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What Kind of "Numbers" can a Company Expect After Implementing Quick Response Manufacturing?

Empirical data from several projects on *Lead Time Reduction*

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Abstract: Quick Response Manufacturing (QRM) is a company-wide approach to lead time reduction that has been shown to be successful at many manufacturing enterprises. Currently, there is detailed literature on QRM principles, how to implement QRM, and also its potential benefits. However, this literature tends to be anecdotal and descriptive, and the link that ties and quantifies actual cost benefits achieved with specific lead time reduction targets has not been formally established yet. The purpose of this study is to obtain more empirical data and develop rules to quantify the benefits of QRM. In this study, we gather detailed data from several company projects on lead time reduction. Then we use a recently developed methodology to quantify the benefits of QRM more accurately, from this data. In parallel to this, based on some hypotheses, we derive a simple functional form for the impact of lead time reduction on costs. We refine this functional relationship via the empirical data. As a result, we derive a simple quantitative "rule of thumb" that managers can use to set lead time reduction targets. The empirical data also clearly shows a baseline-link between lead time reduction and cost savings achieved. In addition, we present data on the impact of lead time reduction on several other performance measures including quality, labor productivity and on-time delivery. Although this is a preliminary study on these issues, we hope the general approach, and the simple rule of thumb, would be of immediate use to both practitioners and researchers in this field.

The Need to Quantify Benefits of QRM

A strategy called Time-Based Competition (TBC) was introduced in the business literature in the late 1980s.[1] The fundamental principle behind TBC is to use speed in order to gain competitive advantage. This strategy can be successfully applied in many fields and industries. However, its specific application to the manufacturing arena has become known as Quick Response Manufacturing (QRM)[2], which not only sharpens TBC concepts but it also adds numerous new dimensions. QRM is a company-wide approach to reducing lead times in an entire organization, focusing on both shop floor dynamics as well as office operations.

A large number of projects on Quick Response Manufacturing have been conducted over the past years, and the success of these projects has demonstrated the validity of the concepts. Lead times have been greatly impacted, with reductions as high as 90% to 95% being achieved in some cases. This in turn has brought significant benefits to the respective companies and their customers' satisfaction. However, we believe that in most cases, the full extent of the benefits achieved has not been quantified. This is an important issue since in many cases, managers are skeptical that the QRM policies would lead to any benefits at all. Indeed, as documented in Suri (1998)[3], a survey of U.S. managers showed that over 70% of the policies in place today are working against lead time reduction. In addition, Suri (1998) gives manifold examples of situations where a QRM policy that would reduce lead time is hard to justify using traditional costing methods. Basically, the relationship between lead time reduction and cost benefits is not well understood. Hence, in order to motivate managers to implement QRM, and to help in justifying some of the investments needed, it would be useful to be able to predict *a priori* the magnitude of the benefits that could be obtained with a given lead time reduction.

Therefore, the main goal of this study is to determine a general rule to allow companies to predict the magnitude of the benefits that could be obtained with a given lead time reduction. Another way to express this goal would be: to determine a general expression to allow companies to predict the magnitude of lead time reduction needed in order to obtained specific target benefits.

Before going into greater detail, we should define what we mean by *lead time*. In general, lead time is viewed as the time a company takes in responding to a customer order. However, in this study we would like to make a more specific definition. Here, lead time refers to the total time it takes for information and/or material to flow through a company for it to complete an order, assuming that the order (or intermediate parts of it) are *not* serviced through stock items made ahead of time. This is also known as *flow time* or *cycle time*. To differentiate this from the definition at the beginning of the paragraph, note that if we manufactured and then stored extra stock of a certain part, then the lead time for a customer that ordered that part would be close to zero (it would be just the office lead time and a little time to retrieve and ship the part). However, we are interested here in the question, how long does it take to actually manufacture this part from start to finish? In other words, we are going to measure the actual time it takes for the material to flow through all the operation steps. (If office operations are involved, it would include the time for information to flow prior to the material flow.) Having clarified what we mean by lead time in this study, we are now going to try to relate cost benefits (and other benefits) to this lead time measure.

The scope of the study involves results for projects conducted by the Center for Quick Response Manufacturing (CQRM) at the University of Wisconsin-Madison, a consortium of over 40 firms working with the university to implement QRM strategies. As a result of this combined effort, a large number of Quick Response Manufacturing projects have been conducted by the center during the past seven years, mainly in mid-western manufacturing companies in the United States. Also, John Deere has conducted many QRM projects under their John Deere Supplier Development Program.[4,5,6] Information that resulted from some of those supplier development projects was used in this study as well.

Traditional Cost Justification

Traditional accounting methods typically underestimate the benefits of reduced lead times. In fact, in many cases they even show that costs may increase as a result of the proposed QRM policies (see the numerous examples in Suri (1998)). This is not a new phenomenon, in fact for over two decades there have been numerous articles discussing why traditional accounting systems do not help in justifying various modern manufacturing strategies.[7,8,9]

The main cost benefits of QRM projects come from two areas. The first is that via the revised organizational structures that QRM uses, there is greater employee ownership of work and thus higher quality and productivity. The second, which is often the greater impact, is that when lead times are dramatically reduced, many dysfunctional dynamics disappear and overhead costs related to managing these problems are eliminated. Suri (1998) gives numerous examples of these dysfunctional items but a simple example is that of schedule changes and expediting: most companies spend a lot of organizational resources on forecasting, planning, re-planning, and expediting, as a result of long lead times and late deliveries. If the lead times are short and predictable, many of the resources used for these activities can be eliminated. This is just one of many such items. Taken together, when a QRM program is put in place, many such costs are reduced. Typically most of these costs occur in the “overhead” category of accounting, and they are not directly connected to lead time in the accounting calculations. Thus their reduction is not easy to predict ahead of time.

A straightforward example of how this can be an obstacle is the case of cross-training of workers. One of the basic concepts in QRM is creating of a “cell” of machines and workers, dedicated to producing a family of products. A cornerstone of this cell concept in QRM is cross-training of the workers in the cell. However, this also implies higher wages for all the workers, leading to a perceived increase in the wage bill for the company. It may be that the predicted reduction in easily quantified costs such as scrap and work-in-process does not justify the wage increase. The only way to justify this cross-training program is to believe that there will be reductions in some of the overhead costs as a result of the short lead times. However, as already mentioned, there is no simple connection between lead times and overhead.

One of the proposed solutions to the problems of overhead allocation has been the development of activity-based costing (ABC), which purports to do a better job of allocating overhead to support decisions congruent with modern manufacturing strategy. However, even ABC has several drawbacks when it comes to implementing QRM. Chief among these is the fact that ABC does not incorporate the impact of system dynamics which influence lead times. A simple example helps to drive home this point. ABC identifies cost drivers, and then the aim of managers' decision making is to reduce the values of these drivers. If one of the drivers is identified as setup on a given machine, we may attempt to reduce the value of this driver by running larger batch sizes. However, the QRM analysis of system dynamics (e.g. using the MPX modeling software[10]) might show that the larger batches will result in longer lead times. These longer lead times, in turn, will result in more of the dysfunctional interactions and thus *increase* overhead, rather than reduce it as the ABC system predicted.

