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ABSTRACT

The hard disk drive industry has been under great cost pressures. Manufacturing has achieved very high levels of efficiencies and there is hardly any room for reducing costs any further by improving manufacturing. An area worth exploring is the design of the hard drives to further reduce the costs. Modular design helps in developing designs that will be amenable to cost reductions by identifying those components that could be designed independently of the rest of the product.

In this paper we describe how modular design can accommodate technological innovations. We then relate it to the hard drive industry, and examine how hard disk drives have incorporated the technological innovations. We describe a model to determine a component's and product's modularity in a quantitative way. The index developed can then be used to allocate design resources in an efficient way.

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INTRODUCTION

In recent years modular design and modular architecture have been receiving much attention from managers and academics (See for example [1], [2], [9], [14], [15]). The renewed interest in this field is mainly due to the supposed reduction in times for developing new products. Modular design speeds up the process by enabling the designers to focus only on the component or subsystem, and not to worry about the interactions between the component and the product, as long as the component matches the interface requirements between itself and the product [14], [15].

This approach has been suggested in other areas too – software development is an obvious example. Similar approaches have been suggested for process development, and even for organizational development. [15]

There are some criticisms about this approach. One common criticism is that modular design stifles the development of radical innovation [7]. There can be no new radical products when the organization is forced to adopt modular design approaches, as the modules are strictly defined in terms of their existing interface requirements.

However, in the face of rapid technological developments, a modular approach can lead to some rapid technological innovations. This paper describes this process in the context of the Hard Disk Drives. The paper is organized into four sections. The first section describes modular design approaches. The next section discusses modular design approaches with technological improvements. The third section gives a brief description of hard disk drives, their components and their developments. The next section explores the application of modular design concepts to the design of hard drives in the face of rapid technological developments in the components. The last section examines the management implications of applying modular design approaches to the disk drive design, and other products.

I Modular Design

In recent years much attention in academia and industry has been given to modular design, though the concept itself has been around for quite some time [17]. According to some proponents modular design can help in reducing costs and time of developing new products [14]. The approach also helps in better manufacturing and vendor relations [13].

Products are comprised of discrete components that work together to produce the functionality needed by the user. In a good design with an outlook for future improvements of a product, the designer develops a product architecture or a platform. A platform defines the system of functional components of the product, and the specifications of how the components interact with each other [10], [12].

With a well-designed product platform (which has taken into consideration the potential technological improvements) the basic architecture can be frozen for a reasonable length of time. One must do a number of things to accomplish this. The basic configuration is decided based on the current technology, and the components are clearly identified. The components are further analyzed using some technological forecasting with the past trends to determine the performance capabilities of the components, their physical characteristics and interface parameters. The forecasts typically look at the next couple of years in fast changing industries like the disk drive. Based on these forecasts, some viable interface features (interfaces between components) are clearly determined.

Improvements in the product (whether for technical reasons or cost reasons) can now be made with modest design effort as all the basic features of the components and their interactions have been fully defined. This leads to faster product introductions with marginal improvements in their appearance, performance, cost or other characteristics. (See Sanderson and Uzumeri, [16], and Myer and Lehnard [12] for a discussion of developing product platforms).

Modular design can accommodate incremental technological improvements. Consider, for example, a product with a number of components and subsystems (i = 1,2,3 …N). At the time of its introduction all these components would be of a particular technology. Let us call the individual component technology of component i as T_{i1}. for ease of reference. With time, there may be improvements in some of the component technologies, giving better performance or cost. Let us call this technology T_{i2} for component i. When the new technology T_{i2} is available for component i, the firm has to decide whether to incorporate this new component technology or continue with the existing component technology. Leading firms in the market may want to adopt this new component technology and redesign the product to take advantage of the improvement. [3]. However, it is no guarantee for success, except for some bragging rights in the industry. Table I illustrates the technological development of a product with 10 components that have technological improvements at different rates over a period of time.

Whether the change required by the introduction of the new component technology can be handled by the modular design with minimum changes to the rest of the product or whether it requires a major architectural change in the product itself can only be determined after a thorough examination of the component technology and its interactions with the product performance. If such an examination reveals that no architectural changes are needed as the interactions from the new component technology are minimal or can be accommodated with minor modifications to the existing design, the component may be designed with the new technology to interface with the existing product, making all changes only to the component. Such incremental improvements can be incorporated into the product resulting in better performance, and faster new product introduction.

There may be a few other technologies available for the component's improvement. The designer's task is to evaluate each of the other technologies and determine which of them is the most appropriate. Some of the new technologies may require a major architectural change for the product, while others may require marginal changes. If a major architectural or technological change is needed, the decision is strategic, and may involve a careful evaluation of many external factors such as market demand for the new variation. Christensen [4] argues that the evaluations are not easily made by established firms as they focus on meeting their existing customers' needs, and may therefore not focus on an important trend in a hitherto unheralded technology catering to a smaller market, leading to dire consequences for the firm. He terms these unheralded technologies "Disruptive Technologies." The arguments about disruptive technologies are not universally accepted. For a brief critique see McKendrick et al [11].

Minor changes to components are known as "evolutionary changes." Over a period of time small evolutionary changes may eventually lead to changes that appear radical. Biology is replete with examples of such changes. In industrial products, however, there may be a need for a greater shift in the architecture itself after some evolutionary changes, as the technologies in the components as well as the underlying technology of the product itself may have changed radically. An example will make this clear. Consider the phonograph. Many evolutionary changes made the turntable of the 1960s a very sophisticated instrument. The technology of all components had been pushed to their limits - highly accurate motor speed, very sensitive well-balanced stylus, etc. However, the advent of a radically different recording medium technology of CDs necessitated the development of a radically different new player, and the phonograph had to be discarded.

In evolutionary changes over shorter periods of time, after a number of changes have taken place some of the earlier components and subsystems may not be capable of handling the marginal evolutionary improvement in some component. Usually in a modular design approach most components are designed after taking into account the forecasts of technologies of other components that interface with them. However, at a later time the interfacing components may reach a stage where they have changed dramatically requiring new configurations for the components. There is a need then to redesign a larger proportion of the product than suggested by a simple evolutionary change in one component. Therefore, even though the product may have been modularly designed, at some stage the modularity may have to be scrapped and a new design developed. In the hard disk drive industry, though the basic technological principles have not changed, the form factors have changed requiring complete redesign of the product.

An interesting question is when one should go for modular improvement, or a complete redesign. A complete redesign is fraught with risks, while modular improvement is relatively safe in the short run. There are no easy answers. Whether one should even consider a complete redesign is also hard question. Some issues of importance for this decision are the costs of making the change in relation to the overall design effort, and the expected improvement in some measure of performance. These issues are explored in the next section.

