ETM
ENGINEERING & TECHNOLOGY MANAGEMENT

Title: The Optimized Management of manufacturing projects in concurrent engineering programs

Course:
Year: 1994
Author(s): D. Murray and S. Vollmoeller

Report No: P94020

ETM OFFICE USE ONLY
Report No.: See Above
Type: Student Project
Note: This project is in the filing cabinet in the ETM department office.

Abstract: This project focuses on techniques that have been successfully applied by manufacturing project managers to ensure that their requirements on concurrently engineered programs are met. Traditional methods for measuring the success of concurrent engineering programs have tended to focus on the manufacturing end and not on the overall program. A method is introduced for modeling the success of concurrent engineering programs that takes account of the time-cost-performance considerations from both engineering and manufacturing perspectives and also the relationship between the two departments. The model is verified with data gathered from several companies.
EMP-P9421

The Optimized Management of Manufacturing Projects in Concurrent Engineering Programs

D. Murray, S. Vollmoeller

P9420

TABLE OF CONTENTS

Subject **Page**

Abstract

Concurrent Engineering programs for product development typically involve project managers in Engineering and Manufacturing who both have their own requirements on the same project and their own cost, time and performance limitations on resources. This typically results in the Engineering project manager regarding the requirements of the Manufacturing project manager as a lower priority than his own. This project focuses on techniques that have been successfully applied by Manufacturing project managers to ensure that their requirements on Concurrently Engineered programs are met. Traditional methods for measuring the success of concurrent engineering programs have tended to focus on the Manufacturing end and not on the overall program. We introduce a method for modeling the success of concurrent engineering programs that takes account of the *time-cost-performance* considerations from both Engineering and Manufacturing perspectives, and also the relationship between the two departments. This model separates the measurement of the program success from its organizational and project dependencies, which allows measurements from one corporation or project to be applied to another. The model is verified with data gathered from several companies. We show how this model can be used to determine priorities and direction within a company, and also how it can be used to benchmark different companies and projects. The result is a useful project management tool that can be of use to Manufacturing, Engineering and Marketing organizations.

Index Terms

Concurrent Engineering, CE, Manufacturing, Marketing, Benchmark, QCD, Project Management.

I. INTRODUCTION

The product development process used in many North American and European companies has tended to be patterned after the phased project planning (PPP) process, originally developed by NASA [2]. With the success of Japanese companies over the last two decades, many western companies are looking to imitate this success. One of the ingredients of this success is the use of concurrent engineering processes, which deviate from the older PPP processes towards a more overlapped approach. Concurrent Engineering is not, in fact, Japanese, but is a way of doing business that transcends quality circles. Blindly following the Japanese inhibits U.S. companies from understanding their unique, culturally different problems [7]. Some of these cultural differences, and their impact are outlined in [5]. Clearly, simply following the processes of a successful company is not enough, and can lead to disaster [2]. What is needed is some way of measuring these successes in a way that will enable their impact on any company to be measured.

[3], [7], [8] and [11] point out that the success of concurrent engineering programs is often dependent on the formation of multidisciplined teams that can work cross functionally. However, measuring the effectiveness of these teams is difficult. [8] points out that other measures of success are early manufacturing involvement, design for manufacturability (DFM) and design for testability (DFT), although [10] indicates that it is not enough that Manufacturing come to the table early on, but that they come prepared and are proactive towards concurrent engineering success. The use of modeling and CAD can also help in concurrent engineering success, and can be used to measure some aspects of it, as pointed out in [4] and [9]. [10] indicates that success is achieved by doing a root cause linkage analysis and fixing any problems that are found. [6] indicates that establishing a central office for measuring the success of the concurrent engineering program is beneficial. However, all of the measurements above tend to be subjective, are difficult to determine accurately, and tend to focus on one aspect of concurrent engineering success,

instead of focusing on the overall company goal - to improve business performance, which ultimately means greater profits [1].

One measurement that is often used is the QCD of a product ([1] and [13]), that takes account of concurrent engineering success from a manufacturing perspective. This refers to Quality, Cost and Delivery or throughput. These amount to the performance, cost and time measurements respectively for a Manufacturing department. QCD is good for measuring the contributions of processes to manufacturing success, but again, it ignores the broader scope of total company success. [12] and [13] point out that another common measurement is that of customer satisfaction. However, this is very subjective, ignores cost and throughput, and again, is not comparable across company boundaries.

Another approach faces up to the fact that companies tend to have customized concurrent engineering programs [2]. This approach generally starts off by comparing different projects within the one company, and benchmarking them against one another to capture the most optimized processes internally available. Then, benchmarking can begin across company boundaries, with the company in question sharing concurrent engineering processes and techniques with other companies [14]. A simple three step procedure for effective measurement of concurrent engineering success is presented in [13]. First, understand the internal processes of the company in question, formulating a list where changes are necessary. Then, benchmark against other companies, retaining their most effective techniques. Finally, using both customer feedback and these benchmarks, reevaluate the list of necessary changes. This approach can often be quite effective [14], but it does have some disadvantages. First of all, techniques obtained from other companies may not be implementable due to a lack of company infrastructure. What worked well in a large company, may not work in a small company, etc.. The benchmarking measurement tends to be governed by subjective judgment, and does not have any standard concrete metrics associated with it. Customer feedback is also difficult to assign measurements to.