Non Traditional Cost Accounting Approach for Lead Time Reduction Projects

A recent study by Schluter[11] presented a framework to approach cost accounting for lead time reduction projects. This framework includes a set of metrics that help overcome most of the problems faced with traditional accounting systems. The study states that usually companies calculate the cost of a product as:

Allocated Product Cost = f (Direct Labor, Direct Material Used, Machine Hours)

It is shown that the basic problem with this approach is that companies often fail in the process of accurately identifying the change on overhead costs due to changes in the manufacturing and/or operating processes. Furthermore, lead time reduction projects normally have a considerable impact in overhead allocated resources. Since the relationship shown above does not clearly identify any of the overhead resources used, the impact will not be properly acknowledged and, therefore, the change in cost will not be properly estimated.

The preceding discussions also help to clarify why ABC cannot easily solve this problem. Essentially, with ABC we would be looking at using an alternative costing formula:

Allocated Product Cost = f (Amount used of each Cost Driver)

but for this to work with lead time reduction programs, one of the cost drivers on the right has to be lead time. As already discussed, it is not easy to establish a connection between the magnitude of lead time and the magnitude of various direct or indirect costs, hence the above formula cannot be easily constructed. Another basic problem here is that the ABC approach is essentially a *linear* formula. However, manufacturing system dynamics that impact lead time are inherently *nonlinear*. For example, as utilization of a resource increases, the lead time of jobs flowing through that resource increases nonlinearly. This lead time can then impact many other costs, as previously explained. Thus, linear increases in the amount used of some resource could result in highly nonlinear changes in cost.

Similar to ABC, the fundamental idea behind the new framework presented in the study, and its set of metrics, is to first identify the actual cost drivers for the products under the scope of the project. However, there are two key differences between Schluter's approach and ABC. The first is that the focus for these metrics is to measure the *change* in product costs rather than to calculate the actual costs. Thus, the amount of resources allocated before the lead time change took place are compared to the amount of resources allocated after the change, for each of the metrics. The second is that QRM theory and modeling tools are used to estimate the impact of system dynamics and other factors on the values of these metrics.[12,13]

The study identifies two main groups of metrics; Operating Metrics and High-level Metrics. The Operating Metrics refer to those activities that are directly related to the production process for the product under the scope of analysis. Examples for this first set of metrics are:

- Scrap
- Rework
- Direct labor and machines used,
- Material handling resources allocated
- Space floor occupied
- Work-in-process inventory levels

The High-level Metrics refer to those activities that are not only related to the production of the products under the scope of analysis but rather to many or all products manufactured in a company. Among these metrics we have:

- Scheduling
- Supervision
- Inspection
- Expediting
- Order Fulfillment

Since all products might share these activities, it is likely that only a portion of the total amount of resources available for each of these activities will be allocated to the products under the project scope. In order to measure the impact on product cost the corresponding portion has to be determined before as well as after the improvements take place.

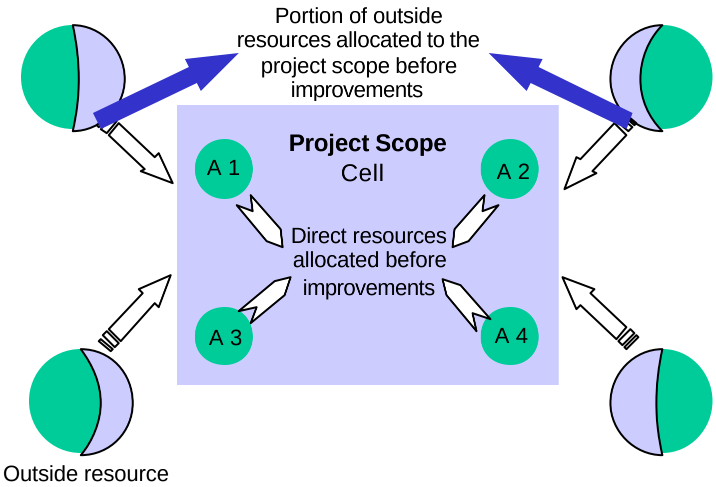

Figure 1. Direct Resources before implementation

After all the metrics have been applied, the final result for cost savings will be the addition of all the individual savings achieved. Only the portion of the resources that are no longer used within the scope of the project are considered part of the savings due to the reduction in lead times. For instance, let us consider the scenario shown in Figure 1, where four assemblers (A1, A2, A3 and A4) were the only direct resources allocated to a cell before a specific QRM project took place. Also, a portion of each of four outside resources was allocated to the cell operations. As shown in Figure 2, after improvements are in place, the fourth assembler is no longer needed but he/she still forms part of the cell. According to this study, this situation will not count towards the cost savings achieved due to lead time reduction. The fundamental reason for this statement is that the fourth assembler is still being allocated to the cell, thus it shows up as part of the resources needed by the cell in order to carry out its activities. Therefore, it cannot be accounted as part of the costs saved.

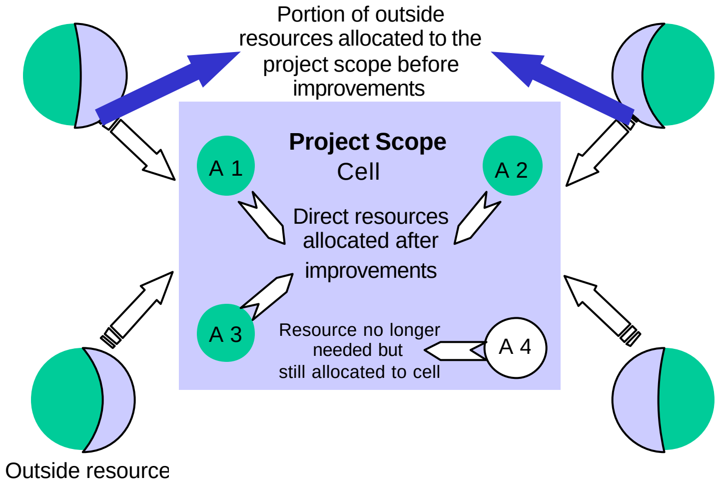

Figure 2. Direct Resources after implementation

Now, let us consider the same cell only this time it was acknowledged that the fourth assembler was no longer needed. Thus, he/she was sent to a different division of the company, as shown in Figure 3. In this case, even though the assembler still is part of the overall organization, he/she is no longer an allocated resource to that specific cell. Therefore, the costs generated by him/her should not be charged to the cell operations, which in turn means that this will account towards the resources saved as part of the lead

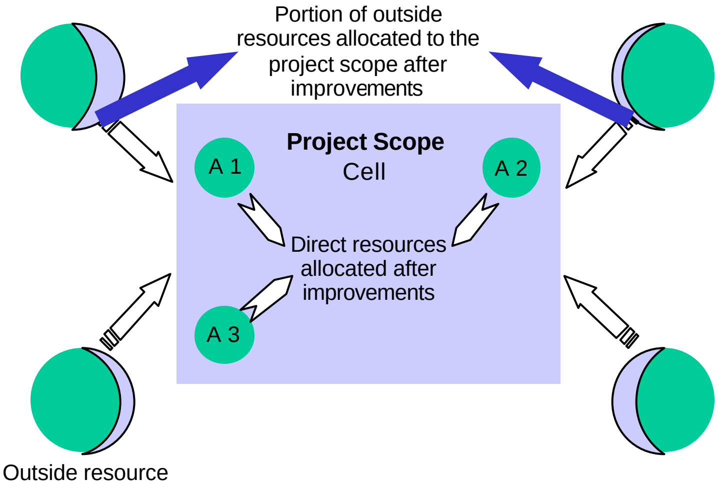

Figure 3. Overall resources allocated after implementation

time reduction project. Also shown in Figure 3 are the changes in the portion of the outside resources allocated to the cell due to the improvements. The difference between the before and after portions of the outside resources allocated will account towards the cost savings for the product as well.

