Optimal Virtual Prototyping for Semiconductor Manufacturing Equipment

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Abstract

Some level of virtual prototyping via computational modeling is currently utilized by all semiconductor manufacturing equipment companies. An important question concerns the optimal level of virtual prototyping in the overall engineering development process. Related questions concern the optimal points in the development process where virtual prototyping has the highest impact and best return. The impact is also affected by the way in which virtual prototyping is implemented company wide, for example, centralized versus distributed modeling.

This paper identifies the points in the development process where virtual prototyping via computational modeling has the highest impact. It presents guidelines that can be used by management to help determine whether modeling is being used effectively. This is based upon several criteria including the use of modeling for concept and feasibility studies, establishing product differentiation, optimizing performance, minimizing risks associated with long-lead items, using preliminary experimental results to feedback into the modeling activity and minimizing re-design activities. The recommended virtual prototyping strategy is illustrated by examples from the semiconductor manufacturing equipment development process.

Introduction

The decision to use virtual prototyping or modeling for many industries and for many aspects of engineering is often made without question. For airplane manufacturers there are government regulations specifying the key structural analyses to be performed and the format and data to be used in the analysis. In the biomedical industry similar government approval processes require certain levels of analysis and modeling to be performed. This paper is concerned with making virtual prototyping or modeling decisions in less structured environments, where the use of virtual prototyping is at the discretion of the engineering management. We discuss considerations similar to those whose industry is more regulated in the modeling aspects where there appears to be similar requirements, for example, safety considerations. However, for the "optional" modeling tasks we propose a structure, schedule and methodology for getting the maximum return from the modeling activity. We also discuss appropriate levels of resources for successful virtual prototyping activity.

Structure of Virtual Prototyping

Several questions need to be considered with regards to the use of virtual prototyping. These questions include: When, What, Why and How Much? In other words, when is the best time to perform virtual prototyping, what aspects of the system benefits most from the virtual prototyping, why is the virtual prototyping activity important, and finally what level of detail (or how much) virtual prototyping is appropriate.

Development Schedule and Virtual Prototyping

Most companies have a product development process, some more formalized than others. In the semiconductor manufacturing equipment industry the overall steps in the development process are:

- C&F (concept and feasibility phase)
- Design
- Test/Verification
- CIP (continuous improvement of product)

We have lumped together some activities, for example, in CIP we include activities such as failure investigations, cost reduction, etc. Some industries must now, or will in the future, need to consider other aspects such as product retirement. Additionally the design/test/verification phase may include alpha and beta products, customer evaluations, etc.

The Lean Design [1] methodology notes that the engineer has the single largest impact on the overall cost effectiveness of the product. This includes aspects such as manufacturability, material costs, part count, etc. We feel that of the engineering disciplines, the modeling or virtual prototyping activities can have the single largest impact on the effectiveness of the engineering contribution.

The answer to the question “When?” is “The sooner the better”. Up front modeling during the design phase can eliminate mistakes, over (and un) conservative assumptions and inaccuracies. Design and release of drawings for long lead or expensive items should always be supported by modeling if there are any questions at all regarding what is needed for the design. The semiconductor industry has often relied on much experimentation during the C&F phase without much modeling support. This works well in an evolutionary type of C&F activity when a current product is extended in a fairly straight forward manner. However, for high risk (and high potential return) type activities the virtual prototyping will be beneficial assuming confidence in the predictive capabilities exists. Building virtual prototypes of high risk C&F products coupled with the subsequent Test/Verification phase helps establish and mature the modeling capability within the organization so that techniques are established and verified. As the capability and maturity of the virtual prototyping develops then it can be relied on with more confidence for future C&F studies. This may require a change of paradigm for organizations that prefer to first design the product or concept in detail and later have the analysis performed as a verification. The modeling and design teams need to work much closer and more interactively in order to make the modeling timely and supportive of the fast paced design activity. Additionally designer engineers need to start budgeting time differently, making first pass designs and passing them to analysts quickly then working on other parallel activities while the rough design is analyzed and/or optimized. Analysts on the other hand would benefit greatly from increased proficiency in the use of CAD design tools so that they could transfer optimized or modified designs back to the designers in more convenient formats. Another option is to have designers responsible for some of the modeling, however, this raises issues regarding training and the ability to develop mature confident modeling organizations which is difficult when an engineer's time is split in too many directions. However, certainly some level of modeling or virtual prototyping activity can be carried out effectively by design engineers.