Market dynamics further complicates the picture. If the competition has introduced a newer redesigned product and is attracting attention from the market, then one may have to follow even if it looks as an unprofitable proposition in the short run. An interesting situation now is the recent introduction of Apple’s new Imac. This is a radical departure from the conventional personal computers – a hemispherical base containing all the works, a flat screen attached to the base by a universal joint which lets it be moved and positioned to suit the individual. This design is a radical change, while most PC makers appear to be introducing incremental changes based on modular design approaches. If the new Apple design takes hold in the market, the PC makers may have to come up with some dramatic changes.

Well-defined interfaces do not necessarily result in independent relationships between components in a product. The product architecture may be such that some components may be interdependent in their interactions with each other. The degree of interdependence is a measure of how the components and the design are coupled – tight or loose. In a loosely coupled system, the interactions between components are independent. A modular design implies a loosely coupled system, where the component interfaces are specified so that substitutions in the components can be made without making major changes to the product design itself [9]. This concept was first explored by Starr [17], who provides a matrix representation of the components and their variations, so that a vast number of product variations can be produced by mixing different component varieties. See Table II for an example.

A product with a high degree of modularization can then be defined as one in which the majority of components are independent or loosely connected [9]. A modular component's redesign does not involve extra engineering effort to modify the designs of other components. But what is a modular component or modular product? There have been no attempts to define modularity of either a component or product in a quantitative manner. Appendix I discusses this issue in more detail and develops a measure for modularity [1].

Most product designs tend towards modular systems as the product matures. As the understanding of the product, its components and their interactions increases, it is possible to define the necessary interfaces completely so that a component's design could be independent of the product design. This approach is being increasingly adopted in the automobile industry, where the principal auto designers ask the vendors to design the component independently after giving them the interface specifications [13]. In these instances it is assumed that there are no other interactions except those that are defined fully by the interface between the component and the product. Such independence between components and subassemblies can lead to better concurrent engineering practices.

From the preceding discussion, we see that modular design provides many advantages –

1. Larger variety of products - new combinations of components can produce a larger variety of products. For example, the automobile can be produced in millions of variations, as most of the components are modular.
2. Faster product introduction to market - concurrent engineering approaches can be easily adopted for new product development as the interface between each component is fully specified, reducing the overall development time.
3. Incremental technological improvements and faster upgrades - by having interface specifications that foresee expected technologically improved components, new upgraded products can be rapidly introduced into the market as soon as the new component technology becomes available.
4. Lower costs of design, production, manufacture and distribution - since many variations can be produced with very little additional costs, by adding components that differentiate products in a later stage of manufacture, inventory and handling costs decrease with the reduced variety of parts [6].
5. Mass customization - modular design can help in developing customized products that can be produced at mass production costs [2].

But there are disadvantages too. We can see from the foregoing discussion that modular design focuses on incremental advances. Major technological breakthroughs will be highly unlikely, as management may want to avoid the extra risk and costs associated with them. It can undermine the innovation process by reducing the opportunities for breakthrough advances [7].

In the next section we discuss modular design and how it can be applied when there are technological improvements.

II Modular Design and Technological Improvements

At the start of a design cycle, the design engineer has a number of options for the architecture of the product. One of the common options pursued is to define each component separately so that its design may proceed independently. This approach is usually called the modular design approach. In this approach, the specifications for each component are developed and firmed up. These specifications take into account the physical features of the component, and the interface requirements in terms of the transfer of energy and information between the component and the rest of the product. Once these are set, the component designer is free to design the component to meet the requirements of the interface specifications only, and not be concerned with the rest of the product.

The design of a component is affected by the components that interface with it. Changes in the technology of a component may affect the characteristics of the interfaces. In a modular component the interfaces are specified in a robust manner such that a minimum or no redesign is required for modest or sometimes larger improvements in the technology of components that interface with it.

When there are rapid technological improvements in component and product technologies, this approach can be difficult to adopt, as the characteristics of the interface parameters may change beyond the capabilities of the component. For example, in the case of the hard disk drive, with the technological improvements in the read head, the interface parameters such as the height of the head over the surface, the speed of the platter, the rate of information transfer, the strength of the magnetic field etc. may change a great deal. If the current design of the head cannot accommodate these changes, one may have to redesign the head completely new to take into account these changed parameters.

So the question then is whether one should design the component with robust parameters such that the component need not be redesigned for some technological improvements, or to redesign the component at frequent intervals to accommodate the changes in technology not only in the component, but also in other related components. This question can be answered by considering the costs of the two alternatives.

Figure 1 illustrates the situation. Let us assume that one of the technological parameters of the interface that affects a component improves as shown by the thin line. The present level of the parameter is t_0. It is forecasted that this parameter will improve to the higher levels $t_{1,}$ $t_{2,}$ t_3 over the next few years. The traditional approach is to design the component to be capable of handling the interface technology at level t_0 but also to be capable to handle marginal increases in the technical parameter to level t_1. The cost of this design effort is c_0.

When the technology improves to t_1 (say n_1 years later) and beyond, this approach suggests redesigning the component again at a cost of c_1. At this time probably the component may have to undergo a major redesign if the other interface parameters have also changed. This will be repeated whenever the technology improves beyond the capabilities of the existing design. The next two steps are necessary when the technology reaches the levels t_2 and t_3 respectively in years n_2 and n_3. The cost curve for this approach is a step function as shown in figure 3 and are incurred at those years.

Costs of incremental design (IC) to year n_T is:

$$IC_{n_T} = c_0 + \sum_{i=1..T} \frac{c_i}{(1+r/100)^{n_i}}$$, where r is the desired rate of return.

The modular design approach suggests taking a longer view of the technology and design the component to be robust enough to accommodate the improvements in technology over a longer time horizon. The cost of incorporating such an approach will of course increase with the time horizon, increasing at a higher rate the further out one wants to accommodate. This cost, unlike the incremental costs above, is incurred at the present time. We assume that that the modular design can be made to accommodate any level of the technological parameter upto t_3. The cost curve is therefore shown as a continuous curve. Any point on the curve shows the cost incurred *at the present time* to design the component capable of handling the improvement in the technical parameter to that level.

As one attempts to make the component capable of handling a larger range of technological parameters, many other interaction effects will have to be taken into account, increasing this cost at a much more rapid rate for larger increases. The functional form is assumed to be a polynomial in time and technological level[1]. The nature of the form is dependent on a number of factors such as the pace of innovation in the component and the technologies of the interfacing components, the number of components interfacing with this component, the nature of the design effort etc. It is surmised that with highly modular products and components this function may be linear or of second degree. With less modular products and components the function may be of even higher degrees. The functional form in figure 1 is assumed to be of the second type.

Costs of modular design (MC) to accommodate technological level of the component to year n_i is:

$$MC_{n_i} = c_0 + f(t_i)$$

where $f(t_i)$ is the cost function of designing the component capable of accommodating technological improvements to level t_i. In the figure the cost of modular design to accommodate the technological improvement of t_2 is lower than the incremental approach ($c_1 + c_2$). However, if one wants the

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[1] The technological level of the interface parameter is assumed to increase linearly with time for illustrative purposes only.

component to accommodate the technology t_3, the cost is larger then doing so with incremental improvements.