Extracting the successful elements of a process from the company structure is difficult to do without developing some measurement tools for doing this. The purpose of this paper is to provide a benchmarking tool that can be used to measure the success of concurrent engineering programs or processes both internal to a company, or externally across company boundaries. Using this tool, companies should be able to benchmark concurrent engineering processes from other companies and measure their impact if applied internally.

II. MODEL FORMULATION

Since the existing models for measuring the success of concurrent engineering programs usually tend to focus on Manufacturing success only, we need to expand the models to reflect total company success. Since concurrent engineering, as applied to ensuring the success of a company, is often viewed as the tradeoff of Engineering success for Manufacturing success (which presumably will generate more revenue for the company), the model should reflect this tradeoff. Assuming that project success is measured in terms of time, cost and performance, it is first necessary to establish these parameters from both a Manufacturing and Engineering perspective.

For Manufacturing, time refers to the time it takes to manufacture a single unit, cost is the cost per unit manufactured, while performance refers to the quality of the finished product. For Engineering, time refers to the development schedule, cost is the development budget, while performance refers to how well the design meets the user requirements for the product. This establishes the following parameters.

Delivery This is the throughput of the manufacturing process and is a measure of the time to manufacture a single unit. Note that this term was chosen to conform with existing models.

Cost This is the cost per unit manufactured.

Quality This is the quality of the finished manufactured product. This clearly is a measure of the performance of the manufacturing process.

Schedule This refers to the Engineering development schedule.

Budget This refers to the Engineering development budget.

Performance This is the performance of the unit as designed (a measure of how well it meets the user requirements).

The achieving of success should not be done at the expense of relationships within the company. Even if a product is designed to be the cheapest, fastest manufactured, greatest quality unit in existence, it is still going to hurt the company if the achievement of this success is followed by the resignation of the core personnel involved. Clearly this model should include some measure of the human aspect of the concurrent engineering program. This yields the following additional parameter.

Relational The human factor. A measure of how communication, teamwork, etc. are improved.

If all of the parameters above are taken into account, the figure of merit, F, for a concurrent engineering program or how well a process or decision impacts such a program, is obtained as in (1) below. Note that the minus sign is present in the equation to represent the concept of tradeoffs between Manufacturing and Engineering success.

$$F = R + (D + C + Q) - (S + B + P) \tag{1}$$

where	F	=	Figure of merit.
	R	=	Measure of contribution towards Relational parameter.
	D	=	Measure of contribution towards Delivery parameter.
	C	=	Measure of contribution towards Cost parameter.
	Q	=	Measure of contribution towards Quality parameter.
	S	=	Measure of negative impact towards Schedule parameter.
	B	=	Measure of negative impact towards of Budget parameter.
	P	=	Measure of negative impact towards Performance parameter.

Clearly, each of these parameters would have varying importance, depending on the organizational structure, project and product involved. This requires the multiplication of each of the parameters with an associated weighting parameter. This is as in equation (2) below. Note that the r, q, c, d, s, b and p values are the weightings just mentioned. The K value is just an optional scaling parameter.

$$F = (rR + qQ + cC + dD - sS - bB - pP) / K \qquad (2)$$

Thus, equation (2) formed our initial model. The R, Q, C, D, S, B and P parameters were assigned values on a five point scale (-2 to +2, with 0 indicating *no significant effect*). It was decided that the values for r, q, c, d, s, b and p should be numerically equivalent to the rank importance of each parameter to the organization or project (between 1 and 7, 7 being the most important). This resulted in our choice of K = 56, to scale F, so that it would lie between -1 and +1.

While this model might, at first glance, seem to limit it's impact to Engineering and Manufacturing, it actually encompasses the entire company structure. This is easily illustrated by examining three other major departments in a typical product driven organization - Customer Service, Marketing and Finance.

Customer Service From this department's perspective, time, cost and performance are measured in terms of *mean time between failures*, *cost to service* and *mean time to repair* respectively. Clearly, if the quality is good, the mean time between failures will be favorable. If the manufacturing cost is low, then the repair cost, and hence, the cost to service is low. If the delivery is high, then the mean time to repair should be low. So, the contribution towards Customer Service success is encompassed by this model.

Marketing From this department's perspective, time and cost are measured in terms of *time to market* and *profit margin* respectively. This department measures performance in two ways. First there is the measure of how well the product meets the *user requirements* and secondly, there is the rate at which Manufacturing can manufacture the product to *meet market requirements*. If the project is within schedule, the time to market requirements will have been met. If the manufacturing cost is low, the profit margin should be helped. If the product is designed to meet the user requirements and the manufacturing delivery is high, clearly the marketing performance requirements should be met. So, the contribution towards Marketing success is encompassed by this model.

