CRITICAL PARAMETER MANAGEMENT

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Early in the systems engineering process many decisions are made. When these decisions are made well, they strongly contribute to success, but only if they are carried through in detailed design and transition to production. It is therefore necessary to work out the implications of the critical early decisions on myriad detailed decisions.

Critical Parameter Management (CPM) is an engineering practice specifically aimed at maintaining the robustness of the system through detailed design and manufacturing. In the early development, ideally during technology development, the critical parameters have their values optimized to achieve robust performance of the system. Subsequently during detailed design of the product system, production development and operation, and field-service development and operation it is all too easy to lose the optimized values of the critical parameters. When that happens, the system no longer has robust performance, and the development is delayed, with great risk of excessive warranty costs once the system reaches the field.

The first distinction to be made is between a critical parameter and a critical specification. Critical parameters are the functional variables that control the physics (and chemistry and biology) of the system. Many of them never appear on the production drawings. For example, a force between a feed belt and a paper stack is critical to the physics of paper handling. This force is therefore a critical parameter of the paper feeder system. This force is determined by a spring constant and some geometric parameters of the design. These parameters do appear on drawings (or are implied by part numbers on a bill of materials). The details on the drawing and bill of materials are called critical specifications.

Table 1 shows how critical parameters are transformed during multiple phases of systems engineering. During detailed design, engineers mapping from critical parameters to critical specifications. During this mapping it is important to maintain the needed nominal values of the parameters and manage the associated variations. Similarly, subsequent transformations must carry the implications all the way to the factory floor.

Table 1. From critical parameters to quality: requiring parameter management through detailed design, production system design, and manufacturing operations.

From	To	Phase of Systems Engineering
Critical parameter	Critical specification	Detailed design
Critical specification	Production process	Production system design
Production process	Quality	Manufacturing operations

The objective of Critical Parameter Management is to assure that the optimized values of the critical parameters are sustained, which requires that the critical parameters are flowed down properly to set manufacturing precision levels that assure the customer satisfaction that was enabled by the robust design. Ideally the production process that is used to produce each critical specification is in control and capable. A manufacturing process that is *in control* is undergoing only random variations. A manufacturing process that is *capable* exhibits a standard deviation small enough compared to tolerances.

THE CRITICAL-PARAMETER DRAWING

The core of Critical Parameter Management is the Critical-Parameter Drawing. It is also the oldest in practice, having been implemented at the Xerox Corporation in the late 1970s. It was implemented in response to the type of problems that have already been alluded to. An example is shown in Figure 1.

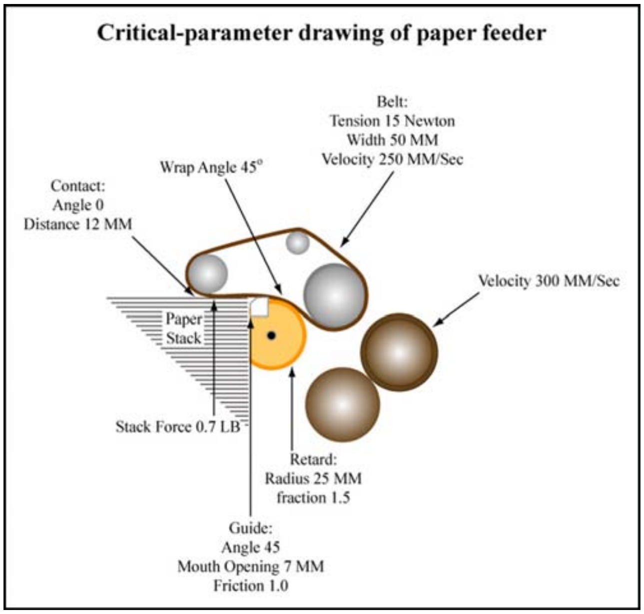

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Figure 1. Critical-parameter drawing of paper feeder.

Figure 1 shows the nominal values of an example of some of the critical parameters. In the actual critical-parameter drawing there were about 30 such critical parameters, and a range, or tolerance, was also given for each critical parameter. Here it has been simplified to concentrate on the basic principles. We will return to the subject of the acceptable range around a critical parameter.