Continuous Improvement of Product (CIP) activities are more straight forward with regards to providing virtual prototyping support. Often the problem statement is fairly clear, such as, modify the structural design for cost reduction or redesign a component for improved performance. The answer as to when to model these is still sooner rather than later and all discussion from the C&F and Design phase presented above still apply.

Identifying and Prioritizing Virtual Prototyping Activities

The answer as to "What?" and "Why?"; that is what activities benefit most and why they benefit, are coupled. We discuss here some considerations that help insure optimal use of the virtual prototyping capability within the organization by answering the "What?" and "Why?" questions in general and with specific reference to semiconductor manufacturing. The brute force answer as to what needs to be modeled is "everything". While this seems to be the trend in certain industries many people wonder if this is indeed optimal. If the answer that "everything" needs to be modeled is based upon an economic analysis of the situation that supports this decision then it can be optimal. Often the "everything" approach may be justified on the shear volume of units being produced. Many industries just adopting virtual prototyping do not have the resources to model "everything" thus want to make decisions supported through some sort of economic analysis. Additionally in the semiconductor equipment sector the volume of units produced currently does not support the model everything approach. The general guidance here is similar to that discussed under the "When?" question, that is, those components which are critical, expensive, risky and/or are long lead items whose design parameters are not completely clear should be the first candidates for virtual prototyping. These items are normally easily identified and often the list is manageable at least for semiconductor equipment. As can be seen part of the "what" question concerns the "why", for example, if an item is risky, or, is long lead these are good reasons as to why the modeling is important. We suggest an approach to quantify these in the following example.

Suppose we look at 4 components (or assemblies) of a system. We will eliminate critical or expensive items that are previously designed and have been established by the organization to be of proven quality and performance. We include in the list newly designed components that are critical to the operation or performance of the system. We also include newly designed items that are any combination of expensive, risky or have long lead times. We want to establish a common based ranking system to decide what should be modeled and it's priority. Suppose we have an estimate of the cost of the item (including any multiplier indicating how many of these items are needed in a single system), call this COG. Suppose for each item we establish a risk ranking, for example, if an item is considered low risk we would assign it a multiplier, Risk=1 while for a moderate risk we assign Risk=1.5 and for very high risk we assign it a risk ranking, Risk=2. This risk ranking is somewhat arbitrary and needs to be established and used consistently. For this example the risk ranking is concerned with the risk that the designed component will not function as required thus impacting the performance, reliability or safety of the system. Finally we identify the lead time for the part. To convert the lead time to a common measure (cost, for example in dollars) we use some information such as from sales or marketing that establishes the potential loss of sales or market penetration if the product is any period of time late to market. We can now establish a Pareto chart for the 4 components by computing for each component the following "value"

Value = Risk * (COG + LeadTime * CostOfDelayPerUnitTime)

This type of analysis allows us to include several factors in our decision making process. The above is an example and more appropriate measures can be established by individual organizations.

This calculation alone does not determine the priority ranking for the virtual prototyping activity. What should be factored into the decision making process is the cost of performing the virtual prototyping. Assume for each component one can establish the approximate modeling costs. This will consist primarily of the analysts time and costs associated with the modeling software and hardware. Normally the cost of the software and computer hardware will be added to the analysts rate, for example, averaged over a year. Call the cost of modeling component i, Cost(i), then, the index indicating the cost benefit of the analysis can be computed as

Rank(i) = Value(i) / Cost(i)   (1)

Components with the highest rank should be considered for modeling and their priority should be influenced by their Rank(i). With this system items that have high modeling Cost and relatively low Value will show up with low Rank and should be lowered in the modeling priority. In addition to this straight forward ranking one must also consider resource allocation and other details that could influence the final priority ranking. For example, even if the Rank does not justify it, an item that can be modeled quickly and gotten "out-of-the-way" may deserve to be completed sooner than the ranking indicates. Items that may tie up an analyst for a long period of time may need to be delayed or put on hold even when the Rank indicates a higher priority. The following table and chart illustrate the use of this priority ranking system.