Finance From this department's perspective, time, cost and performance are measured in terms of *cost schedule*, *total cost* (over time) and *profit margins* respectively. If the development budget and schedule are met, clearly, the cost schedule should be met over the short term. Long term costs are controlled by the cost to manufacture a single unit. Clearly if the product helps achieve the marketing requirements, the profit margins should be helped. So, the contribution towards the success of the Finance department is encompassed by this model.

Clearly, in the three examples above, we see how this model measures the impact of the combined development and manufacturing cycle (concurrent engineering) on the total success of a company. However, it does not encompass other causes of project success or failure, such as whether the product being developed or built meets it's market segment, or whether the sales force is equipped to sell it, etc.. It is *only* designed to measure the *impact* of the concurrent engineering program or process on company success.

III. MODEL ADJUSTMENTS

The first step towards verification of the model involved gathering some preliminary data, trying it out on the model and observing the results. This data was first put together from our own experiences. Then, we got second opinions on this data from other personnel who had worked on these projects with us. We then adjusted the data to correspond with their inputs. The data sets we used consisted of a series of decisions impacting projects involving Engineering and Manufacturing. Data ~~was~~ were chosen that had both positive and negative impacts. The reason we used data from our own experiences here was so that we would have a feel for what the overall impact of the decisions chosen should be (as opposed to the measure they contributed to the parameters in (2)). The data we used also corresponded to projects and organizations where the ranking of the weighting factors was identical for each data set (this made it easier to gauge the correctness of the figure of merit calculations). The weightings are outlined in table 1. The data are outlined in table 2. F is calculated using (2). The company and project names are withheld to maintain confidentiality, but abbreviations are used to enable the reader to group them together. The decisions chosen are as in the following list (abbreviations are used in the tables).

1. Put a manufacturing engineer on the design team.
2. Manufacturing was allowed insufficient input into the design of the product.
3. This project had one manager over Engineering and Manufacturing in a combined organization.
4. Test technicians were placed on the prototype development team.
5. Diagnostics programmers had to work as test technicians for a period of time to use the software they developed.
6. Engineering and Manufacturing had one common networked schedule.

7. The product was designed for testability.
8. The product had insufficient configuration testing performed on it before release to Manufacturing.

Table 1: Initial data weighting factors.

Weighting	r	q	c	d	s	b	p
Ranking	1	4	6	5	3	2	7

Table 2: Initial data to verify model.

Decision/Technique	R	Q	C	D	S	B	P	Co./Proj.	F
Put M.E. on design team	1	2	0	1	-1	0	0	C/C	0.30 $= F_1$
Insufficient mfg design i/p	-2	-2	0	-2	-2	-2	0	C/S	-0.18 $= F_2$
One manager over eng & mfg	2	1	0	1	-1	-1	0	A/H	0.29
Putting test techs on proto.	1	0	0	2	-2	0	0	C/C	0.46
Diags prog. as tech. for while	-1	0	0	1	0	0	0	A/H-I	0.07
Common eng-mfg schedule	0	0	0	0	-1	0	0	C/C	0.05
Design For Testability (DFT)	0	2	0	2	1	0	0	C/C	0.27
Insufficient config. testing	-1	0	0	-2	0	0	0	C/C	-0.20

Given the data gathered, there were some inconsistencies discovered. These are best illustrated by taking the first two entries in the table. The first entry yielded a positive value of F (let us refer to this as F_1 for the purpose of analysis). The second entry yielded a negative value of F (F_2). Now, we felt that the second entry (Manufacturing having insufficient input into the design) had a more negative effect on it's project than the first (putting a manufacturing engineer on the design team) had a positive effect on it's project. i.e. It was felt that $-F_2$ should be greater than F_1, which was not the case. This was a clear indication that there was something wrong with our model.

Our first reaction was to suspect that the weighting factors were ill-chosen. We tried variations on these to see what weightings would yield the correct relative values of F_1 and F_2. To analyze the weightings, it was necessary to simplify the model. We made the assumption that in the discrepancy being analyzed, the main issue would be the relative importance of the manufacturing issues versus all other issues. Taking this into account, we get the simplified model in (3).

$$F = m.(Q + C + D) + e.(R - S - B - P) \tag{3}$$

Note that m and e refer to the relative importance of Manufacturing and other issues respectively. Now, if we apply (3) to F_1 and F_2, we can get an idea of the relative importance of the figure of merits. This yields (4).

$$F_1 = m.(2 + 0 + 1) + e.(1 - (-1) - 0 - 0) = 3m + 2e \tag{4}$$

$$F_2 = m.((-2) + 0 + (-2)) + e.((-2) - (-2) - (-2) - 0) = -4m + 2e$$

Since F1 should be less than -F2, we then get (5).

$$\begin{array}{llll} & F_1 & < & -F_2 \\ \Rightarrow & 3m + 2e & < & 4m - 2e \\ \Rightarrow & m & > & 4e \end{array} \tag{5}$$

Thus, Manufacturing concerns need to be given at least four times the weighting of other issues in order to make the figure of merits turn out the way we felt was appropriate. We felt that the different parameters in our model were not ranked in importance with this much skew towards the manufacturing issues in the projects involved. This convinced us that our discrepancy was not related to our choice of weighting parameters.