The first characteristic to note is that some of these critical parameters are not critical specifications; i.e., they do not appear on any production drawing. An example is belt tension, which is specified as 15 Newtons. At this stage of development all that we care is that in order for the feeder to work well, the tension in the belt must be close to 15 Newtons.

It is left up to the subsequent detailed design to determine the mechanism that will produce the 15 Newtons. In Figure 1 the roller that is pressing up against the belt will produce the tension. The upward force on the roller has to be resisted by the two downward force vectors produced by the tension in the belt on both sides of the roller. The upward force on the roller can be produced by a spring, gravity, pneumatic actuator, solenoid, or other means. The detailed design has to be simple and inexpensive, and consistently produce the necessary upward force that produces 15 Newtons tension in the belt.

However, experience has taught that it is just here that trouble starts to enter in. The detailed designer is usually working in a trade-off space in which the robustness of the system is not included. Rather the emphasis is on characteristics such as manufacturability, maintainability, ergonomics, and safety. In his or her concentration to do well on these characteristics it is easy to lose sight of the ultimate goal – to produce 15 Newtons of tension in the belt.

This is the purpose of the critical-parameter drawing, to keep attention focused on the functionality of they system. It says to the detailed designers, production designers, and production operation people, that they can use their best practices to achieve the other types of characteristics, but they must produce the functional values that are on the critical-parameter drawing.

CUSTOMER SATISFACTION

The critical-parameter drawing is essential to customer satisfaction. In the beginning we deployed the customers' needs into engineering characteristics in the House of Quality. In response to those characteristics we selected and integrated technologies that we judged would provide a strong market-attack plan (MAP). Robust design was done so that the integrated technologies would adhere to customer-satisfaction values in the realistic conditions, which have large variations that tend to throw performance off.

Having done this early work well, now adherence to the critical-parameter drawing will provide functionality that will live up to our expectations when we selected and integrated the technologies. Thus the critical-parameter drawing enables the subsequent activities to achieve values that will provide customer satisfaction.

One approach is to simply include all of the critical parameters in the design matrices of QFD. In principle this seems as though it might work. However, experience has shown that it is beneficial to have critical-parameter drawings to emphasize the necessary attention.

The subsequent activities after the critical parameters have been optimized in robust design are:

1. Detailed design
2. Production design
    - 2.1. Process selection
    - 2.2. Tooling design
    - 2.3. Online quality control design
3. Production operations – Online quality control operation

This can be further extended to include field operations.

FROM CRITICAL PARAMETERS TO THE FACTORY FLOOR

The first step is the detailed design. Let's assume, for example, that the detailed design has six critical specifications (x_1 through x_6), which control the force against the roller F_r that produces the belt tension of 15 Newtons.

$$F_r = F_r\,(x_1, x_2, x_3, x_4, x_5, x_6)$$

Doing the detailed design so that belt tension is nominally 15 Newtons is relatively simple. A much greater challenge, not well understood by most engineers, is managing variation away from nominal. A little history will help explain the current situation.

Until the late 18th century all manufactured artifacts were made by craftsmen. If parts had to fit together, he hand tooled them until they fit. Naturally the parts from one craftsman did not match the parts from another craftsman. Even successive items from one craftsman, even though nominally the same, would have parts that could not be interchanged between the two items. The hand tooling was always a little different for any two items.

Circa 1765 Jean-Baptiste de Gribeauval, a General in the French Army, concluded that they should have muskets with interchangeable parts. His primary objective was to be able to repair muskets in the field. After a battle there would be two broken muskets. If the parts were interchangeable, they could be combined so that there would be one good musket.

The production technology of that time was not up to the task. However, the dream marched on. It was carried into America by French officers who aided the colonists in their battle for freedom from Britain. It took much difficult work, but by 1850 the arsenals at Springfield, Massachusetts and Harpers Ferry, Virginia could produce some interchangeable parts. However, it was expensive to do so, and this approach was slow to spread to other industries. However, by the early 20th century Henry Ford had to have interchangeable parts to operate his famous assembly line.

How were interchangeable parts achieved? By rigorous application of go/no-go gaging. If a shaft had to fit into a hole, both were made to tight upper and lower limits such that the shaft would always fit into the hole with a functional clearance. Thus came about the engineers' obsession with tolerances. If the nominal (target) diameter of a shaft is 25.000 mm, then a tolerance is applied to that; e.g., ± 0.025 mm. This says that all shafts that used should be within that range. That is the no/no-go culture that was started by General de Gribeauval.

