Resource Downgrading*

Ertunga Özélkan
Engineering Management Program
The William States Lee College of Engineering
The University of North Carolina at Charlotte
9201 University City Boulevard Charlotte, NC 28223-0001
Tel: 704-687-4990 Fax: 704-687-2352
E-mail: ecozelka@uncc.edu

Metin Çakanyıldırım
Operations Management
School of Management
The University of Texas at Dallas
P.O. Box 830688, Richardson, TX 75083-0688
Tel: 972-883-6361 Fax: 972-883-2089
E-mail: metin@utdallas.edu

February 28, 2004

Abstract

The aim of this paper is to develop models for managing inventory of resources that can be downgraded for some other purpose after being re-used a number of times and before they are declared unsuitable for their intended purposes. This scenario occurs in several industries including (i) test wafer management in the semiconductor manufacturing where high grade wafers are downgraded to lower grades, (ii) in logistics where a long-range hauling truck is converted to a local hauling truck after a certain mileage, and (iii) without loss of generality resource upgrades such as promotions in personnel management can be treated under the same category of problems as well. The typical decisions are the quantity of resource to purchase, to hold, to scrap and to downgrade at different decision periods. We use a network based structure to formulate the problem.

Keywords: Downgradable resource, inventory management, semiconductor manufacturing.

1 Introduction

In this paper, a new research area related to resource downgrading is introduced. Although the resource downgrade problem is generic and has applications in different industries, our initial motivation stemmed from the test wafer (TW) management in semiconductor manufacturing. Therefore, the semiconductor case is described below to illustrate the problem dynamics:

Semiconductor manufacturing requires TWs for the qualification of various tools and processes. Frequent process monitoring through send-ahead test wafers is required to ensure the tight tolerances dictated by high complexity [1]. The TW process ensures that timely adjustments are made to the tool and chemical settings, reducing the scrap rate of production wafers. TWs become especially important for new fabs and during new product introductions when engineering tries to ensure that the tools and processes are fully reliable for regular production.

Besides the quality aspects, the cost of new test wafers, the impact of TW usage to tool capacity and the space requirements make intelligent TW management extremely important [2]. With ever increasing process complexities and transition to 300 mm, the testing cost is increasingly becoming an area of focus [3]. As reported in Popovich et al. [4] for the Motorola case, TW consumption results in millions of dollars and there is a big opportunity to capitalize on the cost savings by properly managing TWs. A typical metric followed by the industry is the test wafer to production wafer ratio which seems to range from 0.1 to 3 with a typical value of 0.8 [4]. Based on this benchmark, and based on an average cost of $35 to $120 for a 200mm TW, Foster et al. [5] estimated the annual TW spending as $7.8 to $20 M for a typical semiconductor fab of 3000 production wafer starts per week.

From modeling perspective what makes TW management an interesting problem is the TW lifecycle. A TW is downgraded into a lower grade TW after being used a number of times on the same qualification type. When a TW cannot be downgraded to another type of wafer, the TW is scrapped. Therefore, the typical decisions are the quantity of TWs to purchase, to hold, to scrap and to downgrade. Each downgrade can require different preparation and resources creating a specific cost structure.

Our objective in this paper is to formulate a mathematical model to optimize the usage of resources (e.g. TWs) and accordingly drive down the associated costs. The model identifies the resource management plan consisting of optimal purchase of new resources, downgrade of resources from one to another and storage of resources while the customer demand is met and additional business requirements such as allowable downgrades between certain resources and lot sizes are satisfied.
2 Resource Downgrade Model

In this section, we provide a discrete time formulation for resource downgrading over $T$ time periods. Only “indirect” resources are considered. These resources are not consumed by the processes however, they wear out slightly with each process. We suppose that there are $N$ classes of resources. Resource classes can be constructed by grouping processes that require the same (or very similar) resources.

A priori to the planning, number of resources required to perform a process(es) is determined and indexed by $n$, $1 \leq n \leq N$ and $t$, $1 \leq n \leq T$. These requirements are based on the process levels and are called the demand:

- $D^t_n$ is the number of resources required to qualify process class $n$ in period $t$.