During the course of our study a set of High-Level metrics, as well as Operating Metrics was developed and used, based on the metrics previously established by Schluter. A complete list for such metrics is shown in Appendix 1.

To summarize, traditional costing models do not adequately predict the cost benefits of QRM. Worse yet, as shown in Suri (1998), traditional costing models often predict that the changes required for QRM will lead to increased costs. One alternative is to replace the traditional cost model with the detailed analysis of cost drivers as explained above. However, this approach could have three drawbacks:

- This analysis may be too onerous to conduct, particularly if it is early in a QRM project. At such an early stage, one may be interested in some quick measures of success without spending too much time on analysis.
- In addition, at the early stage one may not have sufficient data to predict the changes in the values of all the cost drivers in Appendix 1.
- Finally, even if one is willing to put the time into a detailed analysis of benefits, the same question will recur when predicting some of the cost drivers. For instance we may need to answer the question: if we reduce lead time by 50%, how much will our scrap rate improve?

Thus it would be useful to have a simple model that would predict benefits at the early stage of a project, without requiring too much time or too much data.

Previous Research

While the general importance and overall benefits of QRM have been documented, previous research on the *cost* benefits of QRM is quite limited. Also, there is limited research on the quantitative impact of QRM on other measures. We cite here the few previous studies that exist, to our knowledge.

Stalk and Hout present data to support the impact of response time on a company's growth rate and profitability, but their data is based on industry-wide comparisons and does not apply to a specific lead time reduction project.[14] Another study of a number of companies that reduced their lead times found that on average, there was a 2:1 ratio between reductions of lead time and cost. In other words, a 50% reduction in lead time resulted, on average, in a 25% reduction in overall product cost.[15] A different study looked not directly at lead time but at lot size, and found that there was a 1:1 ratio between lot size reduction and scrap/rework reduction.[16] However, this study did not directly relate lead time to the quality improvement.

Of the various studies above, the one giving the 2:1 ratio appears to provide the simple form that we are looking for. However, there is a good reason for wanting a different rule, and that is an issue of inconsistency in the above 2:1 rule. Consider a simple example. Suppose a product has a cost of $100, and by means of a QRM project the lead time to make it is reduced from 20 days to 8 days, or 60%. Then according to this rule the product cost should be reduced 30% to $70. Now suppose that at a later time we engage in a second QRM project and reduce the lead time to 3.2 days. This is an additional reduction of 60% (using the 8 days as the new baseline). Now the rule says we should get an additional cost reduction of 30% of the new baseline cost of $70, which gives a final cost of $49. But now let us consider an alternative approach, where we engage in one QRM project to begin with, that takes us all the way from 20 days to 3.2 days. This is an 84% reduction in lead time, so the rule predicts a cost reduction of 42%, for a final cost of $58. To summarize, in both situations we start with a lead time of 20 days and end with a lead time of 3.2 days. Yet in one case the rule predicts a final cost of $49 and in the other it predicts $58. Surely the same rule should not give two different answers! Hence this rule seems unsatisfactory as a predictor.

Thus we would like to explore further the possibility of deriving a simple rule for cost improvements as a result of lead time reduction. In addition, we would like to have a similar rule for other performance measures such as scrap and rework, and on-time delivery. We will now propose a new predictor of benefits, and develop some concrete quantitative rules based on empirical data.

A Proposed Model for the Benefits of QRM

In order to develop the algebraic form of our model we will propose two properties for the behavior of the model:

Property P1 (Proportional behavior property). Improvements in a performance measure, as a proportion of the original value of the measure, are a function only of the proportional improvement in lead time.

To support this property, consider one factory that reduces its lead time for a product from 100 days to 70 days. Also consider another factory that reduces the lead time for a product from 10 days to 7 days. We would expect that the improvement in a measure such as product cost or scrap rate would not depend so much on the absolute number of days of lead time reduction (30 days or 3 days) but rather on the proportion of lead time reduced (30% in both cases). This property also states that we need to measure the performance improvement as a ratio. In some cases this requires use of judgement in deciding how to define the baseline metric. We will illustrate this below with practical examples.

Property P2 (Transitive consistency property). Suppose a proposed model predicts that if lead time is reduced from L_0 to L_1, a certain metric will improve from M_0 to M_1. Also, it predicts that if lead time is reduced from L_0 to L_2, where $L_2 < L_1$, this metric will improve from M_0 to M_2. Then, starting with a baseline lead time of L_1 and metric M_1, if lead time is reduced to L_2, the model should predict that the metric will improve to M_2.

This property is simply a formal way of stating that in the earlier example of two different ways of conducting QRM projects, we should get the same prediction at the end.

The above two properties are sufficient to derive the mathematical form of our predictor model. Let L_0 and M_0 be the original values of lead time and some performance measure for a system. Let L be the new lead time, and we wish to predict the resulting value of M, the measure of interest. Then Property P1 says that

$$\frac{M}{M_0} = f\left(\frac{L}{L_0}\right) \qquad (1)$$

where “f(.)” denotes the functional relationship that we are seeking.

Now let us see what Property P2 implies. If lead time is reduced from L_0 to L_1 the model predicts

$$\frac{M_1}{M_0} = f\left(\frac{L_1}{L_0}\right) \qquad (2)$$

and then, if lead time is further reduced from L_1 to L_2, the model predicts

$$\frac{M_2}{M_1} = f\left(\frac{L_2}{L_1}\right) \tag{3}$$

On the other hand, if lead time is reduced directly from L_0 to L_2 the model predicts

$$\frac{M_2}{M_0} = f\left(\frac{L_2}{L_0}\right) \tag{4}$$

Since we can express

$$\frac{M_2}{M_0} = \frac{M_2}{M_1} \times \frac{M_1}{M_0} \tag{5}$$

the above equations imply that the desired function f(.) must obey the relation

$$f\left(\frac{L_2}{L_0}\right) = f\left(\frac{L_2}{L_1}\right) \times f\left(\frac{L_1}{L_0}\right) \tag{6}$$

We can further clarify this by substituting a for L_2/L_1 and b for L_1/L_0, to find that the function f(.) must satisfy

$$f(ab) = f(a) \times f(b) \tag{7}$$

The above relation is satisfied by the function

$$f(x) = x^k \tag{8}$$

for a given constant k. To verify that this function works, note that it gives $f(a)=a^k$, $f(b)=b^k$, and $f(ab)= (ab)^k$. Thus

$$f(ab)= (ab)^k = a^k b^k = f(a) f(b) \tag{9}$$

Hence we have our desired relation. We can state this as follows. In general, if L_0 and M_0 are the original values of lead time and some performance measure for a system, and L is the new lead time, the resulting value of M is given by

$$\frac{M}{M_0} = \left(\frac{L}{L_0}\right)^k \tag{10}$$

We have thus deduced the functional form of the predictor. All that remains is to find the value of the constant k. Since lead time reduction has a different impact on each performance measure, we would expect that the value of k would be different for different measures. We will now proceed to use empirical data to illustrate the value of k for the cost metric. In order to do so, the detailed approach described earlier will be used first to estimate the benefits for each project and then to derive the value of k.