The next step we took was to try developing other equations that we felt might produce more effective models. We decided that since the Q, C and D parameters were related to the volume sold, that perhaps, we should include this. This volume sold would also be reduced if the schedule missed the market window, so it should be a function of the S parameter. Also, if the company is limited on funds, the budget should also be part of this *volume* function. This resulted in (6). For this model, we also decided to simplify issues and assume that the Performance parameter, P, could not be compromised (as it was 0 in all our data cases). Note that we also determined that in most cases, Q, C and D have about equal weighting, so we tried to simplify the equation some more by not giving them their own weighting factors.

$$F = (rR + (Q + C + D)V\{sS,bB\} + sS + bB) / V\{sS,bB\} \qquad (6)$$

We also tried multiplicative combinations such as in (7).

$$F = (rR + Q.C.D.V\{sS,bB\}) / V\{sS,bB\} \qquad (7)$$

In (6) and (7), we encountered problems in estimating the volume function accurately and correctly deriving the impact of the S and B parameters on this function. If we used the actual volume unit count, in some cases, it would make everything other than the Q, C and D parameters insignificant. If we tried to scale it down some how, we had no way of determining if our scaling was helping or hindering our accuracy. We eventually realized that the volume function was not needed, as this was handled in the ability of manufacturing to meet volume throughput (i.e. it was built in automatically into the Q, C and D parameters).

Finally, we discovered the reason for the discrepancy between F_1 and F_2. Equation (2) was essentially correct, but it was our interpretation of some of the parameters that was incorrect. We had assumed that the Schedule and Budget parameters referred to the Engineering schedule and budget respectively. However, the correct interpretation should have been the schedule and budget for the *entire* development. They should have included the time and cost to get Manufacturing ramped to full production respectively. This way, decisions that have a severe negative impact on Manufacturing, but help in the Engineering schedule will not end up with values for S and B that help the figure of merit, but with values that have a negative impact on S and B, as Manufacturing loses time and spends more money in getting production up to speed. So, our final model is represented in (8). Note that the signs of the S, B and P parameters have been changed to positive to simplify the equation (their meanings have been correspondingly changed to be a measure of contribution instead of degradation as in (2)). We also include a recap of the various parameters with their updated definitions.

$$F = (rR + qQ + cC + dD + sS + bB + pP) / K \qquad (8)$$

where

where	F	=	Figure of merit.
	R	=	Measure of contribution towards Relational parameter.
	D	=	Measure of contribution towards Delivery parameter.
	C	=	Measure of contribution towards Cost parameter.
	Q	=	Measure of contribution towards Quality parameter.
	S	=	Measure of contribution towards Schedule parameter.
	B	=	Measure of contribution towards Budget parameter.
	P	=	Measure of contribution towards Performance parameter.
	K	=	Scaling factor.

Relational The human factor. A measure of how communication, teamwork, etc. are improved.

Delivery This is the throughput of the manufacturing process and is a measure of the time to manufacture a single unit. Note that this term was chosen to conform with existing models.

Cost This is the cost per unit manufactured.

Quality This is the quality of the finished manufactured product. This clearly is a measure of the performance of the manufacturing process.

Schedule This refers to the entire development schedule, including the time to ramp Manufacturing production.

Budget This refers to the entire development budget, including the cost to ramp Manufacturing production.

Performance This is the performance of the unit as designed (a measure of how well it meets the user requirements).

Recalibrating our test data, we get the values in tables 3 and 4.

Table 3: Revised data weighting factors.

Weighting	r	q	c	d	s	b	p
Ranking	1	4	6	5	3	2	7

Table 4: Revised data to verify model.

Decision/Technique	R	Q	C	D	S	B	P	Co./Proj.	F
Put M.E. on design team	1	2	0	1	1	0	0	C/C	0.30 $= F_1$
Insufficient mfg design i/p	-2	-2	0	-2	-2	2	0	C/S	-0.39 $= F_2$
One manager over eng & mfg	2	1	0	1	1	1	0	A/H	0.29
Putting test techs on prototype	1	0	0	2	2	0	0	C/C	0.46
Diags prog. as tech. for while	-1	0	0	1	0	0	0	A/H-I	0.07
Common eng-mfg schedule	0	0	0	0	1	0	0	C/C	0.05
Design For Testability (DFT)	0	2	-1	2	2	0	0	C/C	0.32
Insufficient config. testing	-1	0	0	-2	0	0	0	C/C	-0.20

Which is consistent with our estimates on how these techniques impacted the respective organizations. Also note that $F_1 < -F_2$ as expected.

We then provided a more accurate method for measuring the weighting factors. First of all, the parameters are ranked in importance. Then, the most important is assigned a value of 10. The second in importance is assigned a percentage of the first. Then the process is repeated, letting the second in importance have a value of 10 and assigning a percentage of this to the third ranked parameter. This is continued until all the parameters are assigned relative values. This is best illustrated with an example, where we present a more accurate estimate for the weights in table 3 in table 5 below.