The same resource can be reused over and over for a process as long as it is maintained appropriately after each use and it meets the required specifications. We define the age $r$ of a resource with regard to a resource class. Each resource class has a predetermined life time $R_n$ for its resources. This life time indicates the number of times a resource can be used for processes in that class before downgrading becomes necessary. The expected life time for each class $n$ is denoted by $R_n$, then $0 \leq r \leq R_n$. A resource with $r = 0$ is not used at all whereas a resource with $r = R_n$ cannot be used in class $n$ anymore so it must be either scrapped or downgraded. Depending on the resource levels at other classes, economic analysis can indicate downgrading a resource before its life time expires.

In practice, the resource classes can be ordered for downgrading purposes. For $1 \leq m < n \leq N$, a resource of class $n$ cannot be downgraded to class $m$. In this case, we say that class $m$ is higher (requiring higher quality resources) than class $m$. For $1 \leq m < n \leq N$, downgrading from $m$ to $n$ may not be possible or may cost too much. It is not necessarily true that resources of class $m$ can always be downgraded to class $n$. Actually the ordering of classes is only partial; there can be two classes without any downgrading relationship between them.

In our model, without loss of generality, we presume that in any time period $t$, resources of class $n$ are first collected at a downgrade pile $P(n, t)$ before being downgraded to lower classes. Resources put into pile $P(n, t)$ lose their age information, which is not necessary for our model. This is because a resource downgraded to class $n$ always starts with $r = 0$ and life time $R_n$ irrespective of its past
history. If a resource cannot be used for any of the processes then the resource must be scrapped. New resources can be brought in at any quantity and in any time period.

We define cost parameters for our model:

- \( p_{tn} \): The price of a new resource of class \( n \) in period \( t \). The price for resources can differ from one period to another. Typically, the resource prices in a given period are nonincreasing in \( n \).

- \( h_{tn} \): The inventory holding cost of a resource for a period. This cost depends on the class of the resource via \( n \). It may vary with time when \( p_{tn} \) does so.

- \( c_{mn}^t \): The cost of downgrading a resource from class \( m \) to \( n \) for \( 1 \leq m < n \leq N \). For example, in case of semiconductor manufacturing, downgrading requires etching off the surface of TW. The amount of etching depends on the current class \( n \) and the desired class \( m \) after downgrading.

In our formulation, the cost of usage is irrelevant for resource planning because it is proportional to the given demand \( D_{tn} \). The total relevant cost in resource planning is the sum of resource buying, holding and downgrading costs. Our formulation basically strives to minimize total costs such that enough resources are available for all processes in all time periods. It needs to determine how many resources are bought, used, held, downgraded and scrapped so the decision variables are:

- \( b_{tn} \): The number of class \( n \) resources bought at the beginning of period \( t \).

- \( u_{tnr} \): The number of class \( n \) resources of age \( r \) used in period \( t \).

- \( s_{tnr} \): The number of resources stored in class \( n \) of age \( r \) from period \( t \) to \( t + 1 \).

- \( g_{tnr} \): The number of resources sent to downgrade pile from class \( n \) of age \( r \) at the beginning of period \( t \).

- \( d_{mtn} \): The number of resources downgraded from class \( m \) down grade pile \( P(m,t) \) to class \( n \) at the beginning of period \( t \).

- \( e_{tn} \): The number of resources scrapped from class \( n \) downgrade pile \( P(m,t) \) at the beginning of period \( t \).

The order of events in a period is as follows. First we buy new resources and assume that they are delivered instantenously. Then we decide how many resources to downgrade from each class. It
is conceivable that we downgrade a resource from class $m$ to class $n$ without using it for a class $m$ process so that we immediately have enough resources in class $n$. Next we split available resources at each class into two: the inventoried and used resources. Inventoried resources stay in the same class with their age unchanged and passed to the next period. On the contrary, used resources’ ages increase by one. If the age reaches the life time, the resource must be downgraded. Otherwise, the resource remains in the same class.