The design costs are not the only ones to be considered in this decision. Other costs such as costs of changing the manufacturing process (new tooling etc.) and the manufacturing costs resulting from the design changes etc. also have to be considered. For this illustration of the approach we will assume those non-design costs to be constant for both approaches..

Using this approach, the cost based decision can be made by comparing the two costs for different time periods and determining which of them is lower.

These two costs can be compared for different levels of technological parameters, and the proper approach can be taken with regard to design. The method of analysis described here becomes more important when an OEM delegates the responsibility of designing the components to the vendor, as happens with greater frequency in the automobile industry [13].

Developing these costs is not an easy task. Many assumptions have to be made regarding the technology and its impact on other functions of the component. Estimates have to be made about the design effort involved in redesigning the component in the face of unforeseeable technological changes. With modular design it is more difficult as one has to forecast the technological parameters with a greater degree of precision. In evolving technologies that have established a pattern of improvement this task is not too hard. If there are discontinuities in the technological developments the forecasting is not so simple, and may be highly inaccurate. However, if one were to consider the time saved in introducing new technologies, this approach may prove cost efficient.

Under what circumstances should one consider the incremental approach or the modular approach? For components with very few interface connections and higher modularity, the modular approach may be the most suitable. In the case of low modularity components with highly complex interfaces the incremental approach is more suitable. More research is required in this area.

This approach is limited when the technology makes a breakthrough requiring completely different interfaces. In such situations one has to start with a new set of components and design keeping in mind the potential for improvements and designing the components to accommodate the potential improvements.

III Hard Disk Drives[2]:

Ever since the PCs started moving out of the hobbyist niche, there has been a demand for larger storage capacity. The hard disk drives provided the answer. The hard disk drive has gone through a number of changes both in size and in the technologies of the components. The earliest versions were 14 inches in diameter and were used mainly in large mainframe computers. Over the years the physical size has been decreasing. At the present time the most common size (called the form factor) is the 3.5 inch (95 mm). The 3.5 inch drive has seen an impressive increase in its capacity and performance. Starting from a modest 5-MB capacity (around 1982), the drives have increased their capacities to over 100 GB. Figure 2 shows the evolution and progress in the capacities of hard drives over the years (developed by IBM and found on its website)[3]. More capacities are on the horizon as seen in the figure.

Higher capacities of the disk drives are the result of a number of factors, the chief among them being the areal density of the coating on the platter. Areal density is the amount of information that can be stored on a square inch of the platter. Information is stored on the platter in tracks. The tracks are closely packed in concentric circles. The areal density is the product of bits per inch of track (BPI) and the number of tracks per inch (TPI). Figure 3 shows the progress in areal density. Current densities are in the range of 20-30 GB/in^{2,} and are expected to reach over 100 GB/in^2 in the near future.

During all these years the basic architecture of the hard drive has not changed much. The components that make up the disk drive have remained the same, though there have been tremendous evolutionary and some radical improvements in the technologies of the components. There has also been much integration of functions, especially the electronic parts, resulting in smaller and fewer electronic components.

An exploded view of the hard disk drive is shown in figure 4. It is essentially a juke-box with platters to hold the data and a mechanism to position the read write heads. There are as many read/write heads as there are platter surfaces. Instead of music there is data on the platters. The disks spin at very high speeds (from 5400 rpm to 15000 rpm) making the positioning of the read/write heads on the platters very critical. The major components of a hard disk drive are:

1. case and cover
2. platters with coating of magnetic material
3. spindle motor
4. actuator mechanism
5. read/write heads
6. bearings
7. hardware and software.

The case is just a metal case completely sealed to prevent the entry of any dust particles, except for a small hole called the breather hole. The case design is specific to firms, though the overall shape is

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[2] Most of the information in this section is obtained from various web sites (IBM, Seagate, Western Digital for example, and especially the PC Guide website), and from Comstock, R.L. and M.L. Workman, (1988) "Data Storage

rectangular. There are industry standards for the outside dimensions and the locations of connector pins etc. The width of the case (and the mountings) has decreased over the years – starting from 14 in., through 8 in., 5.25 in. (130 mm), and 3.5 in. (95mm). There are some special application drives that are even smaller. The most popular size currently is the 3.5 inch (95 mm). This typically refers to the size of the mountings for the hardware, and is usually known as the form factor. The diameter of the platter is related to the form factor obviously, but it can be different from the form factor value. Table III shows the currently used platter sizes for the 3.5-inch (95 mm) form factor drives.

The earlier platters (and even some present ones) were made of aluminum. In recent years they are made of glass substrate as glass provides a far smoother surface needed for the newer coating technology and the resulting higher data densities. The technology of the coating medium and, in parallel, the technology of reading and writing have improved vastly over the years. The platters are coated with a magnetic medium capable of storing information. The coatings are proprietary compounds that have seen great improvements in their capacity to hold information.

Information is stored in circular tracks on the platter's coated surface. To store more information in a given area the track density (known as Tracks per inch – TPI) and the bit density (BPI) have to increase. The product of TPI and BPI is known as the areal density (bits per square inch). Increased density produces higher storage capacities.

The earlier coating media was iron oxide (rust). Developments in the media technology and in the method of depositing on the platter have been advancing rapidly. The current media technology is known as thin film technology (TF), which allows for greater track and bit densities. Along with advances in the read/write technology, areal densities of 20 GB per square inch have been obtained

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and Rigid Disks," in *Magnetic Recordings (vol. II),* edited by Mee, C.D., and E.D. Daniel, New York: McGraw-Hill.

[3] This information is already outdated. Now there are HDDs with 150 GB capacity.

(See figure 2), and are increasing at a fast pace. Higher densities of over 100 GB per square inch are projected in the next few years.

Information is recorded and retrieved from the platter by a read/write head. In older designs there was one head that did both reading and writing. The dual function slowed the operation of the disk drive. The modern disk drives have two heads, one for reading and the other for writing. However the two heads are incorporated in one compact head unit.

There have been many improvements and innovations in the head technology over the years. The heads are capable of retrieving information in a very short time (in milliseconds) from a very dense information store.

The earlier read/write technology was known as the ferrite technology. It consists of a small ferrite piece with a coil that picked up the reversals in the magnetic flux on the surface of the disk, inducing a small electric current in the coil. This current was then interpreted as bits of data. For writing, a small current was sent through the same coil around the ferrite piece that created a magnetic flux on the coating on the platter. As the ferrite head is relatively large its sensitivity is limited and the signals are placed on a larger surface of the disk, resulting in lower areal densities and capacities. The ferrite head was replaced by thin film technology (TF) where the head was made of a thin film of magnetic material. The sensitivity of this head for reading is far greater than the ferrite head resulting in larger capacities. The underlying principle is the same as the ferrite head.