In the 1920s Dr. Shewhart at the Bell Labs realized that production processes have some natural variation, which can be characterized by the standard deviation, σ. He also observed that the production processes can have variation due to *special causes* (also known as *assignable variations*). The effects of the special causes can be eliminated in the short term, while the natural standard deviation can only be improved by longer-term quality improvements.

Any feature on a part can be produced by one of several production processes. Therefore, production-process selection is an important decision. Each process is characterized by its cost and its precision; i.e., standard deviation. For more than a century engineers have put tolerances on drawings. When they did that, they implicitly chose a production process. As product engineers became more and more separated from production, they often did not understand this connection very well. This led to battles between the design engineers and manufacturing engineers. When the design engineers don't understand production and the manufacturing engineers don't understand the justification of the design, a standoff frequently ensues as depicted in Figure 2.

Figure 2 removed due to copyright restrictions.

Now let's seek a more effective process than we see in Figure 2. One is suggested by a story from Don Clausing. Circa 1984 Clausing took Dr. Taguchi to the countryside south of Rochester. They hiked and then went to a country restaurant for lunch. Summarizing a common view of a good systems engineering process, Don said, "First we do robust design, and then we put tolerances on the drawings." Taguchi replied, "No." Don repeated that thought in various ways, always with the response, "No." Finally they got into a dialogue, from which Don emerged with a new understanding of what to do after robust design -- select the production process to attain optimum overall economy!

Here is how we view the situation. For each feature to be produced we have several production options. To simplify the primary point, let's assume that there are two production options. For example, a 25 mm shaft could be turned on a lathe or it could be ground in a cylindrical grinder. Turning will typically achieve precision of 0.05mm on a 25mm diameter. Cylindrical grinding can typically achieve precision of 0.01mm. Such values are readily available for most manufacturing processes as depicted in Figure 3. But the added precision comes at a cost, perhaps a factor of two or three times the cost of turning. Cost implications of process precision can be estimated (roughly!) with charts such as Figure 4. In fact, the dependence of cost on precision more complex – it is not so smooth as in Figure 4 because at some point you are forced to “jump” from one process to a fundamentally different process. But for an initial estimate, cost models as depicted in Figure 4 are fine.

Note, however, how deeply tolerance based thinking is rooted in the current culture of engineering. Figures 3 and 4 label axes with “dimensional tolerance” when standard deviation or precision would be a more accurate label!

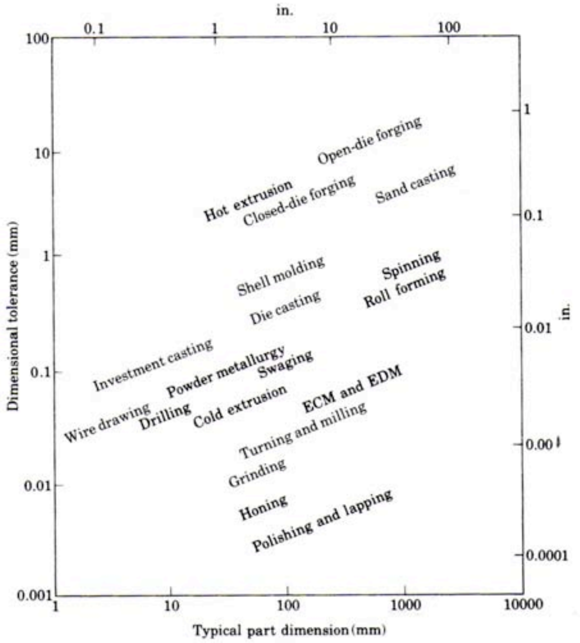

Figure 3. Process selection and precision (from Kalpakjian,1992).