Table 5: More accurate weight value assignment.

Param.	Value	Next	Value	Weight
p	10	q	8	0.8
q	10	c	10 *	0.8
c	10	d	10 *	0.8
d	10	s	8	0.64
s	10	b	5	0.32
b	10	r	5	0.16

Then, in order to calculate the correct weighting factors, one just has to assign the highest ranked weight a 1, and for each subsequently ranked parameter, multiply the number from the value column on the right divided by 10 (to yield a percentage). For example, the s value is %q x %c x %d x %s = 0.8 x 1 x 1 x 0.8 = 0.64. These are the values in the rightmost column in table 5. Note that with this weighting scoring model, one can have parameters with equal weighting (as in the case of * in table 5). Now, some of the data we collected used this scoring model, while some others used the original scoring model (as some people had difficulty determining the weighting with any more accuracy than this). If the original ranking method is used, then the value of K in (8) is 56, as before. If the new, more accurate scoring model is used to determine the weighting factors, a K value of 14 is used. This keeps the values of F between -1 and +1. Note that if a mix of scoring models is used, it is inadvisable to mix the results as the different methods do not correlate linearly. The best solution, in this circumstance, is to use equation (9) below instead of (8). This way, the values are scaled appropriately regardless of the technique used to determine the weighting. The rank values can then be just divided by 7, yielding values between 0 and 1 (for comparison with the other weighted values).

$$F = \frac{rR + qQ + cC + dD + sS + bB + pP}{2(r + q + c + d + s + b + p)} \quad (9)$$

IV. DATA ACQUISITION

The next phase was to acquire more data and to examine what results this model yielded when applied to the data. A mix of techniques were used to acquire the data. Some of the data were acquired by questionnaire, while other data were collected through interviews. From each source, we asked for the following information in the following order.

1. We asked them to identify some decisions or processes that they felt helped or hindered concurrent engineering on a particular project.
2. For this project and organization, they had to rank the importance of the parameters in (9) from 1 to 7 (7 being the most important).
3. They then had to create a table similar to that in table 5 to determine more accurate relative weighting factors.
4. Then, for each of the items listed in question 1, they had to determine the values for the parameters in (9) to the best of their ability.
5. Then, they had to rate each of these items relative to one another on a scale of -10 to +10. This gave us a feel for the accuracy of the data they provided. Note that the subjects were not aware of how we were going to combine the data together, so they could not *fix* this parameter.

The subjects were known to us and were guaranteed confidentiality, which further ensured the accuracy of the data gathered. The data is presented in tables 6 and 7. The decisions/processes chosen are presented as follows.

1. This project had one manager over Engineering and Manufacturing in a combined organization.

2. Diagnostics programmers had to work as test technicians for a period of time to use the software they developed.
3. Manufacturing was allowed insufficient input into the design of the product.
4. Test technicians were placed on the prototype development team.
5. Put a manufacturing engineer on the design team.
6. Engineering and Manufacturing had one common networked schedule.
7. The product was designed for testability.
8. The product had insufficient configuration testing performed on it before release to Manufacturing.
9. A manufacturing engineer was put on the cabinet design team early on in the project.
10. No manufacturing engineers were involved until the product reached the production phase.
11. A manufacturing engineer was involved on the project from the beginning.
12. A manufacturing engineer was involved on the project from the beginning (different project than 11).
13. A layout technician was a member of the core design team.
14. A test technician was a member of the design team.
15. Manufacturing performed frequent design reviews.
16. There were standard guidelines implemented for design for manufacturability (DFM).
17. A manufacturing technician was a member of the design team.
18. Manufacturing was involved in early component selection.
19. Manufacturing performed the environmental testing on the prototype.
20. Extensive use of simulation was made during the design to increase reliability and quality.
21. Manufacturing had no input into the design.
22. Manufacturing participated in design reviews.
23. Manufacturing build all prototypes.
24. Manufacturing order all prototype parts.
25. Diagnostics were not started until very late in the development cycle.

26. A fast Engineering change order (ECO) mechanism was put in place with minimum paperwork.

27. There was no revision control on schematics.

Table 6: Weighting factors for data gathered.

Co./Proj.	r	q	c	d	s	b	p	sum
A/H	0.160	0.800	0.800	0.800	0.640	0.320	1.000	4.520
A/H-I	0.160	0.800	0.800	0.800	0.640	0.320	1.000	4.520
C/S	0.160	0.800	0.800	0.800	0.640	0.320	1.000	4.520
C/C	0.160	0.800	0.800	0.800	0.640	0.320	1.000	4.520
S/1	0.026	1.000	0.900	0.720	0.432	0.259	0.003	3.340
S/2	0.315	0.900	0.630	0.063	1.000	0.012	1.000	3.920
S/3	0.026	0.900	0.630	0.132	1.000	0.441	1.000	4.129
G/1	0.327	1.000	0.583	0.900	0.810	0.408	0.729	4.757
N/1	0.640	0.800	0.192	1.000	0.041	0.069	0.173	2.915
P/1	0.429	1.000	0.571	0.714	0.857	0.143	0.286	4.000
P/2	0.714	1.000	0.429	0.571	0.857	0.286	0.143	4.000
P/3	0.714	0.857	0.429	1.000	0.571	0.286	0.143	4.000
AS/C	0.400	0.360	0.400	0.058	1.000	0.144	0.800	3.162
E/S	0.389	0.648	0.810	0.900	1.000	1.000	0.900	5.647
M/C	0.09	0.900	0.72	0.180	1.000	0.360	0.72	3.970

Table 7: Parameter data gathered.