The thin film technology was the most common until a few years ago. It was replaced by the MR (Magneto Resistive) technology, which operates on a completely different principle from the ferrite head technology. In this case, the head has a special conductive material that changes its resistance in the presence of a magnetic field. A sensor detects these changes and interprets them as bits. An improved version called the GMR (Giant Magneto Resistive) technology has been introduced in recent years. The giant refers to the effect, not the physical size. It operates on the same general principles as MR but with a different design that makes it far more sensitive. Now there is talk of CMR (Colossal Magneto Resistive or more technically the Tunneling Junction Magneto Resistive) head that will be even more sensitive leading to aerial densities of 100 GB/Sq.in. or more.

The number of heads in a HDD depends on the number of platters. The platters are coated on both sides, requiring two heads for each platter. The heads are held at a very close distance from the surface of the platter, and they actually fly over the disk surface. Elaborate mechanisms are involved in maintaining the heads at a predefined distance from the surface, as well as in preventing them from crashing on to the surface and damaging the disk. Since the head is one of the costliest components some designs economize by having only one head per platter, at the cost of capacity.

The heads (consisting of both the read and write heads) are mounted on an actuator arm that lets the head float just above the platter. The arm swings over the platter and positions the head at the appropriate position on the platter. Since the heads float at a height of a couple of microns above the surface of the platter, it is critical to maintain the drive dust free.

The platters are mounted on a spindle that rotates at a high speed. Depending on the capacity needed there are one or more platters on a spindle. The spindle is supported on both ends through bearings (the clamshell design) or on one end at the bottom plate (the cantilever design). This latter design was more common as manufacturing was easier with robotic assembly. There were some vibration problems as there is no support at one end. The vibration problems have been solved by a more robust design of the spindle and the case. In recent years, with better manufacturing processes, the clam shell design (where the spindle is supported at both ends) has made a comeback.

A dc motor drives the spindle directly. Typical motor speeds have increased from 3600 rpm to 7200. Most popular speeds currently are 5400 and 7200 rpm. Some new, high performance drives (called enterprise drives) have motors running at 10,000, 12000 and even 15000 RPM. Like all components of the drive, the motor should be capable of functioning reliably over the lifetime of the HDD. There are advances in each of the components of the motor itself to increase the longevity and reliability, and to reduce power consumption, vibration and noise. The actuator mechanism moves the head across the radius of the platter. The actuator should be capable of positioning the head instantaneously at the right location where the needed information is recorded. Since there are more than one head, the actuator mechanism has to determine which head should be doing the reading/writing based on where and on which platter the information is to be found. The movement of the head over an arc is controlled by a voice coil motor similar to the voice coil in a loud speaker.

To manage all these functions there is some hardware consisting of some ASICs (Application Specific Integrated Chips) mounting on a PC board and the appropriate software. The software has become more sophisticated to keep pace with the developments in technology of the recording head, as well as the recording itself based on the coating medium. The developments in hardware through integration of functions have resulted in a reduced size of the firmware chips.

All these components are enclosed in a sealed case to protect the working parts from dust. This is very critical as the presence of any dust particles can reduce the integrity of the data. Also as the heads fly over the platter with a very small clearance, any dust particles may actually jam the heads on to the platters crashing the drive. To keep the internal pressure of the case the same as the external pressure, there is a small filtered vent (breather) hole at the top of the case.

From the above brief description it is apparent that the basic architecture of the HDD has remained virtually the same over the years. Of course, this is like saying that the basic architecture of the automobile has remained the same since the 1920s. There have been enormous improvements in most of the components that go to make the automobile or the hard disk drive.

There have been many technological improvements in all components in hard disk drives. First the recording medium and the coating have undergone huge increases in their performance. The areal density of the recording surface has increased more than a 1000 fold. This has led to smaller disk sizes and fewer platters within the drives. Some standardization in the industry has taken place in terms of the physical size of the HDD and the platters and also the interfaces between the disk drive and the outside world – PCs and storage devices etc (IDE/ATA – Integrated Data Electronics/AT Attachment and SCSI – Small Computer Systems Interface, for example). At this time the 3.5 inch format is the standard form factor for most computers and storage arrays. The information transfer interface is either IDE or SCSI. Usually SCSI is used for the high-end disk drives.

The portable computers and Lap Tops use the smaller 2.5 inch (65 mm) drives. There are even microdrives (1”) used in digital cameras, PDAs and similar other products. The increased areal density of the platters has resulted in HDDs with fewer platters, requiring fewer heads, leading to a reduction in costs. A summary of the technological changes is shown in Table IV.

In the next section we will review modular design and its ability to incorporate technological improvements.

IV Modular Design and the Hard Disk Drive

In spite of the highly complex components in the hard disk drive, it is essentially a modular design. For this discussion, we will focus on the 95 mm form factor hard disk drive. This form factor is currently the most prevalent, and has been in the market for over 15 years. There have been significant changes in the performance capabilities, and many technological innovations have been incorporated. Table IV shows some of the major components, their technologies, and when they were introduced.

We will examine a few selected components in detail to illustrate how modular design and component technology innovations have been integrated. Table V shows the major components, the interface parameters, the items that are relatively fixed, and those that are changeable depending on technological and other improvements in the component technology. Table VI illustrates the calculations of the coefficient of modularity (See Appendix I) for a typical disk drive using the unweighted approach. It is seen that it has a relatively low C.M. If the actual costs for redesign or the appropriate weights had been used based on the relative effort needed for the redesign, the C.M. will be higher.

The case and the cover are the most modular components in the disk drive. They need only conform to the form factor specifications, and provide appropriate physical supports and openings for the rest of the components and connections.

The platters are also modular. Earlier platters were made of aluminum. IBM introduced glass platters in 1992. These platters are more reliable, smoother, can hold more data, and can spin faster resulting in a faster access time and faster data transfer rates. Though this was a new technological innovation it could easily replace the earlier aluminum/magnesium platters. It did not require any major changes in other components – spindle, read/write head – that are in immediate physical (or close physical) contact with the platters. Any future developments in this area (new material for the platter, for example) will not significantly affect the design of the drive.

Changes in the technology or design of the slider affect the design of the drive, though the effect can be incremental. The technological innovations are mostly in the improvements in the speed of travel across the disk, and in the height the head floats above the disk. Changing these parameters with the introduction of newer technology does not require major changes in the other components of the drive. But they affect the software to position the head and read data.

The actuator, which pushes the heads over the disks, is operated by a voice coil similar to the coil in a speaker. The technology has been the same for over 20 years. Improvements in this technology have been incremental leading to smaller, more robust and more reliable parts. Changes in the design of the voice coil do not significantly affect other component designs.