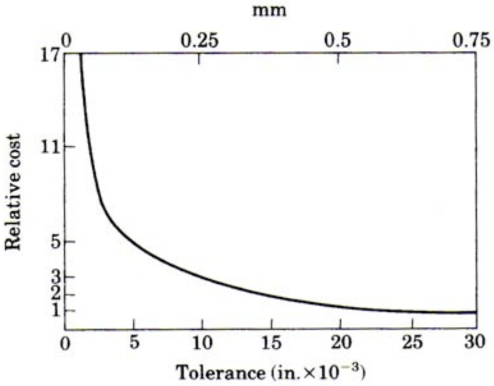

Figure 4. Process cost vs precision (from Kalpakjian,1992).

Now let’s return to the choice between turning and grinding. Is the improvement in precision for grinding worth the incremental cost? That is the core of the issue. The economically-based decision method is to minimize the total cost, which is the sum of manufacturing process cost and quality loss due to variations. To estimate total cost, we must flow down from the quality losses due to deviation from ideal function to variation in critical parameters then down to critical specifications. In our example of the roller with a force applied, we have six critical specifications. If we assume that there are two production-process options for each of the six critical specifications, then we have 64 total options. Fortunately, it is generally not necessary to consider all 64 options and pick the overall winner. The quality loss implications of each critical specification can generally be allocated and each one can separately be optimized to minimize the overall cost. This is a consequence of the fact that within the small range of manufacturing variations, most engineering systems behave almost linearly. If this assumption holds, the details of the total cost calculation work out as follows:

- Recall that the critical parameter, force, is a function of six critical specifications, that is, $F = F(x_1, x_2, x_3, x_4, x_5, x_6)$

- The quality loss because of not meeting the target value is proportional to the variance with some constant measured in dollars per Newton squared. A useful way to estimate this constant is to consider a "customer tolerance" Δ_C which prompts a typical customer to seek rework and a cost (economic loss) to do the rework, L_C

$$E(\text{Quality Loss}) = \frac{L_C}{{\Delta_C}^2}\sigma_F^2$$

- The variance of the critical parameter is a linear combination of the variances in the critical specifications.[1] The weightings on each term correspond to a squared sensitivity of force, F, to each critical specification, $x_1, x_2 \ldots x_6$.

$$\sigma_F^2 = \left(\frac{\partial F}{\partial x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\partial F}{\partial x_2}\right)^2 \sigma_{x_2}^2 + \left(\frac{\partial F}{\partial x_3}\right)^2 \sigma_{x_3}^2 + \left(\frac{\partial F}{\partial x_4}\right)^2 \sigma_{x_4}^2 + \left(\frac{\partial F}{\partial x_5}\right)^2 \sigma_{x_5}^2 + \left(\frac{\partial F}{\partial x_6}\right)^2 \sigma_{x_6}^2$$

- Therefore quality loss due to variance in each critical specification x_i is simply

$$\frac{L_C}{{\Delta_C}^2}\left(\frac{\partial F}{\partial x_i}\right)^2 \sigma_{x_i}^2 \,.$$

- And the minimum overall cost requires minimization of each total cost which is the sum of the quality loss and production cost for that each critical specification x_i.

In some cases, the "total cost minimization" approach to selecting the manufacturing processes is replaced by other processes. For example, for some systems the performance demanded is set by a contract. In other cases, management has set a firm target based on a forecast of the competitor's capabilities which must be matched. For example, for a space-based imaging system may have clear specifications on pointing accuracy. In such cases, it may be preferable to view the performance needed as fixed and to minimize production cost. This approach is traditionally called *error budgeting* because it seems to suggest that error is a fixed quantity to be allocated across the system. However, for most systems engineering in competitive commercial industries a better solution can be attained by minimizing the sum of production cost and quality loss.

The other method for the selection of production processes is knowledge-based engineering (KBE). For specifications that are not critical, this is almost always the method that is used. It can also be used for some critical specifications, but caution is needed. All too often such decisions have been based solely on either initial cost or on quality, with very bad results.

After the production processes are chosen, the production tooling is designed and put into use to make parts. The production online quality control is designed and implemented in production. Any and all of this is referred to as critical-parameter management, or similar names such as

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[1] This equation entered into the engineering literature as early as 1953 (Kline and McClintock 1953). The equation is valid only if the critical specifications are independent (see Frey, 2004). This will not be applicable for example to resistances on an integrated circuit. When Equation 2 is inadequate, the variance can be determined by several different means including Monte Carlo simulation, Latin Hypercube Sampling, or using orthogonal arrays (for an example see Phadke, 1989; pp. 190–193).

critical-parameter implementation or critical-parameter deployment. The exact names that are used is not important. It all has to be done.