#	Decision/Technique	R	Q	C	D	S	B	P	Co/Pr	F	Est
1	One manager over eng & mfg	2	1	0	1	1	1	0	A/H	0.32	7
2	Diags prog. as tech. for while	-1	0	0	1	0	0	0	A/H-I	0.07	1
3	Insufficient mfg design i/p	-2	-2	0	-2	-2	2	0	C/S	-0.46	-9
4	Putting test techs on prototype	1	0	0	2	2	0	0	C/C	0.34	7
5	Put M.E. on design team	1	2	0	1	1	0	0	C/C	0.35	8
6	Common eng-mfg schedule	0	0	0	0	1	0	0	C/C	0.07	1
7	Design For Testability (DFT)	0	2	-1	2	2	0	0	C/C	0.41	8
8	Insufficient config. testing	-1	0	0	-2	0	0	0	C/C	-0.19	-5
9	M.E. on Cab. team from start	1	2	0	1	-1	0	0	S/1	0.35	5
10	No M.E. involved until prod.	-1	-1	1	-2	-1	0	0	S/2	-0.22	-5
11	M.E. on design from beginning	2	2	-1	2	0	0	2	S/3	0.42	5
12	M.E. on design from beginning	1	1	2	2	0	-1	1	G/1	0.48	5
13	Layout tech. on design team	2	1	0	1	-1	1	0	N/1	0.53	5
14	Mfg. tech. on design team	1	1	1	2	2	-1	0	P/1	0.62	3
15	Frequent des. reviews by Mfg.	0	1	2	1	2	-2	0	P/2	0.45	5
16	Standard guidelines for DFM	2	2	1	1	0	0	0	P/3	0.46	2
17	Mfg. tech. on design team	2	1	0	2	2	1	2	AS/C	0.79	10
18	Mfg in early component select.	2	-1	1	2	2	0	2	AS/C	0.72	5
19	Mfg did envir. testing of proto.	2	2	0	0	1	0	0	AS/C	0.40	5
20	Extensive use of simulation	1	2	0	0	0	-2	0	E/S	-0.03	10
21	No Mfg input to design	-2	-2	0	-2	-2	2	0	E/S	-0.34	-10
22	Mfg participate in des. reviews	2	1	1	1	0	0	1	M/C	0.34	5
23	Mfg build all prototypes	1	1	2	0	1	0	1	M/C	0.52	5
24	Mfg order all prototype parts	1	1	1	0	1	1	1	M/C	0.48	5
25	Late diagnostics development	0	-1	0	-1	-1	-1	-1	M/C	-0.4	-5
26	Fast ECOs with min paperwork	1	1	0	1	1	0	1	M/C	0.36	6
27	No rev. control on schematics	0	-1	0	0	-1	0	-1	M/C	-0.33	-3

Note that the sum column in table 6 is the value of $r + q + c + d + s + b + p$ for use in (9). The F column in table 7 is calculated using (9). Note the slight differences between the first few entries in table 7 and the same entries in table 4. These are due to the use of (9) instead of (8), yielding more accurate and scalable values (across projects and companies). The *Est* column is a list of the estimates provided by the subjects of the study as to overall impact of the processes/decisions to overall project success. Note that these values are only meant to be relative within the company in question and are useful for assessing the accuracy of the relative values of F calculated from data provided by one person.

While (9) eliminates much of the company dependence on the figure of merit, there is still some skewing of the data due to personal bias that shows up in the scoring values themselves. However, this is only relative when comparing data provided by different people, as they tend to be over or under zealous in their scoring. This is best illustrated by rows 11 and 12, where the identical decision results in values of 0.42 and 0.48 respectively. However, it was not expected that the model would be extremely accurate, and, as expected, it does provide values that are relatively close together. There also are some aberrations, such as rows 17 and 18, which score the processes above 0.70, which is considerably higher than other scores. This high score is the result of the increases in performance achieved by the implementation of the process or decision (highly unusual, as performance is rarely compromised in any case, so the implementation of a concurrent engineering process will rarely be needed to help meet the user requirements).

V. DATA ANALYSIS

The process decisions or techniques that were most successful according to table 7 were those that involved the assignment of resources cross functionally. Placing a manufacturing engineer or test technician on the design team and getting manufacturing involved in early project phases clearly are to be recommended. Design for manufacturability and manufacturing involvement in the prototype bringup also have significant merit according to table 7. On the other hand, not having manufacturing involved in early project phases has a clear negative impact on project success, from both a perceived and actual perspective (from the Est and F columns in table 7 respectively). This is not made up for by having manufacturing involved later in the project, and rows 10 and 25 of table 7 attest to this. Also, a lack of controls when the project reaches production (such as schematic control as in row 27 in table 7) can have a significant negative impact.