Analysis of Empirical Data

Now we present empirical data on the impact of lead time reduction projects. Information was collected for twelve different projects. Although there have been around a hundred QRM projects conducted by the Center for Quick Response Manufacturing alone, there are two reasons why the analysis here is limited to twelve projects. First, the specific approach used to quantify the benefits of QRM, along with the detailed metrics in Appendix 1, has only recently been developed. Thus we needed to focus on projects that have been recently completed, as data for older projects is not readily available. Second, to do a good job of quantifying all the benefits, the amount of data and level of detail needed is considerable, and in the available timeframe analyzing data for twelve companies was itself a substantial task. The names of the companies analyzed here will remain anonymous due to the sensitive nature of the information being discussed.

We should clarify here that we are presenting some *early* results of research into this complex issue. In other words, we do not claim that this study consists of a completely scientific approach and statistically significant analysis. Rather, we would like to show some preliminary results that are sufficiently interesting, and also demonstrate the potential for additional research on this subject. Also, even though these results are preliminary, we feel we have derived a rough "rule of thumb" for managers to use to quantify the results of QRM projects. We hope that this rule can be refined in the future, but in the meantime we feel it will serve as a "ballpark" guide for QRM projects.

Due to the timeframe of the projects conducted and the information available, the same level of data and analysis was not available for all the projects. We can divide the 12 projects into three categories. In the first category, consisting of five projects, we were able to get detailed data for most of the items shown in Appendix 1, 2 and 3. For these five projects, the actual cost reduction numbers derived from these data are used below. (Four of these projects were analyzed by us in detail, and one was carried out by a group from John Deere.) The two generic data collection sheets shown in Appendix 2 and 3 were instrumental in the process of extracting the corresponding information for each project. A series of interviews, mainly with the project leaders, were conducted in order to obtain the numbers sought. Since in most cases the project had been conducted before the study, the interview process required several iterations to allow people to track the information back or simply to remember how things had been done before the project took place. As expected, they had the most difficulties quantifying the changes in high-level metrics. Again the fundamental reason for this is that the resources involved as part of the high-level metrics are usually shared by different products and/or divisions in the company. Therefore, the people interviewed had to basically estimate the portion of those resources that was allocated to the products under study.

In the second category, which consisted of three John Deere projects, only a partial analysis of the items in Appendix 1, 2 and 3 was possible, due to lack of data. Thus the full cost reduction could not be properly estimated. After discussion with a high level manager at Deere who was intimately familiar with these projects, it was determined that if we computed the (partial) cost reduction from this data and multiplied it by 1.5, this would be a reasonable estimate of the total savings and would take into account the missing items. The third category consisted of four John Deere projects for which little data was available for the items in Appendix 1 and 3. In these projects, the cost reduction had been estimated primarily on traditional metrics. Again, after discussion with a high level manager at Deere familiar with these projects, it was agreed that multiplying the "traditionally measured" cost reduction by 2 would give a reasonable estimate of the total cost reduction actually achieved. While these correction factors may seem somewhat arbitrary, they are supported by two facts. First, the previously cited study by Schluter showed that the ratio of actual cost reduction to traditionally computed cost reduction is greater than 2.0, and thus our assumption above is conservative. Second, we will show below that the corrected data appear to fit a trend for the projects with the complete data, supporting our observation that these corrections are reasonable.

Table 1 shows a summary of the data on cost savings achieved due to lead time reduction for each of these projects. This data is also displayed in Figure 4. The figure shows a clear positive trend, i.e., on average a greater lead time reduction also means a greater reduction in costs.

Project #	Lead Time (% Reduction)	Overall Cost (% Reduction)
1	36.0	36.0
2	39.0	2.0
3	54.5	18.0
4	57.1	13.0
5	60.0	16.9
6	79.0	49.0
7	80.0	32.0
8	85.6	33.0
9	86.7	16.5
10	88.0	13.1
11	92.9	28.0
12	93.8	40.0

Table 1: Empirical results gathered for Cost Reduction as a result of Lead Time Reduction

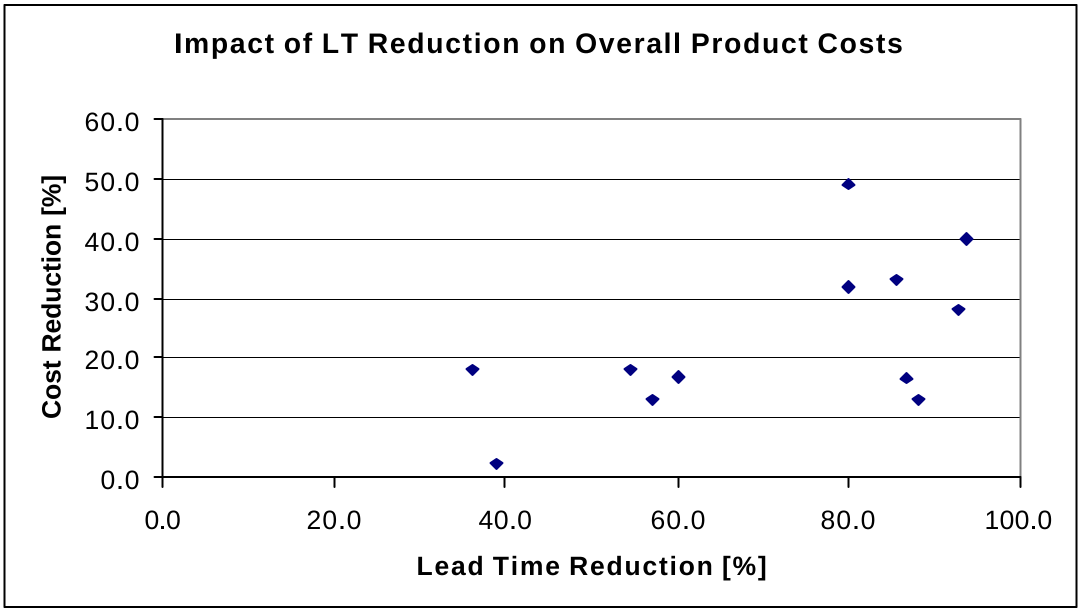

Figure 4: Impact of Lead Time Reduction on Overall Product Costs (Empirical Data)

However, we would like to make this relationship more precise, using the functional relationship derived earlier in this article. If we take logarithms of both sides of equation (10), and let the metric M be the cost (symbol C below), we get

$$\log\left(\frac{\mathrm{C}}{\mathrm{C}_0}\right) = k\log\left(\frac{\mathrm{L}}{\mathrm{L}_0}\right) \tag{11}$$

This is a linear relationship between $\log(C/C_0)$ and $\log(L/L_0)$. Thus we can use linear regression on these *log* values to find the best-fit k. Performing this regression on the data in Table 1 (after converting the data to the ratios above and taking logarithms), we get a value of $k = 0.17$. In other words, we have derived the fundamental and simple relation that we were seeking: the cost saving obtained by reducing the lead time of a process is given by:

$$\frac{C}{C_0} = \left(\frac{L}{L_0}\right)^{0.17} \tag{12}$$

where C_0 and L_0 are the original cost and lead time, and C and L are the new cost and lead time.

We should emphasize here that the specific equation above is based on preliminary research, and we envision that some refinement may be necessary. Nevertheless, as we show below, this equation seems reasonable and may serve the purpose of providing quick and rough initial estimates for lead time reduction targets. We will also show below that it leads to a simple rule of thumb for managers.