CRITICAL-SPECIFICATION TOLERANCES

Although the selection of the right process (or grade) is usually the most important step, it is also necessary to determine the best tolerance value that will go on the production drawing. This can be used to sort the good from the bad when it is required.

There are three “tolerances” (Figure 5). We start with the customer tolerance.

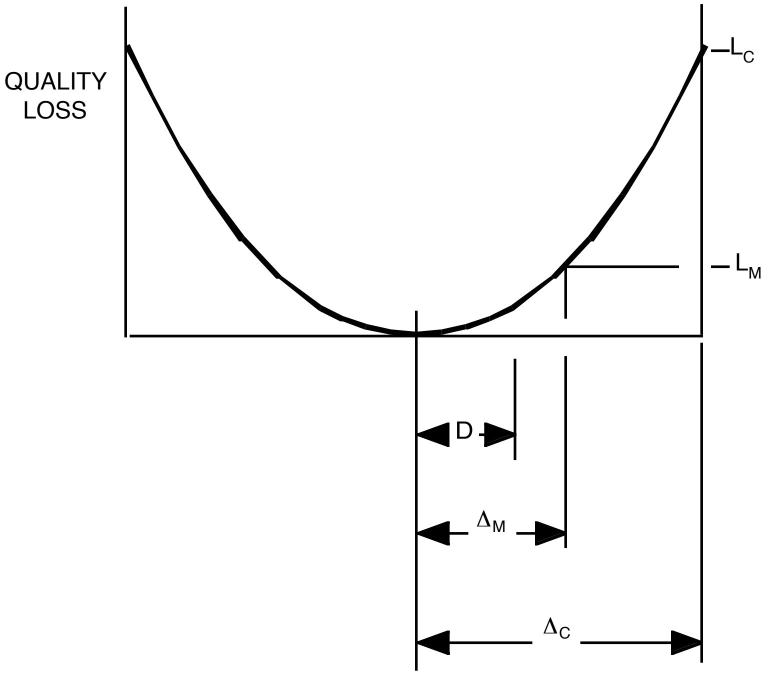

Figure 5. Three-tiered Tolerances.

Again, the customer tolerance (Δ_C) is the value at which the average customer (sometimes thought of as the 50th percentile customer) will be sufficiently dissatisfied so that they will call for corrective action. Associated with the customer tolerance is a quality loss in dollars (L_C) that is the cost of the countermeasure in response to the customer. This cost will be relatively large because of the field logistics that will be involved.

The same countermeasure could have been done much more cheaply in the factory. This much smaller quality loss in manufacturing (L_M) has associated with it a manufacturing tolerance (Δ_M). The manufacturing tolerance will be much smaller than the customer tolerance because it costs much less to implement the countermeasure in the factory. This is the tolerance that goes on the drawing.

We can save still more money by using the adjustment limit D to limit variation during production. The customer tolerance and the quality loss that would be incurred at the customer's site establish the quality loss function. In factory operations we limit the usual variation to the range of ±D, the adjustment limit. As is indicated in Figure 5, we save a great deal of money in quality loss avoidance by limiting the range to ±D instead of $\pm\Delta_C$.

This concept of three-tiered tolerances based on the quality loss function clearly leads to production operations with the units of production bunched tightly around the customer-satisfaction target value.

The manufacturing tolerance is calculated to minimize the total cost. The quality loss is given by the quadratic relationship:

$$L = \frac{L_c}{\Delta_c^2} \Delta^2$$

where L is the expected quality loss, $L_{C,}$ the loss at the customers' tolerance (in other words the cost of the countermeasure in the field), Δ_C the customers' tolerance, and Δ the actual deviation from the customer-satisfaction target for a specific unit of production.