Next we examine the coating on the platter. The coating on the platter determines the areal density. Earlier models used brown ferrous oxide coating. However, by the time the new form factor of 95 mm came into existence, the thin film technology was prevalent, although a few firms continued with the coarser oxide film. There was no physical difference in the thin film coated platter from the previous oxide coated platter, except that the coating was thinner, denser and was able to store a larger amount of information. Finer coating using thin film technology requires decreasing the separation height between the disk and the read/write head. This separation in turn requires changes in the actuator mechanism and the suspension system.

The earlier ferrite heads designed for the oxide coating could read information stored on the thin film disks. But they could not exploit the higher density of information stored on the disk. A new head was developed, called the Thin Film Head, requiring a major engineering effort. The head and the coating go in tandem. Any changes in the coating require a change in the head to take advantage of the increased information density. Additionally, this change also affects the firmware (microprocessor) that controls the read/write operations. The head is not a modular component when the coating changes. If the coating does not change it is a modular component.

The head was redesigned to implement the Magneto Resistive (MR) technology. Further redesigns were necessary with the introduction of the GMR technology.

Firms specializing in head assemblies design and manufacture the head assemblies. Based on detailed specifications provided by the HDD manufacturer, the vendor usually completes the design of the head assembly. While developing the specifications, the HDD manufacturer can examine the two approaches described above (incremental or modular) to derive the specifications for the head assembly.

The spindle hardly affects any other function as it simply provides a support for the platters to rotate. In earlier models the spindle was anchored to both the top and bottom plates of the case (called clamshell). It provided a rigid support to the fast spinning platters and minimized the vibrations. However, the robotic assembly operations in manufacturing were not suited to align the bearings at both ends of the spindle resulting in quality problems in the earlier years. The process has improved in recent years to allow robotic assembly. One way to avoid the alignment problem was to support the spindle at one end at the bottom of the case only (cantilever). Though it was prone to produce more vibrations, it was adapted by designing a stiffer spindle to reduce the vibration problem significantly. The effort involved in making this design change involved a number of other components - the case, cover and the motor. At the present time, most disk drives have clamshell spindles as the manufacturing process has improved. Improvements to the spindle in terms of reduction in weight, and increasing stiffness can be modularly designed, without reference to the other parts of the disk. At this stage in the life of the product, the spindle can be considered modular.

The motor is an interesting component. There have been technological improvements to the motor in terms of speed, reliability and uniformity of rotation, vibration and noise. Most of these improvements are modular, except for changes in speed. Change in speed requires a redesign of the head, and the firmware for reading and writing. There have been other marginal changes to the motor. The bearings were changed from ball bearings to fluid bearings providing greater stability and reliability.

Different versions of a model of the HDD differ mainly in their capacities. The capacity of a hard disk drive is changed by simply changing the number of platters and having the corresponding heads and actuator mechanism. This is similar to the product variety suggested by [16]. We see from the above discussion that the components of the hard disk drive are, by and large, modular. Only a few components require the interactions to be studied in detail before any changes are incorporated.

The capacity and performance characteristics of the hard disk drives have been improving at a phenomenal rate though there have been no major technological breakthroughs. Most of the improvements have been made through incremental innovations in the various components. Even within a given technology the improvements have been impressive. For example, by making improvements to the thin film (TF) heads, the ability to read/write in smaller areas on the disk has increased without major changes in the coating on the platter.

It is seen that some components are highly modular (at the current time), while some are of low modularity. The highly modular components can be redesigned with much less effort, while the partly modular components need additional effort and coordination with other designers working on other components. Such categorization of the components can help management in allocating resources to maximize the return on design effort investment.

V Managerial Implications

Modular design approach is a powerful tool to develop new product variations fast. Newer component technologies can be incorporated into the products much more easily to produce better performance, and reduce costs of manufacture. It can help focus management’s attention in allocating resources for design in an optimal way.

The hard disk drive industry has consistently shown a great capability to develop new and better products at a rapid rate by incorporating the modular approach. Cost pressures have been forcing firms in the industry to constantly look for ways to reduce costs. The major focus for cost reduction has been on manufacturing. As McKendrick et al [11] discuss in their book, the cost pressures have moved the manufacturing of disk drives to Singapore. At present the manufacturing operations of disk drives are extremely efficient, making it very hard to squeeze any further reductions in costs through manufacturing efficiencies.

Cost reductions can still be achieved by attacking the design of the product. There are two approaches to design – the traditional (incremental) and the modular. In the traditional approach, some components may be redesigned to use less expensive materials, or less materials, or eliminating some items from the component, or reducing the number of manufacturing steps, and so on. In the second approach, components and subassemblies may be designed modularly so that the redesign effort is lessened whenever new incremental technologies are available.

A classification of components according to their modularity can help in allocating the appropriate amount of resources for maximum results. Full attention can be paid to the improvement of a fully modular component without getting bogged down with how the changes in the component affect the product.

The modularity of a component and product is determined by how extensive the redesign process is for the component. (See Appendix I for a more comprehensive discussion of how to evaluate the modularity of a component and a product.) After determining the modularity of the product, management has to consider whether that is an acceptable level of modularity for the product. A lower coefficient of product modularity will lengthen product innovation time, as any redesign in some components may require redesigns in a number of other components. It will also add to the cost of the design. A higher coefficient of modularity, on the other hand, will enable the company to quickly introduce new variations with less effort and cost.

For products with low coefficients of modularity, management may require the design team to increase the modularity of the product first. The focus should be on identifying the low modularity components within the product and designing them specifically to make them suitable for a wider range of future operational requirements. Taguchi methods [8] can be employed to design components that can be used with the system even with a wider range of variations. Such design efforts will help in developing a more modular architecture for the product.

Since technological innovations are relatively frequent in the hard disk industry (resulting in the increase in areal density and the capacity) component design should take into account the potential changes in the disk and head technologies and design the other components to be capable of handling the improved performance characteristics with minor changes to the component. Such an approach will increase the modularity of the component, and will reduce the costs of redesign contributing to an overall reduction in costs.

A modular product can then be improved upon almost continuously with much less effort. If the modularization of the product has been done well, such changes can be incorporated quickly and implemented in manufacturing at a rapid rate.

When evolutionary technological innovations become available, a well designed modular product would be capable of absorbing the innovation with ease. If, however, the technological innovation is significant and can cause major changes in the interface requirements of the components, there may be a need for a major integrated redesign of the product. This major redesign would examine the optimization of features incorporating the new technology. Understanding modular design, using the methods of evaluation described in this paper, and focusing on developing products with a higher modularity, will result in product designs that are nimble in the market place that can take advantage of costs and changing technologies and market needs.

V CONCLUSIONS

Cost reductions can be achieved by examining the design of the product in addition to improving the manufacturing processes. Using the modular design concepts, one can achieve significant decreases in the cost of the product, by reducing the design effort to produce better products that take advantage of technological innovations. Modular designs will also help in developing new product variations at a much faster pace, without increasing the design costs. The cost pressures on the hard disk drive industry are increasing. Obtaining cost reductions in manufacturing are very limited as the manufacturing operations have been squeezed of most of their efficiencies.