First, we tried taking the data from one company and applying it to another (i.e. using another's weighting factors). However, when we did this, we had no way of verifying if the cross-company impact calculated was correct. For example, examining rows 11 and 12, one might get the impression that the same decision was applied to both company S and G. However, company S was a high technology firm, while company G was a heavy electro-mechanical firm. As a result, the two decisions do not impact the other company by an equal amount. This cross-company use of the model is best analyzed, when similar technology is involved. For example, companies P and C involve similar technology. If we compare rows 5 and 7 with rows 14 and 16 respectively, we would achieve a result like that in table 8. Note that even though these rows are not identical, their subject matter is close enough to be of use.

Table 8: F, using data from one company with another's weighting factors. (Rows = Data, Columns = Weighting)

#	5	7	14	16
5	0.35		0.5	
7		0.41		0.55
14	0.48		0.62	
16		0.39		0.46

As can be seen from table 8, when we use the data from company C with the weightings from company P, we get values of 0.5 and 0.55 respectively for F compared to 0.35 and 0.41

respectively for the same calculation with their own weightings. As can be seen, the relative difference between the impact of the different processes remains the same (0.5 / 0.55 ~ 0.35 / 0.41 ~ 0.9). Similarly, if we look at the data from company P with the weightings from company C, we get values of 0.48 and 0.39 respectively for F compared to 0.62 and 0.46 respectively for the same calculation with their own weightings. Again, we see the same relative differences being roughly maintained. This is what one would expect if the data were transferable. This is made all the more credible when one takes into account the fact that these examples were not identical, just similar. So, from this example, one can conclude that the relative impacts of different concurrent engineering processes or decisions can be transferred across company boundaries.

The data collected can also be used as a benchmark between different competing companies. Three of the companies surveyed were chosen because a segment of their markets overlap (companies C, S and P). This overlap allows us to analyze the data from the benchmarking perspective. The data for these companies are presented below in tables 9 and 10 with a bold line separating the different company data. Note that only the data for the competing projects is presented. Note also, that the row numbers from table 7 have been retained to avoid confusion.

Table 9: Weighting factors for competing companies.

Co./Proj.	r	q	c	d	s	b	p	sum
C/S	0.160	0.800	0.800	0.800	0.640	0.320	1.000	4.520
C/C	0.160	0.800	0.800	0.800	0.640	0.320	1.000	4.520
S/1	0.026	1.000	0.900	0.720	0.432	0.259	0.003	3.340
S/2	0.315	0.900	0.630	0.063	1.000	0.012	1.000	3.920
S/3	0.026	0.900	0.630	0.132	1.000	0.441	1.000	4.129
P/1	0.429	1.000	0.571	0.714	0.857	0.143	0.286	4.000
P/2	0.714	1.000	0.429	0.571	0.857	0.286	0.143	4.000
P/3	0.714	0.857	0.429	1.000	0.571	0.286	0.143	4.000

Table 10: Parameter data for competing companies.

#	Decision/Technique	R	Q	C	D	S	B	P	Co/Pr	F	Est
3	Insufficient mfg design i/p	-2	-2	0	-2	-2	2	0	C/S	-0.46	-9
4	Putting test techs on prototype	1	0	0	2	2	0	0	C/C	0.34	7
5	Put M.E. on design team	1	2	0	1	1	0	0	C/C	0.35	8
6	Common eng-mfg schedule	0	0	0	0	1	0	0	C/C	0.07	1
7	Design For Testability (DFT)	0	2	-1	2	2	0	0	C/C	0.41	8
8	Insufficient config. testing	-1	0	0	-2	0	0	0	C/C	-0.19	-5
9	M.E. on Cab. team from start	1	2	0	1	-1	0	0	S/1	0.35	5
10	No M.E. involved until prod.	-1	-1	1	-2	-1	0	0	S/2	-0.22	-5
11	M.E. on design from beginning	2	2	-1	2	0	0	2	S/3	0.42	5
14	Mfg. tech. on design team	1	1	1	2	2	-1	0	P/1	0.62	3
15	Frequent des. reviews by Mfg.	0	1	2	1	2	-2	0	P/2	0.45	5
16	Standard guidelines for DFM	2	2	1	1	0	0	0	P/3	0.46	2

From table 9, we can glean information about company focus. Let us deal with each in turn.

First, company P has it's focus in the quality, schedule and relational areas. This, coupled with the higher impact of some of the techniques applied (row 14 has F = 0.62), seems to imply that the company was having too much focus on schedule in Engineering, and this resulted in relational problems with Manufacturing's requirements not being met in the design, resulting in some reliability problems in the final product. The company is trying to fix this problem by focusing on quality and relational issues. It appears that this problem is being fixed by the significant impact their solutions are having. It is worth noting that the figure of merit should be higher in such cases, as the company has that much further to go in order to reach perfection in terms of manufacturability. A marketing analyst from company C confirmed that company P was having reliability problems in the field and that their product is aimed at the very high end of the overlapping market segment. This would result in their satisfaction with the product's performance, and hence, the low relative importance being placed on the performance parameter currently. Clearly, this reliability issue extends to manufacturability, as can be seen by the significant emphasis being placed on the delivery parameter in table 9 (i.e. they are having problems isolating faults on their test floor, and their throughput is low as a result).