The countermeasure can be performed in the factory at a much lower cost, L_M, than in the field, and this defines the manufacturing tolerance. Putting the cost of the countermeasure in the manufacturing site and the unknown value of manufacturing tolerance into the loss function gives

$$\Delta_M = \sqrt{\frac{L_M}{L_c}}\ \Delta_c$$

which establishes the value of the manufacturing tolerance. If a specific unit of production has a measured value of Δ that is greater than Δ_M, then it should not be shipped. It is cheaper to fix it in the factory at a cost of L_M than incur the greater value of the quality loss in the field. Conversely, if the value of Δ is less than Δ_M, then the product should be shipped. The quality loss in the field will be less than the cost of the countermeasure in the factory, L_M. Thus the value of Δ_M is the boundary between products that should be shipped, and the products that should be reworked.

Because the cost of the countermeasure in the manufacturing site will usually be much less than the cost of the countermeasure at the customer's site, the manufacturing tolerance is significantly less than the customer tolerance. If the repair work (countermeasure) in the factory is very cheap, it pays to "repair", or adjust, nearly all of the units. Then the manufacturing tolerance becomes very small, so that only the units that are already very good do not have the inexpensive adjustment that improves customer satisfaction. The manufacturing tolerance is the tolerance that is put on the drawing. If the product has to be inspected, no product outside of the manufacturing tolerance should be shipped.

In actual practice, the value of the performance parameter is usually held to the tighter range of the adjustment limit, ±D, during on-line QC. Therefore, there should never be any products outside of the manufacturing tolerance, and inspection (after production is complete) should not be needed. The only operational use for the manufacturing tolerance is in the unusual case that the on-line adjustment process failed. Then the products that have been made while the adjustment process is not operational will have to be inspected, and the manufacturing tolerance is then used to determine whether they should be shipped or reworked.

To summarize the selection of production processes and the establishment of tolerances we compare the traditional approach with the approach that has been featured here.

TRADITONAL APPROACH	SUGGESTED APPROACH
1. Put tolerance on drawing (Usually very tight)	1. Select production process (Minimize total cost)
2. Select production process (By negotiation; see Figure 2, usually leads to changing the tolerance on the drawing.)	2. Put tolerance on drawing (Based on economics; product engineers and production engineers do not need to negotiate.)
3. Inspect production parts to assure that those outside of tolerance are not used.	3. Use on-line quality control to detect special causes. Inspect only in extraordinary circumstances or where capable processes do not exist.

DOCUMENTATION

The objective of the documentation is to focus attention on the critical parameters during the detailed design, production-tooling design, and online QC design and implementation. All too often in the past this work has inadvertently changed the optimized values of the critical parameters, with devastating results.

The core of the documentation to focus attention on the critical parameters is the critical-parameter drawing. This is the beacon during all subsequent work. It keeps the importance and the values of the critical parameters visibly in front of everyone whose work has some influence on them.

Beyond the critical-parameter drawing, there is much supplementary documentation that can be very useful. The critical specifications can display their effect on the failure modes. For example, let's assume that the detailed design includes a spring and lever to create the force on the roller, F_r. Then a critical specification is the spring constant K. If the nominal value of K is 10 newtons/mm, then a value somewhat less than 10 will cause the failure mode of multifeeds. (Too little tension in the belt will produce too little force against the retard roll, and thus let the second sheet through too frequently.) Let's assume that happens at 9 newtons/mm. On the other hand a value of 11 newtons/mm will produce excessive damage to the sheets of paper, and excessive wear on the belt and/or the retard roll. This can be displayed as:

$$10^{+1.0\ (\textit{Damage}\ \&\ \textit{wear})}_{-1.0\ (\textit{multifeeds})}$$

This can be displayed on the production drawing or on an enhanced version of the production drawing that is kept in a critical-parameter-management database. This keeps the failure modes visible and prominent in the thinking of the people who subsequently do the tooling design, component purchasing, and online QC. This states loud and clear: DO NOT allow the spring constant to exceed 11, or excessive wear and damage will cause customer dissatisfaction. DO

NOT allow the spring constant to be less than 9, or excessive multifeeds will cause customer dissatisfaction.

Another form of CPM documentation is the failure-mode catalog. This is a data base that shows all of the failure modes of the system. For each failure mode the relevant critical-parameter drawing is referenced. The relevant critical specifications can also be referenced.

The exact details of the CPM documentation can be varied and still be successful. The guiding principle is to keep the organization focused on the critical parameters and their values that are required for successful performance and reliability.