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APPENDIX[4]

A measure for modularity of components in a product:

Modularity can be at many different levels of the product's configuration. At the most obvious level, it is in the major components and subassemblies of a product. The PC is a good example. Its components – the monitor, the hard drive, the processor and other components – are designed so that many different components made by different manufacturers can all be substituted without any loss of functionality. This is the modularity at the industry level.

On the other hand modularity can be hidden or inside the product. Components to which the user has no access may be modular, while the exterior may look completely unique. Take the case of hard disk drives.. The customer never sees the inside of the drive. However, many of its components are designed using modular architecture.

Very little empirical or even theoretical work has been done in either measuring or quantifying the modular design of a product. We propose a method of measuring the modularity of a product. The measure should capture the extent of modularization in the product. We define modularization in this context as the ease with which new component designs can be introduced.

Modularity is at the component interface level. A product's components are usually attached to one another through interfaces. The interface can be very simple as in the case of a physical attachment, or it may be very complex where much information flows between the component and other parts of the product. Modular architecture suggests that the interface should be very well defined leaving the internal workings of the component to the choice of the designer. The interface may include a number of factors. [14].

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[4] This is based on Balachandra (2002) "Evaluating Modular Designs," *Decision Sciences Institute 2002 Proceedings*, San Diego: CA, Nov. 22-26, 2002.

The redesign of a modular component involves just the component itself as long as it meets the interface parameters. On the other hand the redesign of a non-modular component requires the examination and possible redesign of other components and subsystems which it may affect because of interdependencies between that component and others. These interdependencies may be hard to specify fully. The effort involved in such redesign is usually larger for components with interdependencies than for a more modular component as the design process is more complex and requires the coordination with other design groups.

This suggests that the modularity of a component within a product can be measured by the effort involved in a redesign of the component and other affected components. If the redesign involves the reworking of an existing design to achieve certain benefits (performance, cost, ease of manufacture etc.) without performing significant modifications to other components in the system, that component can be called a fully modular component. The face plate of a cell phone is a good example. Such components can be developed in a wide variety of shapes and sizes to provide a limited amount of customization without making any modifications to other components and subsystems.

On the other hand, a component, whose redesign even at a minimum level impacts on some other components or subsystems which have to be redesigned, thereby increasing the total design effort, is not modular.

There is a third category that needs to be considered. Some components can be redesigned to incorporate many incremental innovations without affecting other components. However, when the incremental innovations produce major changes over a period of time requiring changes in other components to increase the overall efficiency of the product, then this component is not fully modular. For example, in the hard disk drive, the change in the coating of the disk from oxide to thin film needed a better head than the ferrite head. The ferrite head was constantly improved (sustaining technology) to handle the increased capabilities of the thin film disk. When the capabilities of the ferrite head reached its maximum capability (or it was less efficient than other available technology - the thin film head) a redesign of the head became necessary. Therefore, such components may be called partially modular.

We present below a model for determining the modularity of a component in a product, and the modularity of the product itself..

Let the total number of components and sub-assemblies at the level of consideration in the product structure tree be N. Typically this is the 1st or 2nd level in the tree.

Let c_{ij} be the cost of redesigning component j because of a redesign of component i. (i,j € N).

Then c_{ii} is the cost of redesigning component i alone.

The total cost (C_i) of redesigning component i (including the costs of redesigning other components) is:

$$C_i = \sum_{j=1 to N} c_{ij}$$

The modularity (m_i) of a component i, is defined as

$$m_i = c_{ii} / C_i$$

With this definition, the modularity of a component is 1 (fully modular) when its redesign has no effect on the redesign of other components (all $c_{ij} = 0$ for all i ?j). The component modularity decreases rapidly with increasing costs of redesign of other components.

The modularity of a product, which we call the Coefficient of Modularity (C.M.), is an aggregate measure of component modularities of the product. It is defined as the weighted average of the modularities of all the components in that level of the product tree. The weight of a component can be assigned to reflect the component's importance in the design of the product. This can be subjective. To avoid such subjectivity, we can define the weight (w_i) of the component as the ratio of the cost of redesigning the component to the sum of the costs of redesigning all the components (without the interaction effects):

$$w_i = c_{ii} \Big/ \sum_{i=1toN} c_{ii}$$

The product's modularity (Coefficient of Modularity – C.M.) is then:

$$C.M. = \sum_{i=1toN} m_i * w_i$$

This measure is dependent on the level of the product tree which should be clearly defined, as otherwise even in simple products the number of components can be very high. The components or subassemblies should be at the same level in the product structure tree.

The information necessary to calculate the modularity of components and the product may not be easy to obtain. It may be very difficult to estimate, *a priori*, what the costs of redesign would be in other components that may be affected by a redesign of the component under consideration. In the absence of actual cost information for the redesign effort, as a first step, one may simplify the model by considering only whether the redesign has any effect on the redesign of other components. If it has, it can be represented by a 1, if no by a 0. In the formula above all the c_{ij} take values of either 1 or 0. This simpler approach usually gives a lower value for the coefficient of modularity, as some of the inconsequential components receive the same weight.

For example, take the cell phone with different colored face-plates. At the 1st level of its product tree, for simplicity, there are only three components - the main assembly, the battery, and the faceplate. The redesign of the faceplate (as introducing new colors, or having logos, etc.) will not require the redesign of the other two components. The redesign of either the battery or the main assembly may affect the design of the other two, if it involves a major redesign in the form of size or shape. This information can be represented in a matrix form as shown below. In this matrix representation, the values in the cells represent the costs (in this case the effect) of redesign of the component in the column by redesigning the component in the row. For example, cell (1,2) which has a value of 0 implies that redesigning the face-plate component 1) has no effect on the redesign of the battery (component 2). (See the table below).

Modularity of components and product
(no cost estimates)

No.	Component	1	2	3	Component Modularity	Weight
1	Face Plate	1	0	0	1	0.33
2	Battery	1	1	1	0.33	0.33
3	Main Assembly	1	1	1	0.33	0.33
	Product Modularity					**0.548**

(a 1 represent dependence of redesign, and a 0 represents no dependence)

The overall coefficient of product modularity of the product is 0.548. This assumes that the weights and effort for the redesign of all components are the same. Because of that assumption, the modularity appears to be low, as it gives a higher weight for the face plate.

If we assume cost estimates of redesigning had been used the coefficient of modularity would be higher as shown in the table below.

Modularity of components and product
(with cost estimates)

	Component	1	2	3	Component Modularity	Weight	Product m_i*w_i
1	Face Plate	500	0	0	1.0	0.077	0.077
2	Battery	500	2000	1000	0.571	0.308	0.176
3	Main Assembly	500	1000	4000	0.727	0.615	0.447
	Product Modularity						**0.694**

Though the discussion above has focused on engineering designs, the approach can easily be applied to other systems – process, organizations or software.