Although at the first glance the resource downgrading problem resembles a network problem, upon careful examination one finds additional side constraints which result in an integer programming (IP) problem. Nevertheless, for ease of exposure and for further analysis, we present the model in Table 1 as a network problem with some side constraints. In this table, we define the resource downgrade network with nodes primarily for downgrade pile and resource classes, while define arcs primarily for decision variables. Note that the side constraints are resulting from the usage of resources with different ages to satisfy the demand. In other words we need to consider the aggregate usage flows coming from various nodes of a class. This is not possible to represent in a network framework without loosing age information.

3 Summary, Conclusions and Future Research

After defining resource downgrading problem a network based discrete time model with side constraints has been proposed. Due to the demand side constraints, the general problem becomes an IP problem. We believe that the proposed resource downgrade model can be helpful to decision makers to manage the downgradable resources optimally with minimal cost.

Some of the future research directions include investigation of specific cases under which the model simplifies into a “pure” network structure as well as those cases in which additional business requirements are incorporated. Besides model extensions, a numerical study can certainly provide additional managerial insights. One can also suspect that as the number of resources increase the IP problem might run into computational issues. At that point, it might be possible to develop some heuristics which can hopefully result in lower cost and shorter run times.
**NODES:**

- Source Node $B$.
- Class Node $(n, t, r)$ for class $n$, age $r$ and time period $t$, exists if $1 \leq n \leq N$, $0 \leq r \leq R_n$, and $1 \leq t \leq T + 1$.
- Dowgrade Pile Node $(n, t)$ for class $n$ and time period $t$, exists if $1 \leq n \leq N$ and $1 \leq t \leq T$.
- Scrap node $S$.

**ARCS:**

- Buy Arc $(B, n, t)$ from Source Node $B$ to Class Node $(n, t, 0)$ with flow $b_{nt}^t$ and cost $p_{nt}^t$ per unit of flow.
- Use Arc $(n, t, r)$ from Class Node $(n, t, r)$ to Class Node $(n, t + 1, r + 1)$, exists if $1 \leq n \leq N$ and $1 \leq t \leq T$ and $0 \leq r \leq R_n - 1$.
  
  With flow of $u_{nt}^t$ and cost of zero.
- Store Arc $(n, t, r)$ from Class Node $(n, t, r)$ to Class Node $(n, t + 1, r)$, exists if $1 \leq n \leq N$, $1 \leq t \leq T$ and $0 \leq r \leq R_n$.
  
  With flow $s_{nt}^t$ and cost $h_{nt}^t$ per unit of flow.
- Dowgrade Pile Arc $(n, t, r)$ from Class Node $(n, t, r)$ to Downgrade Pile Node $(n, t)$, exists if $1 \leq n \leq N$, $1 \leq t \leq T$ and $0 \leq r \leq R_n$.
  
  With flow $g_{nt}^t$ and cost of zero.
- Downgrade Arc $(m, n, t)$ from Downgrade Pile Node $(m, t)$ to Class Node $(n, t, 0)$, exists if $1 \leq m < n \leq N$ and $1 \leq t \leq T$.
  
  With flow $d_{mn}^t$ and cost $c_{mn}^t$ per unit of flow.
- Scrap Arc $(n, t)$ from Downgrade Pile Node $(n, t)$ to Scrap Node $S$, exists if $1 \leq n < m \leq N$ and $1 \leq t \leq T$.
  
  With flow $e_{nt}^t$ and cost of zero.

**SIDE CONSTRAINTS:**

- Satisfy Demand: $\sum_{r=0}^{R_n-1} u_{nt}^t = D_n^t$, exists if $1 \leq n \leq N$ and $1 \leq t \leq T$.

Table 1: Nodes, arcs and side constraints of the Resource Downgrade Network.
4 Acknowledgments

The authors would like to thank Bryce Foster and Tefen Ltd. for sponsorship by providing insights on TWMS™.

References