SUMMARY

The total practice is summarized in Figure 6. The system architecture and selected technologies determine the ultimate potential system performance and reliability. No amount of subsequent good work can make a silk purse out of a sow's ear. The objective of the subsequent work is to capture as much of the inherent ultimate performance and reliability as possible.

Robust design attempts to optimize the values of the critical parameters. If they are completely optimized, then all of the ultimate potential system performance and reliability will be enabled. The objective of the subsequent work is to carry this out to the factory floor and then to the customers. Critical Parameter management therefore begins after robust design and is intended to deliver the quality made possible by the earlier steps. If CPM is done well, then the optimized values of the critical parameters will be achieved for the customers. That is the goal of CPM.

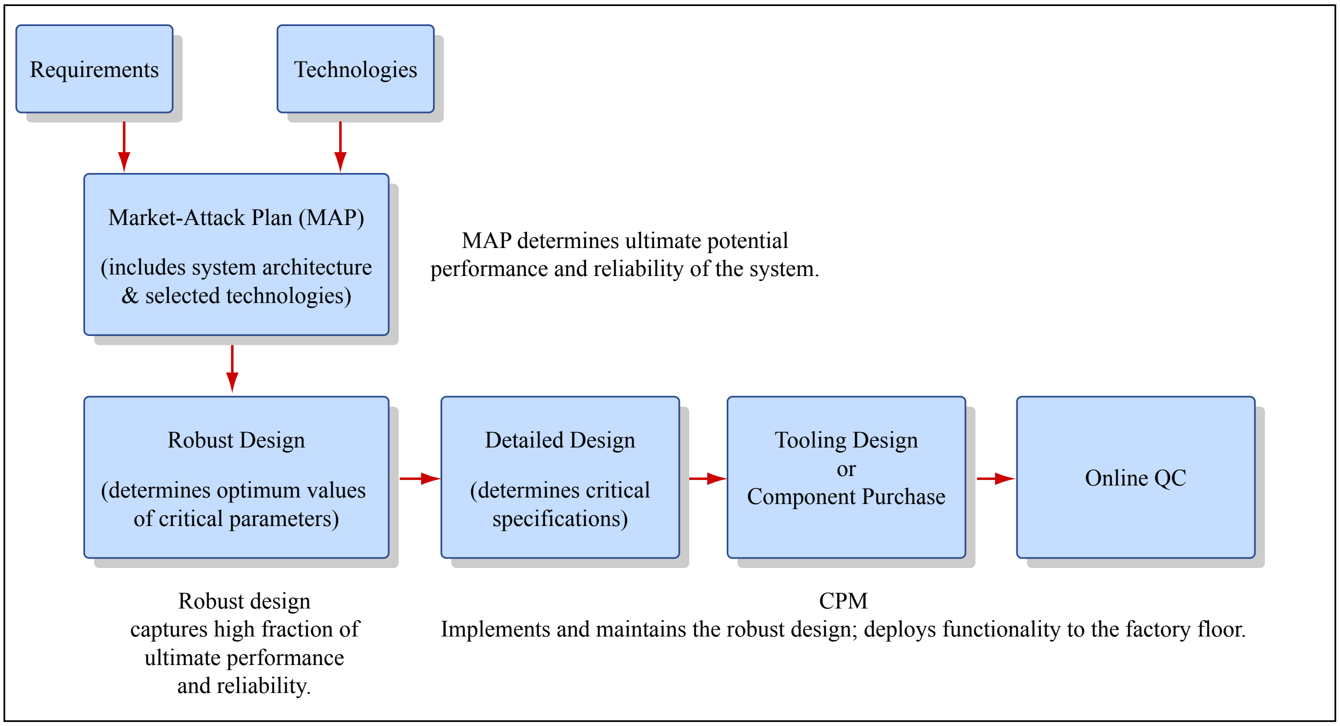

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Figure 6. Total process.

Some authors include Robust Design as part of CPM; i.e., they extend the scope to the left in Figure 3. Exactly what is called CPM, and exactly what name is used, is not important. It is important to do the complete process.

This course note provides the basic principles and motivation of CPM. One brand of CPM is presented in great detail in Creveling, et al (2003; pp. 249-336).

Critical-parameter management is essential to successful system-engineering practice. It helps to greatly reduce development time, improve customer satisfaction, and reduce life-cycle costs.

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