasking team, depending on the size of the project and the nature of the gaps. Some or all of these efforts may end up designing and running an experiment to investigate process parameters. We have found fractional factorial screening experiments followed by confirmations extremely effective if there are many factors that might cause the performance gaps. Once the results have been experimentally confirmed, any process changes should be systematized as part of the day-to-day controls. This triggers reinitiating the short-term acceptance testing. When the performance gaps have apparently been closed in the short term, the improvements are verified with the long-term study.

BOTTOM-LINE GAINS USING THE OPTIMUM START-UP METHODOLOGY

If you follow this methodology from start to finish on new equipment installation, the following list tells you what you will get for your investment.

- The new equipment will be operating in a state of statistical control and at the maximum level of capability possible (or at high process performance capabilities) for those product and performance variables you designated in the beginning.
- The new equipment will be operating at the minimum cost profile available given the parameters defined by the process and management goals.
- A complete quality operating system that is related to the critical product and process variables including:
  - Master and process block QFD matrices
  - Design, process, and equipment FMEAs
  - Product control plans and appropriate control systems
  - Process and measurement control plans and control systems
  - Maintenance control plans and control systems
  - Reaction plans for all critical product and process variables
  - SOPs and a workforce that has been trained to use them

Depending on the size, complexity, and focus of the start-up, the cost savings can be astounding. In situations in which the equipment had already been ordered or changes were made to existing equipment, none of the advanced quality planning benefits were possible. Yet in every instance, the cost savings due to the start-up methodology saved in excess of the cost of the start-up activities. In most cases, the company saved more than the capital cost of the entire project due to detecting and correcting issues that affected product performance or liability before any product was released. See Table 3 for a sample of savings from optimum start-ups. You will recall too that the costs of starting up a new piece of equipment are capital costs, and are subject to depreciation. The losses you would have experienced with the traditional start-up and turnover to production are not depreciable and directly impact your bottom line.

Table 3. A sample of optimum start-ups and savings.*

Line/Process	*Existing or New*	*Savings Mainly From*	*Money Saved*
#3 Coating line	Existing	Increased throughput	$23.6 million/year
Multi-shearing	New	Improved reliability	$1.7 million/year
Y-line	New	Increased throughput	$16 million/year
Product defect	Existing	Decreased returns	$750,000/year

* *Some information in this table has been coded to protect client confidentiality.*

FREQUENTLY ASKED QUESTIONS

Won't it cost more time/money/effort to do the methodology?

A vice president of operations once challenged us about the presumably large amount of time, money and effort required to perform an optimum start-up. When questioned about his oldest plant, the vice president admitted that although the plant had been in operation for 12 years, none of the critical product and process conditions were operating in a state of control or capability. Our reply to him was that after 12 years, he was still "starting up" the plant. Having got the point, the vice president enlisted our aid for a start-up on two new plants. The first of the two came in at about $80,000 a month under budget, at a higher than projected level of production. This was in a plant with less than 100 hourly and salaried workers.

We are buying new equipment off the shelf. Do we need to use the methodology?

It is just as important to use the methodology in this case, although the data from previous installations (if available) will make your job somewhat easier. It is particularly important that you give thought to a design FMEA to make sure that the piece of equipment designed for general use is giving you what you need in your particular application.

We have installed equipment like this before. Do we need to use the methodology?

We would still recommend using the methodology. If you have not followed the methodology on the similar equipment, the rigor will help you with both the old and new processes. If you have, it should be easy to follow the discipline of the methodology and to be prepared in case this equipment does not perform like its predecessor did.

We really like our vendor, and we don't want to imply that we don't trust them.

As logical as the first few questions are, this one is actually the most common real reason for not wanting to use the methodology. As engineers, we know that you work with the vendors, eat with them, talk with them, and form a comfortable relationship with them—and there is nothing wrong with that. However, we can sometimes lose sight of the fact that they are there to provide a service that will end up making us money for a fair price. You are not asking anything from them other than guarantees that what they promised will come true. You may end up paying a bit more for them to work with you in the design phase and the acceptance testing, but you should not pay them more for a guarantee that the equipment will perform as you request. This is in the vendor's best interest as well, both to keep their current customer satisfied and coming back for more, and to generate data which can be used to improve their products and bring in new customers.

CONCLUSION

The rigor and discipline of using the optimum start-up methodology provides a system for vendor and purchaser multidisciplinary and multi-departmental communication before, during, and after equipment installation. Its strong basis in statistical sampling and experimentation along with the information exchange this method facilitates between vendor and customer ensures that the customer's needs are known, and that the vendor provides a process to meet those needs. In the unfortunate event that the vendor does not supply a process to produce the critical product parameters needed, the customer will have options in the contract to offset (at least partially) the cost they will bear as a result. Establishing maintenance and production metrics as part of a day-to-day control system ensures that when the shine has worn off of the new equipment, it will still be performing equal to or better than what it did on the first day of production. These conclusions are supported by numerous case studies we have compiled over the past 14 years in disparate industries that show vast reductions in total start-up costs and/or improved profit associated with the methodology.

REFERENCES

Cohen, L. 1995. *Quality Function Deployment: How to Make QFD Work for You.* Reading: Addison-Wesley.

Krausch, D. L. 1994. *Advanced Product Quality Planning (APQP) and Control Plan.* Detroit: AIAG.

Luftig, J. T. 1997. *An Overview of a Statistical Start-Up™.* Southfield: Luftig & Warren International.

Luftig, J. T. 1996. *Statistical Start-Up™ The Low/No Cost Key to Equipment Qualification and Optimization.* Southfield: Luftig & Warren International.

Luftig, J. T. 1989. *A Quality Improvement Strategy for Critical Product and Process Characteristics.* Southfield: Luftig & Warren International.

Luftig, J. T. 1996. *Advanced Statistical Process Control and Capability.* Southfield: Luftig & Warren International.

Medlin, C. H. 1992. *Reliability Methods for Processes and Equipment.* Southfield: Luftig & Warren International.

Petrovich. M. V. 1995. *Problem Solving.* Southfield: Luftig & Warren International.

Petrovich, M. V. 1997. *Quality With Confidence in Manufacturing.* Chicago: SPSS, Inc.