Company S has it's focus on quality, schedule and cost issues. Again the analyst from company C was able to inform us that this company is targeting the middle to lower performance (and thus, priced) market. Most of their customers require significant up-time, and hence, the high quality weighting factor. This marketplace changes fast, and hence, the high schedule weighting factor. Since they are competing in the lower end, they require significantly lower production costs than company P for example, and this is reflected in the high cost weighting factor. Their delivery is clearly adequate, based on the weighting factor, but they have had some problems in the past in this area, as indicated in row 10 in table 10. However, the F figures are not significantly high, implying that the impact of the changes were not extremely high, which, in turn, implies that their manufacturability is reasonably good already. Performance within their market segment is also important to them.

Company C has its focus on manufacturability and performance. Their product is new to this competing market segment, and so, there are some unknowns as yet. However, from row 3 in table 10, we can deduce that there were significant manufacturability problems in the past, which has driven the focus to the QCD parameters. Competing in the high end places a great focus on performance, while schedule is significant in order to maintain adaptability to a changing market. Their F figures are not significantly higher than company S, which would imply that both companies products are at about the same level of manufacturability.

Another area where this data can be useful is in determining how the subject is in line with company objectives. Any significant deviations can indicate morale problems at that company. Examine, for example, the data from company E, as presented in tables 11 and 12.

Table 11: Weighting factors for company E.

Co./Proj.	r	q	c	d	s	b	p	sum
E/S	0.389	0.648	0.810	0.900	1.000	1.000	0.900	5.647

Table 12: Parameter data for company E.

#	Decision/Technique	R	Q	C	D	S	B	P	Co/Pr	F	Est
20	Extensive use of simulation	1	2	0	0	0	-2	0	E/S	**-0.03**	**10**
21	No Mfg input to design	-2	-2	0	-2	-2	2	0	E/S	-0.34	-10

Here, we see that for row 20, the F figure came out to be -0.03, while the subject estimated it to be a significant contributor to project success. Now, one can draw one of two conclusions here. Either the company places too much emphasis on the budget parameter, or the subject's views of company priorities differs from that of the company, implying a morale problem. On further inquiry, it was confirmed that there is, indeed, a morale problem at this company.

VI. CONCLUSION

We have successfully come up with a benchmarking tool that can be used to measure the success of concurrent engineering programs or processes, and their impact to different companies. This tool can be used to both measure the success of an internal concurrent engineering program, or to determine what concurrent engineering practices should be copied from other companies. It can be used to determine priorities and direction within a development or manufacturing organization. It can also be used as a marketing tool to analyze strengths and weaknesses in competitive products and in the structure of competitive companies, as it measures the design, development and manufacturing process used to bring the product to market. It also has potential uses for customers of multi-bid projects, such as government agencies. This measuring tool can be used to determine the best engineered product amongst several competing bids.

References

[1] John R. Hartley, "Concurrent Engineering", *Productivity Press.*

[2] Preston G. Smith and Donald G. Reinhold, "Developing Products in half the time", *Van Nostrand Reinhold.*

[3] Schonberger, "World Class Manufacturing", *The Free Press*, New York, 1986, p147.

[4] "Computer Support for Concurrent Engineering", *IEEE Computer*, January 1993, (The entire magazine).

[5] Tom Inglesby, "An Interview with Teruyuki Yamazaki", *Manufacturing Systems*, June 1993, p38-43.

[6] Archie Ossin Vladimir Mandl, "Production Operations' Vital Role in Concurrent Engineering", *Manufacturing Systems*, May1993, p33-40.

[7] "Engineers Look at Concurrent Engineering", *Design News*, June 3, 1991, p32.

[8] Siegal, "Organizing for a Successful Concurrent Engineering Process", *Industrial Engineering*, v23, Dec. 1991, p15.

[9] Ulerich, "Tips for Concurrent Engineering", *Machine Design*, v64, Aug. 20, 1992, p54.

[10] Vasilash, "Design for Assembly: Only Part of Competitive Equation", *Production*, v104, Sept. 1992, p54

[11] Whiteley, "New Roles for Manufacturing in Concurrent Engineering", *Industrial Engineering*, v23, Nov. 1991, p51.

[12] Structural Dynamics Research Corporation, "Benchmarking Your Company For Concurrent Engineering", *Machine Design*, Nov 26 1993, p77-80.

[13] Structural Dynamics Research Corporation, "Measuring Success from Concurrent Engineering", *Machine Design*, Nov 26 1993, p77-80.

[14] Kevin Parker, "Big Blue's tips on best practices", *Manufacturing Systems*, June 1993, p14.