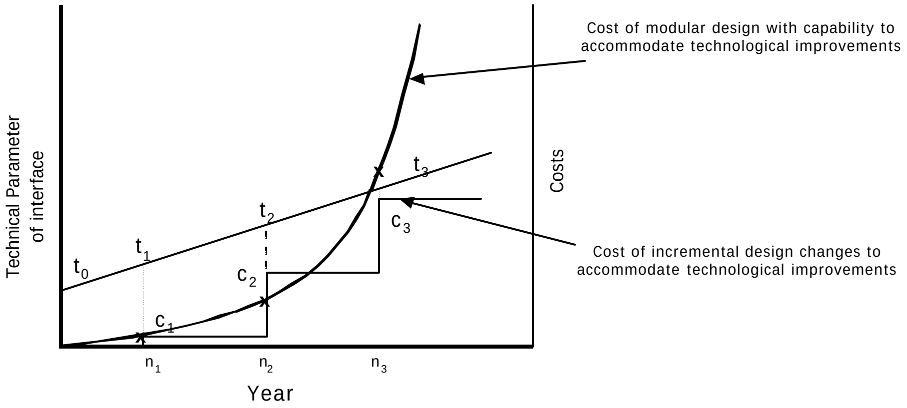
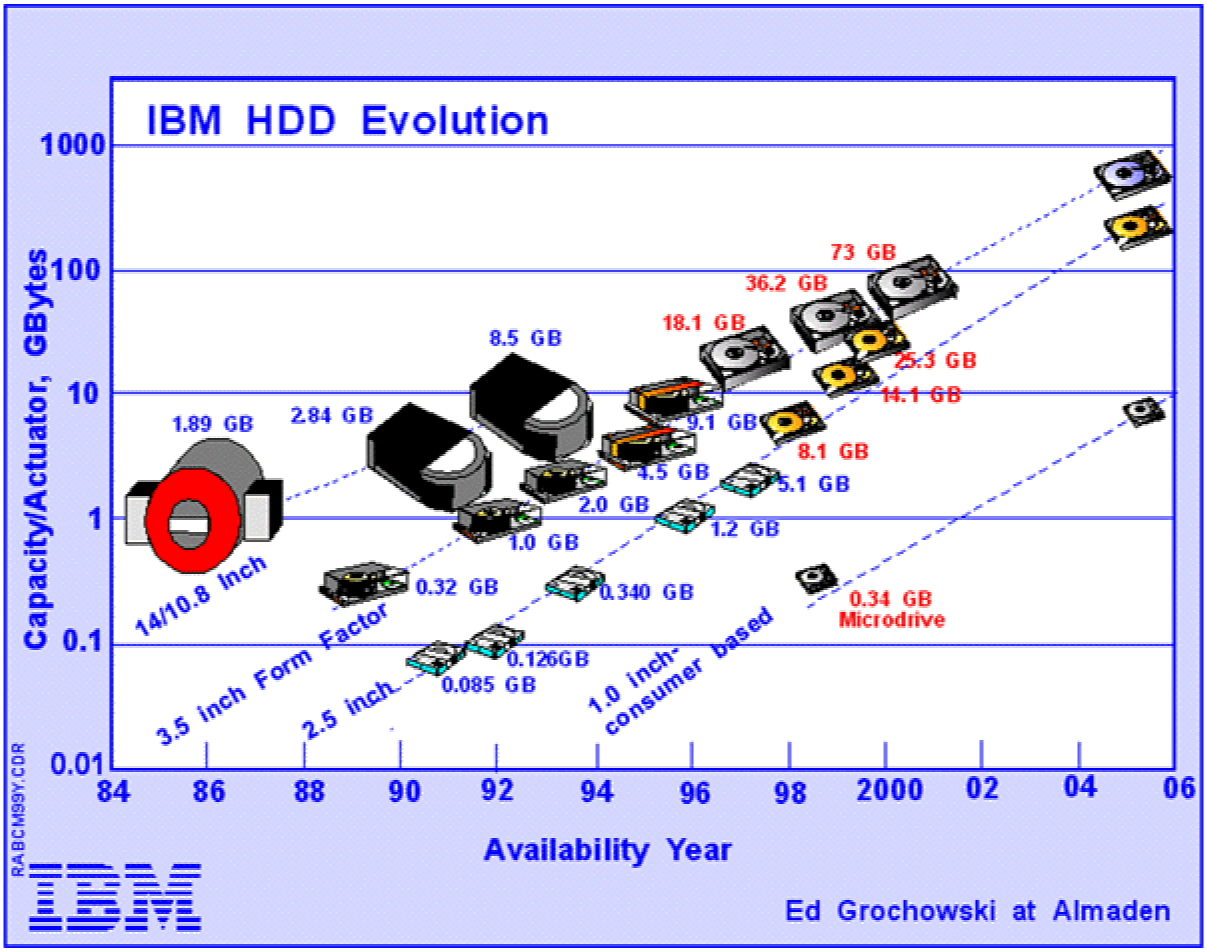