Table 1 – Hypothetical Value Ranking Data for Modeling Activities

Component/ Assembly	Risk	COG	Lead Time	Cost of Delay	Modeling Cost
1	1.	$60,000	8 weeks	$10,000 / wk	$6,000
2	1.5	$30,000	4 weeks	$10,000 / wk	$5,000
3	2.	$30,000	2 weeks	$10,000 / wk	$5,000
4	1.5	$20,000	2 weeks	$10,000 / wk	$3,000

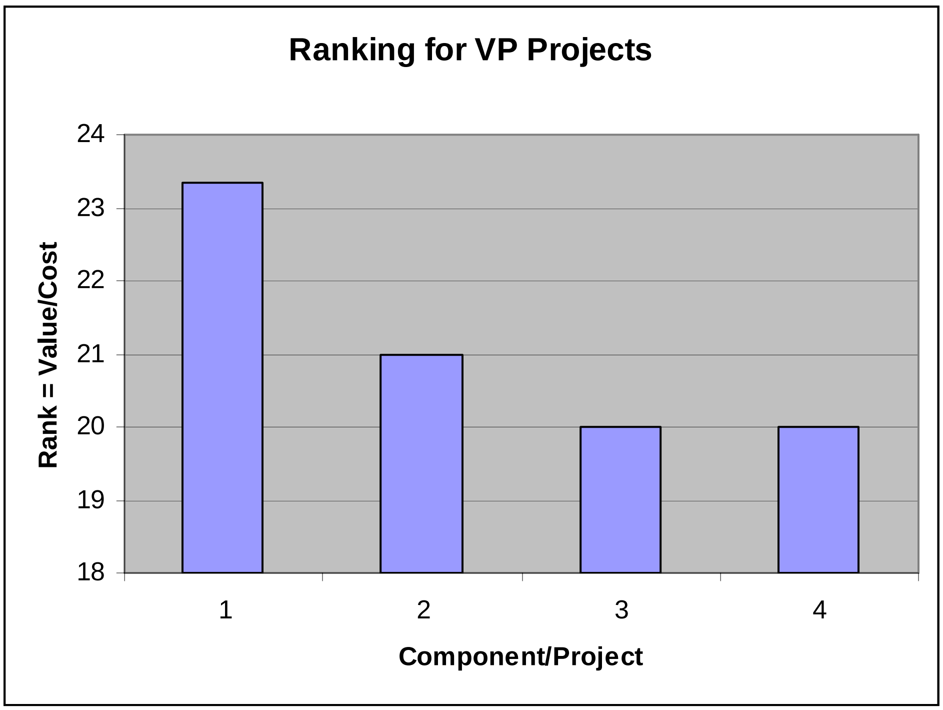

Figure 1 – Pareto Chart Ranking Various Potential Virtual Prototyping Activities

Figure 1 applies Equation (1) to the data of Table 1. As can be seen the higher cost long lead items rank higher using this approach assuming that the modeling costs is not significantly different from the second tier items. A high risk item (Component/Project 3) ranks equivalent to a moderate risk item which can be modeled at a much more economical rate (Component/Project 4). Thus some judgment is still needed to help decide between these two options, one might lean towards prioritizing Component 3 higher due to the higher COG and higher risk, even though the modeling is substantially more costly compared with Component 4.

Individual Component Cost Benefit Analyses

An alternate way to establish the cost benefit of individual components is to study the effect of re-designs. The theory here is that the virtual prototyping should help avoid redesigns. This can be established post-priori on some component development projects and then once a representative number of cases have been established it can be used to guide modeling priorities. The approach is to establish the cost of the component development in terms of material costs, engineering costs and testing/verification costs. Then an approximation must be made if something went wrong with the initial design (assuming no virtual prototyping). The cost of correcting that problem including re-engineering, re-manufacturing and re-testing of that part is then computed. As will be seen in the example here, if only 1 design iteration was avoided a benefit was shown when considering the additional cost and schedule associated with the virtual prototyping activity. If more than 1 design iteration was performed in the absence of virtual prototyping then even greater saving are realized through the use of modeling. The example given here is from a semiconductor equipment component development activity and is as follows.

Table 2 shows the activities, schedule time, elapsed time and associated costs for development of an average complex assembly. We total the design, manufacturing and testing costs then show the costs associated with performing 1 man month of virtual prototyping on this assembly. Table 2 shows that the virtual prototyping constitutes about 10% of the total project cost. Table 3 assumes that the initial design does not function as anticipated and needs to be redesigned, remanufactured and retested. Table 3 shows that the cost for 1 additional design iteration is about 30% of the first design.