This theoretical relation is plotted in Figure 5. Note that, for the initial values for both ratios we have:

$$C = C_0, L = L_0 \tag{13}$$

hence
$$\frac{C}{C_0} = 1, \frac{L}{L_0} = 1 \tag{14}$$

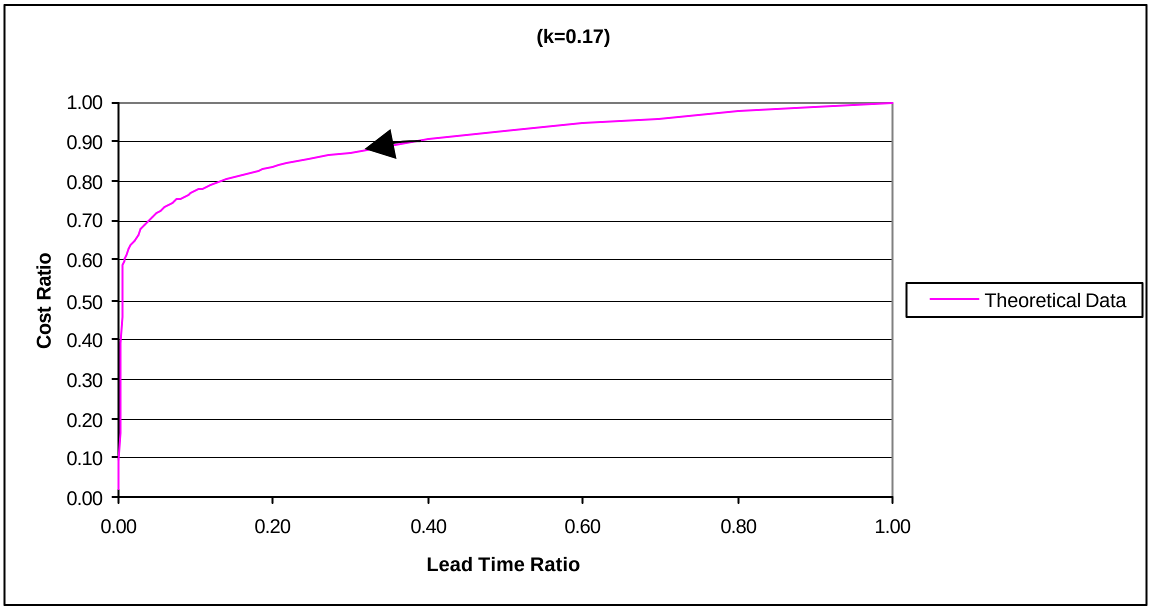

Figure 5: Impact of LT Reduction on Overall Product Costs (Theoretical trend for ratios)

Therefore, the values that describe the initial scenario intersect at the upper right corner of the graph (1,1). When lead time reduction is achieved, a lower value for the *Lead Time Ratio* will be obtained. The same applies for the *Cost Ratio*. Thus the respective lead time ratio and the cost ratio will shift to the left and downward. Therefore, a QRM project drives this curve in the direction of the arrow shown. Since the cost of a product will never reach zero (there are always some inputs needed) looking at Figures 5 and 6 requires us to make a comment on the range of validity of our formula. First, we give an analogy. In many empirically derived formulas, there is usually a range of validity specified. For instance, for fluid flow there are formulas that apply only as long as the flow is laminar. Similarly for forces stretching a metal, there are formulas that hold as long as the metal stays in the elastic region. In the same way, we feel that our formula applies as long as the cost ratio does not fall too low. In most companies, the raw materials and purchased parts inputs account for 30-50% of the product cost, so that internal operations account for some 50% of the cost, and it is hard to envision this number being completely eliminated. Thus we do not feel the formula applies once the cost reduction target approaches 50% or so. Another way to arrive at this range of validity is to observe the sharp drop of the empirical curve on the left of the diagram. The "knee" of the curve seems to be at a cost ratio of around 0.5, or a cost reduction of 50% as just stated. In this steep section of the graph, the cost ratio is highly sensitive to small changes in the lead time ratio. This is not what we want in a simple rule of thumb. Quite the opposite, we want such a rule to be robust. Therefore we assume here that the range of validity of our rule is confined to cost ratios in the range of 0.5 to 1.0.

While the graph in Figure 5 assists in predicting cost savings due to lead time reduction, we believe that a graph expressed in terms of percent changes will be much easier to interpret and apply by industry. Thus, we define the percentage in lead time reduction as:

$$L\% = 1 - \frac{L}{L_0} \tag{15}$$

and the percentage in cost reduction as:

$$C\% = 1 - \frac{C}{C_0} \tag{16}$$

When we plot the above expressions we obtain the graph in Figure 7. In this Figure we have shown the area (shaded portion) where our formula does not apply (when cost reduction is between 50% and 100%).

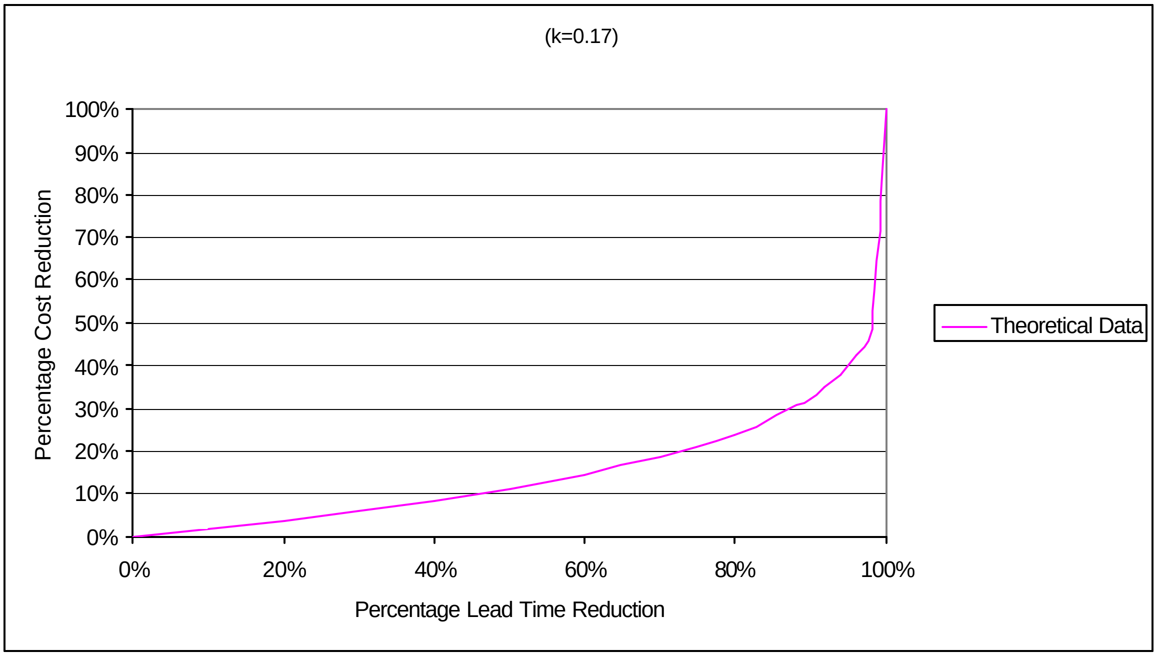

Figure 7: Achievable Impact of LT Reduction on Overall Product Costs (Theoretical trend as a percentage)

Now let us try to use these expressions for the benefit of a real life scenario. Assume that a manager is required to reduce costs by a certain amount based on QRM principles. Then the question he/she then needs to answer is:

By what amount (L%) should I have to reduce the lead time in order to reduce costs by the amount (C%) required?