Table 2 – Cost and Time Estimates for First Design Cycle (Design Iteration 1)

Activity	**Time/Schedule (1st Iteration)**	**Elapsed Time**	**Costs ($)**
Brainstorm/Design Decision Process	1 man week	1	2400
CAD Model & Drwgs	3 man months	6	28800
Manuf Assembly	6 weeks manuf + 2 man wks assbly	6	39800
Testing & verification	2 man months	4	19200
Sub Total		**17**	**90200**
Modeling	**1 man month**	**3**	**10560**

Table 3 – Cost and Time Estimates for Subsequent Design Cycle Iterations

Activity	**Time/Schedule (Each Iteration)**	**Elapsed Time**	**Costs ($)**
Brainstorm/Design Decision Process	1 man week	1	2400
CAD Model & Drwgs	1 man months	2	9600
Manuf Assembly	6 weeks manuf + 1 man wks assbly	6	12400
Testing & verification	3 man weeks	3	7200
Sub Total		**12**	**31600**

If the component is designed adequately in the beginning as in Table 2 the virtual prototyping appears to add about 10% additional cost. As can be seen from this example, if the virtual prototyping avoids only 1 subsequent design iteration then the cost savings associated with the virtual prototyping work is approximately $20K. This corresponds to a ROI for this activity corresponding to 200%. Figure 2 expands on this analysis and includes the effects of multiple design iterations and shows both the effects of cost and time. It shows that with accurate virtual prototyping avoiding 1 extra design iteration saves $20K and 12 weeks of schedule time. If one avoids multiple design iterations the saving is even larger. If one avoids 2 extra design iterations the savings are $50K and 24 weeks of schedule. Even though this analysis assumes ideal conditions (that using the virtual prototyping gets the design correct on the first design iteration) it non-the-less shows the strong savings associated with avoiding subsequent design iterations. Even if modeling was required in subsequent iterations the savings associated with avoiding say 3 or 4 design iterations is still substantial.

The skeptic might point out that if one stills requires several design iterations (even with the use of virtual prototyping) that the subsequent costs are even higher than if one abstained from virtual prototyping altogether. This of course points to the need for competent analysts using accurate modeling methodologies thus providing reliable design direction. This leads one to possibly prefer a centralized modeling organization where experience and high standards of accuracy are promoted and fostered.

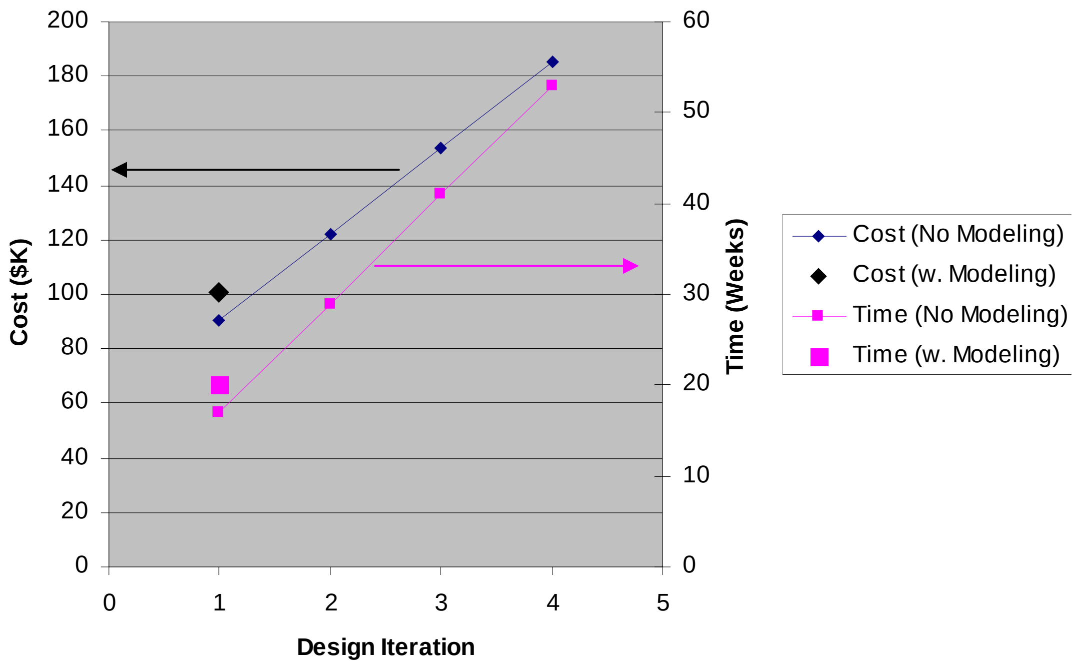

Figure 2 – Cost and Elapsed Time for Initial Design (Iteration 1) and Subsequent Redesign Iterations

How Much Virtual Prototyping is Optimal?

The last question regarding "How Much?" virtual prototyping or modeling is appropriate is somewhat more difficult. The previous analyses allow us to rank the modeling activity and show cost benefits for certain projects. However, the ranking process can be used on as many components as one desires' thus trending in the limit of "modeling everything". Certain industries trend in this direction as cited previously and is probably caused by the volume of units that are produced or other factors such as safety or regulation. In extremely high volume production situations the costs associated with a mechanical or structural failure can be devastating. What about moderate or low volume production situations? Costs of failures or poor performance even in low volume production situations are more than just warranty costs and down-time. In Reference 2 we gave some idea as to the number of wafer produced in a typical fab and by a typical semiconductor processing tool and showed that fabs are extremely sensitive to down time and tool unavailability.

One needs to at least satisfy the development needs of current C&F and design phases of product development (PD) work. Once the components and virtual prototypes have been prioritized then the "must have" items need to be established along with associated schedules. Resources able to complete the "must have" items within the schedules that are required are needed. Then one decides whether second tier virtual prototyping models can be supported and if the anticipated schedules are acceptable. In addition to these PD activities other on-going projects such as CIP of mature products need to also be prioritized and treated similar to the PD activities. The ultimate decision as to whether to add resources to support more virtual prototyping is probably best based on first satisfying the "must have" activities using the first "Value" based ranking described above along with required schedules. After the "must have" activities are satisfied, then, the second methodology (Individual Component Cost Benefit Analysis) can be used to decide whether additional virtual prototyping activities can be economically justified and whether or not to support those activities through increased resources. Additionally return on investment (ROI) analyses as described in Reference [3] can also be used to help make business decisions regarding virtual prototyping resources.

At Novellus we have most virtual prototyping performed by a central group that services multiple business units (BU's). Thus needs of each of the BU's are identified, prioritized and rolled up in order to establish appropriate resource levels. While the centralized concept for virtual prototyping has draw-backs, the strength is that it more easily adjusts to changing needs by allocating more resources towards appropriate BU activities while removing resources from other BU's whose current product development activities are low. It allows optimal analyst allocation based upon modeling specializations so that any given BU can receive the highest level of expertise addressed to their particular issue. The key leanings and techniques developed for difficult modeling tasks are captured and retained in this central group thus improving accuracy and efficiency of future virtual prototyping activities. Finally it provides a natural cross-fertilization where designs and solutions used in one BU can be identified and recommended as potential solutions for similar problems in other BU's.

Intangible Benefits of Virtual Prototyping

While the majority of this discussion is to help quantify the financial benefits and identify a strategy for optimally allocating virtual prototyping resources, one must also realize that certain intangible benefits also exist. An intangible benefit is something like product differentiation, wherein one can establish that a product clearly is different from a competitors' product in a good way. This is often needed when attempting to penetrate a product market. Virtual prototyping can often be used to establish such product differentiation through modeling. For example if publicized specifications exists for a competitors' product and one can show through modeling and virtual prototyping that your product exceeds those specifications then this can be used to help differentiate the product.

Another somewhat intangible benefit of virtual prototyping is displaying a strong engineering and technology capability for the organization. Many potential customers are favorably impressed by modeling and virtual prototyping activities that demonstrate companies capabilities and provide fundamental insight. This is actually seen today in many consumer product advertisements where the technology behind the product is showcased. It's intangible but seems to be established in the advertising arena as a positive factor in purchase decisions.

References

[1] Design Prophet, Lean Design Course Notes, Munro & Associates, Inc., 2001

[2] Woytowitz, P.J. "Interdisciplinary Analysis as a Requisite for Virtual Prototyping of Semiconductor Processing Equipment," MSC.Sofware 2004 Americas Virtual Product Development Conference, Huntington Beach, CA., October 2004.

[3] How to Grow Your Sales and Profits by Using Simulation, MSC.SOFTWARE White Paper.