Just by looking at the graph shown in Figure 6 the manager would be able to quickly answer with a rough estimate. Alternatively, with a hand calculator or spreadsheet he/she could easily estimate the lead time reduction needed. For instance, assume that the manager is required to reduce costs by 15% (C%=0.15), what should the lead time reduction target be? From expression (12) we have that:

$$\frac{C}{C_0} = \left(\frac{L}{L_0} \right)^{0.17} \tag{17}$$

Making the lead time term the dependent variable gives

$$\frac{L}{L_0} = \left(\frac{C}{C_0} \right)^{5.88} \tag{18}$$

The percentage cost reduction required implies that

$$\frac{C}{C_0} = 1 - C\% = 1 - 0.15 = 0.85 \tag{19}$$

thus

$$\frac{L}{L_0} = (0.85)^{5.88} = 0.38 \tag{20}$$

From expression (15) we have that the percentage lead time reduction is

$$L\% = 1 - \frac{L}{L_0}$$

therefore,

$$\begin{aligned} L\% &= 1 - 0.38 \\ L\% &= 0.62 \end{aligned} \tag{21}$$

In other words, the manager would have to reduce the lead time of the process by 62% in order to achieve a 15% reduction in costs. In Figure 8 we have plotted the empirical data along with the theoretical trend derived. Looking at Figure 8 presented in this study it can be observed that the 62% needed for this case lies close to three of the points plotted, and these projects achieved cost reductions of 13-18%, close to the 15% number the manager desires.

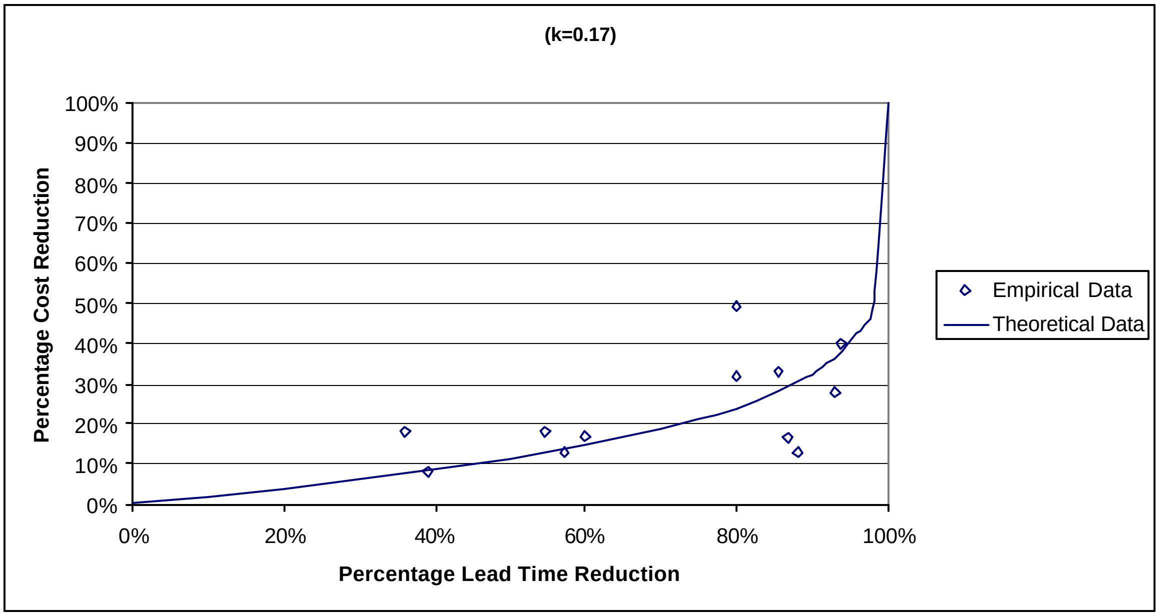

Figure 8: Impact of LT Reduction on Overall Product Costs (Theoretical and empirical data)

The "Power of Six" Rule: A Simple Rule of Thumb for QRM Projects

Based on the preceding analysis, we would like to propose a simple rule of thumb to help set "ballpark" lead time reduction targets in the initial phases of QRM projects. The rule we propose is easy to remember.

> Take the desired cost ratio (cost after/cost before) and raise it to the sixth power. The result is the target lead time reduction ratio (lead time after/lead time before).

In mathematical terms, we are approximating equation (18) by the rule:

$$\frac{L}{L_0} = \left(\frac{C}{C_0}\right)^6 \tag{22}$$

We justify this as follows. First, since we are proposing a rule for rough estimation, we feel it will be easier to remember the "power of six" rule than to remember the 5.88 decimal power in equation (18). Second, our empirical analysis is preliminary and does not warrant three significant digits of accuracy. Finally, in any case we wish to get a ballpark target for QRM teams to aim at, rather than a precise and absolute number, and the power of six rule should suffice for this.

Additional Empirical Data

Given the set of metrics used during the course of this study, we not only were able to gather information for the total cost reduction of the processes under the scope of each project but by doing so we identified specific changes in various areas. Here, we present results for some of the other metrics analyzed. Even though we had twelve projects worth of data, not all of them showed changes for each metric. The reason for this is rather simple. While the main driver for each project was lead time reduction, the way to accomplish the respective targets varied considerably. Some projects presented different opportunities for improvement and, therefore the focus was different. For instance, one company dramatically reduced the overtime used in order to satisfy production requirements while another company did not even use overtime to begin with, thus overtime did not change. Instead, this company was able to considerably reduce the Work in Process Inventory (WIP) as a result of the lead time reduction.

The result of this was that it reduced the available data points for metrics other than Cost Reduction. Thus, at this point we do not wish to analyze any trends in this data for other metrics. As stated earlier in this study it is not our intention to present a statistically significant analysis but rather help industry in obtaining a ‘ballpark’ prediction of the benefits coming from lead time reduction. Therefore, we have gathered the data into two tables for our readers to inspect (see Appendix 4). The first table sorts the data by Percent Lead Time Reduction achieved, while the second sorts it by Percent Cost Reduction. In this way readers can observe the data to identify any trends of interest.

Complete tables containing empirical results can be found in Appendix 3.

Conclusions

Quick Response Manufacturing with its relentless focus on lead time reduction has proven to be tremendously beneficial to many companies around the world. There are hundreds of examples[17] where reduction of the time taken to respond to customer orders has converted a company into a formidable competitor. However, despite the current detailed literature on QRM principles, its implementation, and also its potential benefits, there was little said about the specific cost benefits that can be achieved. As mentioned earlier, the available literature tends to be anecdotal and descriptive, and the link that ties and quantifies actual cost benefits achieved with specific lead time reduction targets had not been formally established yet.

Based on a recently developed framework to approach cost accounting for lead time reduction projects we were able to establish a relationship between lead time reduction and cost reduction. Furthermore, based on some hypotheses we derived a simple rule of thumb that will allow industry in general, and management in particular, to quickly predict cost benefits when applying QRM concepts in lead time reduction projects. We call this rule of thumb the “Power of Six Rule” since it states that when the target cost ratio (cost after/cost before) is raised to the sixth power, the desired lead time reduction ratio (lead time after/lead time before) will be obtained. We also established the region where this rule applies based on typical internal operations in a company. The “Power of Six Rule” generally will apply when the target cost reduction does not exceed 50%. Our ongoing work will attempt to solidify the relation between lead time reduction and other metrics as well.

We hope that result of this study will provide managers with the necessary ammunition to make the lead time reduction justification process more direct and simple yet solid.

Appendix 1: Metrics used to measure impact due to lead time reduction

The following metrics are intended to help measure the impact of implementing QRM concepts in a company. The main goal is to assist companies in translating the changes achieved into dollars saved per piece produced. Thus, every metric involves the Estimated Annual Usage of a product as part of the calculation, or is somehow expressed in terms of dollars per unit.

In this study two main groups of metrics were identified. The first one is High level-metrics, which intends to measure the change in those activities performed at a higher level, not specific to any given product but, instead, oriented to general activities like scheduling, expediting and supervision. The second one is Operating Metrics, which intends to measure the change for those activities more specific to the products manufactured and/or processed in the area involved in the given project.

High-Level Metrics

Supervision: change in supervisor requirements, multiplied by the corresponding average salary.

$$\mathit{Before}\left(\frac{\text{Supervison allocated} \times \text{Salary}}{\text{EAU}}\right) - \mathit{After}\left(\frac{\text{Supervison allocated} \times \text{Salary}}{\text{EAU}}\right)$$

Scheduling: change in scheduler requirements, multiplied by the corresponding average salary.

$$\mathit{Before}\left(\frac{\text{Scheduling allocated} \times \text{Salary}}{\text{EAU}}\right) - \mathit{After}\left(\frac{\text{Scheduling allocated} \times \text{Salary}}{\text{EAU}}\right)$$

Expeditors: change in expeditor requirements, multiplied by the corresponding average salary.

$$\mathit{Before}\left(\frac{\text{Expediting allocated} \times \text{Salary}}{\text{EAU}}\right) - \mathit{After}\left(\frac{\text{Expediting allocated} \times \text{Salary}}{\text{EAU}}\right)$$

Inspection: change in inspector requirements, multiplied by the corresponding average salary.

$$\mathit{Before}\left(\frac{\text{Inspection allocated} \times \text{Salary}}{\text{EAU}}\right) - \mathit{After}\left(\frac{\text{Inspection allocated} \times \text{Salary}}{\text{EAU}}\right)$$

Inventory Count: change in costs due to periodic inventory counts.

$$\mathit{Before}\left(\frac{\text{Cost of Inventory Count}}{\text{EAU}}\right) - \mathit{After}\left(\frac{\text{Cost of Inventory Count}}{\text{EAU}}\right)$$

Workers Comp./Safety: change in costs for worker's compensation or cost of lost production days due to injury.

$$\begin{aligned}&\mathit{Before}\,[\text{Worker Comp Payments} + (\text{Hours lost to Safety} \times \text{\$per Hours Labor Cost})/\text{EAU}] - \\ &\mathit{After}\,[\text{Worker Comp Payments} + (\text{Hours lost to Safety} \times \text{\$per Hours Labor Cost})/\text{EAU}]\end{aligned}$$

Engineering Changes:	change in engineering requirements to support production, multiplied by the corresponding average salary. $\mathit{Before}\left(\frac{\text{Engineering allocated}\times\text{Salary}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Engineering allocated}\times\text{Salary}}{\text{EAU}}\right)$
Parts' Tracking:	change in tracking requirements due to confusing/complicated routings, multiplied by the corresponding average salary. $\mathit{Before}\left(\frac{\text{Labor lost to Parts' Tracking}\times\text{Salary}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Labor lost to Parts' Tracking}\times\text{Salary}}{\text{EAU}}\right)$
Procurement:	change in supply management requirements, multiplied by the corresponding average salary. $\mathit{Before}\left(\frac{\text{Supply Management allocated}\times\text{Salary}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Supply Management allocated}\times\text{Salary}}{\text{EAU}}\right)$
Order Fulfillment:	change in order fulfillment costs. $\mathit{Before}\left(\frac{\text{Cost of Order Fulfillment}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Cost of Order Fulfillment}}{\text{EAU}}\right)$
Improvement Tasks:	change in improvement tasks' requirements, multiplied by the corresponding average salary. $\left(\mathit{Before}\,\frac{\text{Labor invested in Process Improvement}\times\text{Salary}}{\text{EAU}}\right)$ $-\left(\mathit{After}\,\frac{\text{Labor invested in Process Improvement}\times\text{Salary}}{\text{EAU}}\right)$

Operating Metrics:

Inventory Costs:	change in the costs incurred due to carrying inventory (Raw Materials, WIP and Finished Goods). $\mathit{Before}\left(\frac{\text{Inventory Level}\times\text{\%Carrying Cost}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Inventory Level}\times\text{\%Carrying Cost}}{\text{EAU}}\right)$
Floor Space:	change in floor space requirements. $\mathit{Before}\left(\frac{\text{Floor Area}\times\text{Cost of Floor Area}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Floor Area}\times\text{Cost of Floor Area}}{\text{EAU}}\right)$
Direct Labor/ Productivity:	change in production worker requirements, multiplied by the corresponding average salary. $\mathit{Before}(\text{Hours per Unit}\times\text{Average hourly pay rate})-$ $\mathit{After}(\text{Hours per Unit}\times\text{Average hourly pay rate})$

Overtime: change in overall overtime requirements, multiplied by the corresponding average salary.

$$\mathit{Before}\left(\frac{\text{Overtime Hours}\times\text{Overtime Factor}\times\text{Salary}}{\text{EAU}}\right)-$$
$$\mathit{After}\left(\frac{\text{Overtime Hours}\times\text{Overtime Factor}\times\text{Salary}}{\text{EAU}}\right)$$

Scrap: change achieved in the amount of scrap.

$$\mathit{Before}\left(\frac{\text{Amount of Scrap}\times\text{Value of Scrap}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Amount of Scrap}\times\text{Value of Scrap}}{\text{EAU}}\right)$$

Material Handling (travel): change in material handler requirements multiplied by average hourly pay rate.

$$\mathit{Before}\,\frac{\left(\dfrac{\text{Feet per Lot}}{\text{Feet per Hour}}\right)\times\text{Labor\$ per hour}}{\text{Lot Size}}-\mathit{After}\,\frac{\left(\dfrac{\text{Feet per Lot}}{\text{Feet per Hour}}\right)\times\text{Labor\$ per hour}}{\text{Lot Size}}$$

Material Handling (moves): change in material handler requirements multiplied by average hourly pay rate.

$$\mathit{Before}\left(\frac{\text{\# of Loads}\times\text{Hours per Load}\times\text{Labor\$ per Hour}}{\text{Units moved}}\right)-$$
$$\mathit{After}\left(\frac{\text{\# of Loads}\times\text{Hours per Load}\times\text{Labor\$ per Hour}}{\text{Units moved}}\right)$$

Rework: change in costs related to materials and labor required reworking parts or products.

$$\mathit{Before}\left(\frac{\text{\% of Rework}\times\text{Cost of Rework}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{\% of Rework}\times\text{Cost of Rework}}{\text{EAU}}\right)$$

Set-up: change in production worker requirements for set-up operations, multiplied by the corresponding average salary.

$$\mathit{Before}\left(\frac{\text{\# Hours per Lot utilized}}{\text{Lot Size}}\right)-\mathit{After}\left(\frac{\text{\# Hours per Lot utilized}}{\text{Lot Size}}\right)$$

Materials: change in cost of materials required for production.

$$\mathit{Before}\left(\frac{\text{Material \$ allocated}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Material \$ allocated}}{\text{EAU}}\right)$$

Downtime: change in resources lost to downtime, multiplied by the corresponding average salary.

$$\mathit{Before}\left(\frac{\text{Labor Hours lost to Downtime}\times\text{Salary}}{\text{EAU}}\right)-\mathit{After}\left(\frac{\text{Labor Hours lost to Downtime}\times\text{Salary}}{\text{EAU}}\right)$$

Machine cost: annual machine cost including depreciation, maintenance and repair costs.

$$Before\left(\frac{\text{\$ allocated to machines}}{\text{EAU}}\right) - After\left(\frac{\text{\$ allocated to machines}}{\text{EAU}}\right)$$

Warranties: change in costs related to warranties submitted to customers.

$$Before\left(\frac{\text{Warranty \$ allocated}}{\text{EAU}}\right) - After\left(\frac{\text{Warranty \$ allocated}}{\text{EAU}}\right)$$

Appendix 2: Input Data used for Project Metrics at Company XX

Cost Data Input Worksheet Company XX

	Before	After
EAU (Estimated Annual Usage) in units per year	15,000.00	20,000.00
% Carrying Cost Inventory	0.17	0.17
Annual Cost of Inventory Count	No change	No change
Annual Worker's Compensation Payments	No change	No change
Annual Order Fulfillment Costs	No change	No change
Value of Component at Scrap	Not tracked	Not tracked
Cost of Rework	Not tracked	Not tracked
Floor Area Cost	3.65	3.65
Annual Machine Cost in Cell	Not tracked	Not tracked
Supervisor Annual Salary and Benefits	20,000.00	20,000.00
Scheduler Annual Salary and Benefits	35,000.00	40,000.00
Parts Tracker Annual Salary and Benefits	28,000.00	28,000.00
Expeditor Annual Salary and Benefits	Not present	Not present
Engineer Annual Salary and Benefits	40,000.00	45,000.00
Procurement Annual Salary and Benefits	32,000.00	32,000.00
Improvement Tasks Annual Salary and Benefits	42,000.00	42,000.00
Production Worker Wage and Benefits per hour	14.72	14.72
Inspector Wage and Benefits per hour	No change	No change
Material Handler Wage and Benefits per hour	15.00	15.00
Other Indirect Labor Wage and Benefits per hour	None	None
Lot size	30.00	20.00
Percent Utilization	Not tracked	0.80
Average Product Selling Price	N/A	N/A
Average Profit Value	N/A	N/A
Average Product Cost	550.00	550.00
Overtime Factor	1.50	1.50
Investment Needed		180,000.00

Appendix 3: Sample sheet with information gathered at company XX

PROJECT AT COMPANY XX

Project Metrics	Before	After	% Reduc
Lead Time (weeks)	14	8	43
Percent Value Added Act.	3 - 3.5	10	
Percent Office Operations	70	75	
Payback Time (months)			3.80

High Level Metrics					Cost Savings			
	Before	After	Units	% Reduc.	($/piece)	%	%(Cost Red/Product Cost)	Comments
Supervision	5.0	2.0	Superv.	60.0	3.40	5.82	0.62	3 people no longer needed
Scheduling	1.0	0.5	Schedulers	50.0	0.90	1.54	0.16	1 person from 100% to 50%
Expeditors	Not Present			None	-	-	-	
Inspection	No Change			None	-	-	-	
Inventory Count	No Change			None	-	-	-	
Workers Comp./Safety	No Change			None	-	-	-	
Engineering Changes	3.0	1.0	Engineers	66.7	5.30	9.07	0.96	
Parts' Tracking	1.0	0.7	%	30.0	0.80	1.37	0.15	1 person from 70% to 40%
Procurement	3.0	2.0	Procur.	33.3	1.70	2.91	0.31	
Order Fulfillment	No Change			None	-	-	-	
Improvement Tasks	0.6	1.8	People	(200.0)	(3.40)	(5.82)	(0.62)	3 people from 20% to 60%
Operating Metrics					**Cost Savings**			
	Before	**After**	**Units**	**% Reduc.**	**($/piece)**	**%**	**%(Cost Red/Product Cost)**	**Comments**
Inventory Raw Material	Not Available			None	-	-	-	
Inventory WIP	1,500,000.0	900,000.0	$	40.0	2.90	4.96	0.53	
Inventory Finished Goods	Not Available			None	-	-	-	
Floor Space	16,268.0	10,050.0	sqft	38.2	0.90	1.54	0.16	
Direct Labor	2.0	0.75	hrs/unit	62.5	18.40	31.49		
Overtime	340.0	40.0	hrs/week	88.2	19.70	33.71	3.58	
Scrap	Not Measured			None	-	-	-	
Material Handling (travel)	680.0	125.0	ft	81.6	0.04	0.07	0.01	
Material Handling (moves)	No Change			None	-	-	-	
Rework	No Change			None	-	-	-	
Set-up	No Change			None	-	-	-	
Materials	No Change			None	-	-	-	
Downtime	60.0	8.0	hrs/week	86.7	7.80	13.35	1.42	
Total Savings per Unit					**58.44**	**100.00**	**7.28**	

Appendix 4: Empirical Results for all Metrics

Project	Lead Time Reduction	Cost Reduction	Quality Defects Reduction	On-Time Delivery Increase	Inventory WIP Reduction	Floor Space Reduction	Material Handling Reduction	Supervision Reduction	Parts' Tracking Reduction	Scheduling Reduction	Overtime Reduction	Downtime Reduction	Expediting Reduction
1	36.0	36.0	55.2	99→100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	39.0	2.0	70.0	No change	22.0	No change	75.0	No change	50.0	15.0	No change	No change	No change
3	54.5	18.0	0.0	40→97	58.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4	57.1	13.0	96.7	20→97	26.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	60.0	16.9	No change	No change	No change	38.2	76.2	50.0	42.9	50.0	88.2	83.3	No change
6	79.0	49.0	50.0	No change	No change	No change	No change	No change	No change	33.3	No change	No change	75.0
7	80.0	32.0	99.0	40→95	N/A	20.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8	85.6	33.0	87.5	40→88	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
9	86.7	16.5	93.3	74→99	N/A	50.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10	88.0	13.1	No change	No change	67.1	26.3	59.8	No change	No change	21.4	No change	No change	No change
11	92.9	28.0	97.0	40→98	87.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	93.8	40.0	83.3	43→99	N/A	30.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table A: Empirical Data sorted by Lead Time Reduction (All entries are in %)
N/A: Not Available

Project	Cost Reduction	Lead Time Reduction	Quality Defects Reduction	On-Time Delivery Increase	Inventory WIP Reduction	Floor Space Reduction	Material Handling Reduction	Supervision Reduction	Parts' Tracking Reduction	Scheduling Reduction	Overtime Reduction	Downtime Reduction	Expediting Reduction
2	2.0	39.0	70.0	No change	22.0	No change	75.0	No change	50.0	15.0	No change	No change	No change
4	13.0	57.1	96.7	20→97	26.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10	13.1	88.0	No change	No change	67.1	26.3	59.8	No change	No change	21.4	No change	No change	No change
9	16.5	86.7	93.3	74→99	N/A	50.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	16.9	60.0	No change	No change	No change	38.2	76.2	50.0	42.9	50.0	88.2	83.3	No change
3	18.0	54.5	0.0	40→97	58.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11	28.0	92.9	97.0	40→98	87.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7	32.0	80.0	99.0	40→95	N/A	20.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8	33.0	85.6	87.5	40→88	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1	36.0	36.0	55.2	99→100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	40.0	93.8	83.3	43→99	N/A	30.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
6	49.0	79.0	50.0	No change	No change	No change	No change	No change	No change	33.3	No change	No change	75.0

Table B: Empirical Data sorted by Cost Reduction (All entries are in %)
N/A: Not Available

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