Figure 1
Costs of Incremental Design and Modular Design

Figure 2
Evolution of Hard Disk Drive



Source: http://www.pcguide.com/ref/hdd/hist.htm

Figure 3
Areal Density – History and Projections

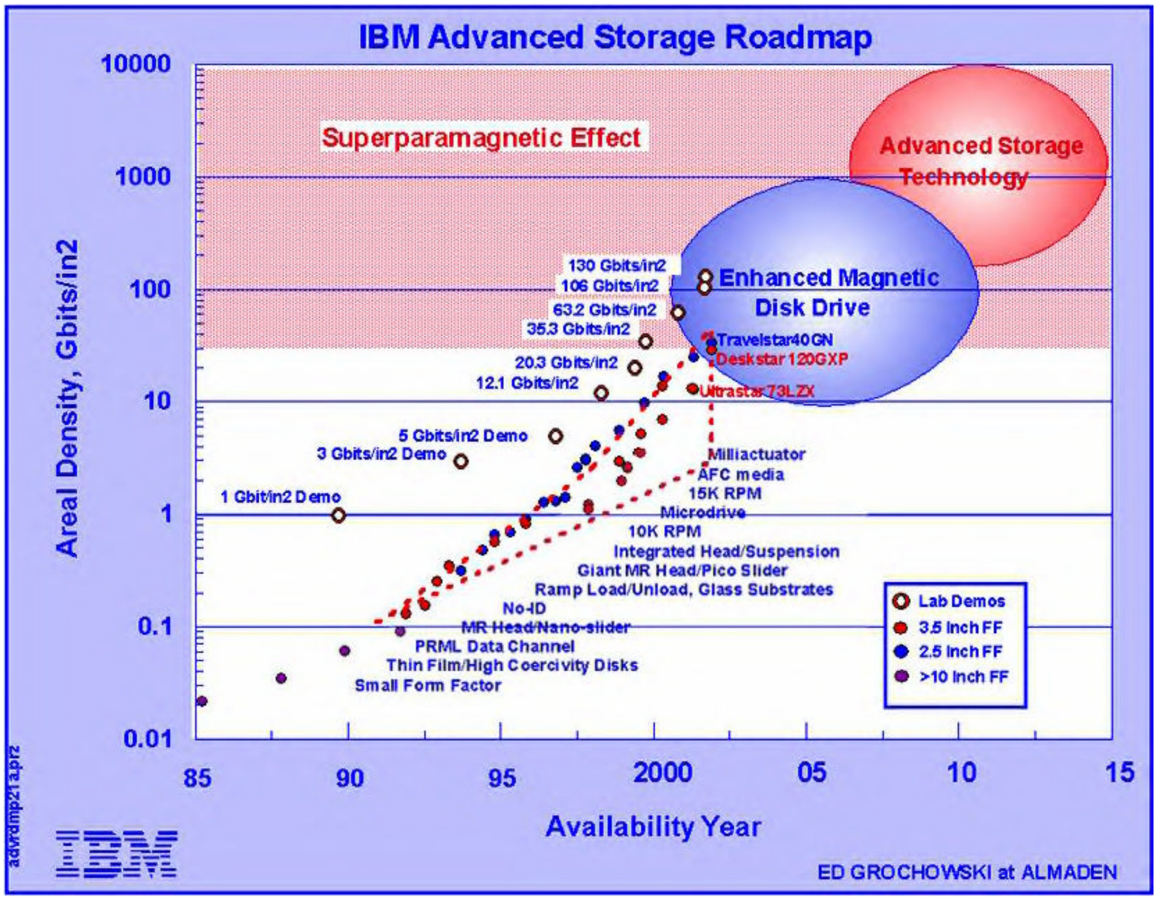
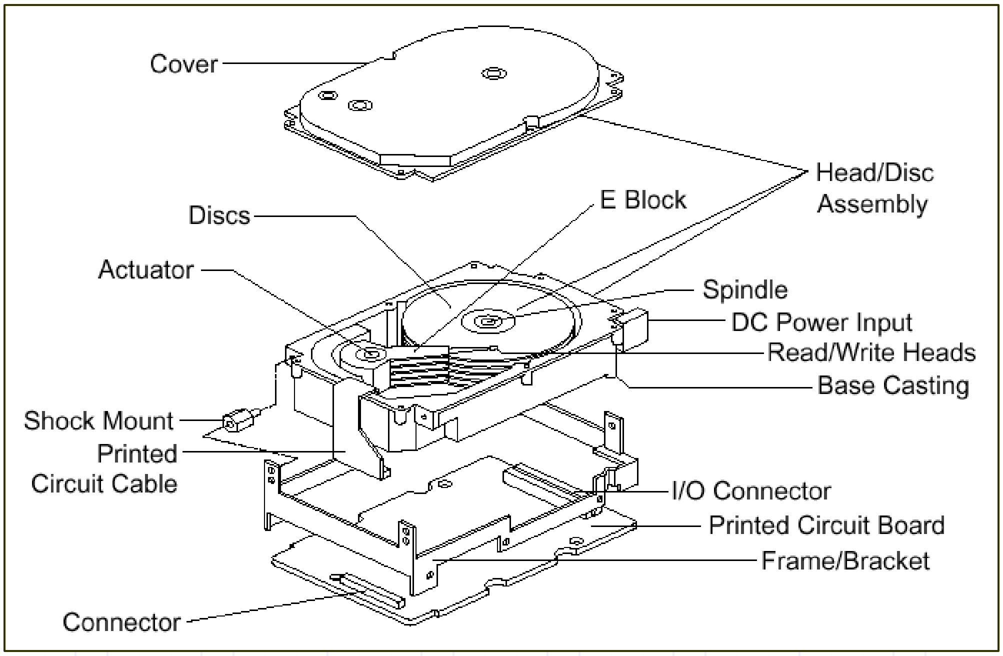


Figure 4

Exploded view of a hard disk drive (95 mm)



Source: http://pcguide.com/ref/hdd/op/over.htm

TABLE I

EVOLUTION OF A PRODUCT WITH TECHNOLOGICAL IMPROVEMENTS IN COMPONENTS

	YEAR									
Component	1	2	3	4	5	6	7	8	9	10
1	T_{11}	T_{11}	T_{11}	T_{12}	T_{12}	T_{12}	T_{12}	T_{13}	T_{13}	T_{13}
2	T_{21}	T_{21}	T_{22}	T_{22}	T_{22}	T_{23}	T_{23}	T_{23}	T_{23}	T_{23}
3	T_{31}	T_{31}	T_{31}	T_{31}	T_{31}	T_{31}	T_{32}	T_{32}	T_{32}	T_{32}
4	T_{41}	T_{41}	T_{41}	T_{41}	T_{42}	T_{42}	T_{42}	T_{42}	T_{42}	T_{42}
5	T_{51}	T_{51}	T_{51}	T_{51}	T_{51}	T_{51}	T_{51}	T_{51}	T_{51}	T_{51}
6	T_{61}	T_{61}	T_{61}	T_{62}	T_{62}	T_{62}	T_{62}	T_{62}	T_{63}	T_{63}
7	T_{71}	T_{71}	T_{71}	T_{72}	T_{72}	T_{72}	T_{72}	T_{72}	T_{72}	T_{72}
8	T_{81}	T_{81}	T_{81}	T_{81}	T_{81}	T_{81}	T_{81}	T_{81}	T_{81}	T_{81}
9	T_{91}	T_{91}	T_{91}	T_{91}	T_{91}	T_{91}	T_{92}	T_{92}	T_{92}	T_{92}
10	$T_{10,1}$	$T_{10,1}$	$T_{10,1}$	$T_{10,1}$	$T_{10,1}$	$T_{10,1}$	$T_{10,1}$	$T_{10,1}$	$T_{10,2}$	$T_{10,2}$

The product consists of 10 components. In year 1 all components are at technology 1 (arbitrary classification). In year 3, component 2 has a new technology, and is incorporated into the product. This change did not need a major redesign of other components. In year 3, new technologies appeared in components 1, 6 and 7.

Such substitutions can be made until the time when a substitution requires a major redesign of most other components.

TABLE II

Platter Sizes for 3 ½ in Hard Disk Drives

No.	**Platter Dia.**	**Typical Applications**
1	3.74 in.	Most common hard drive in PCs.
2	3.0 in,	High-end 10,000 RPM drives
3	2.5 in.	15,000 RPM dreives

Source: www.pcguide.com/ref/hdd/op/mediaSize-c.html

TABLE III

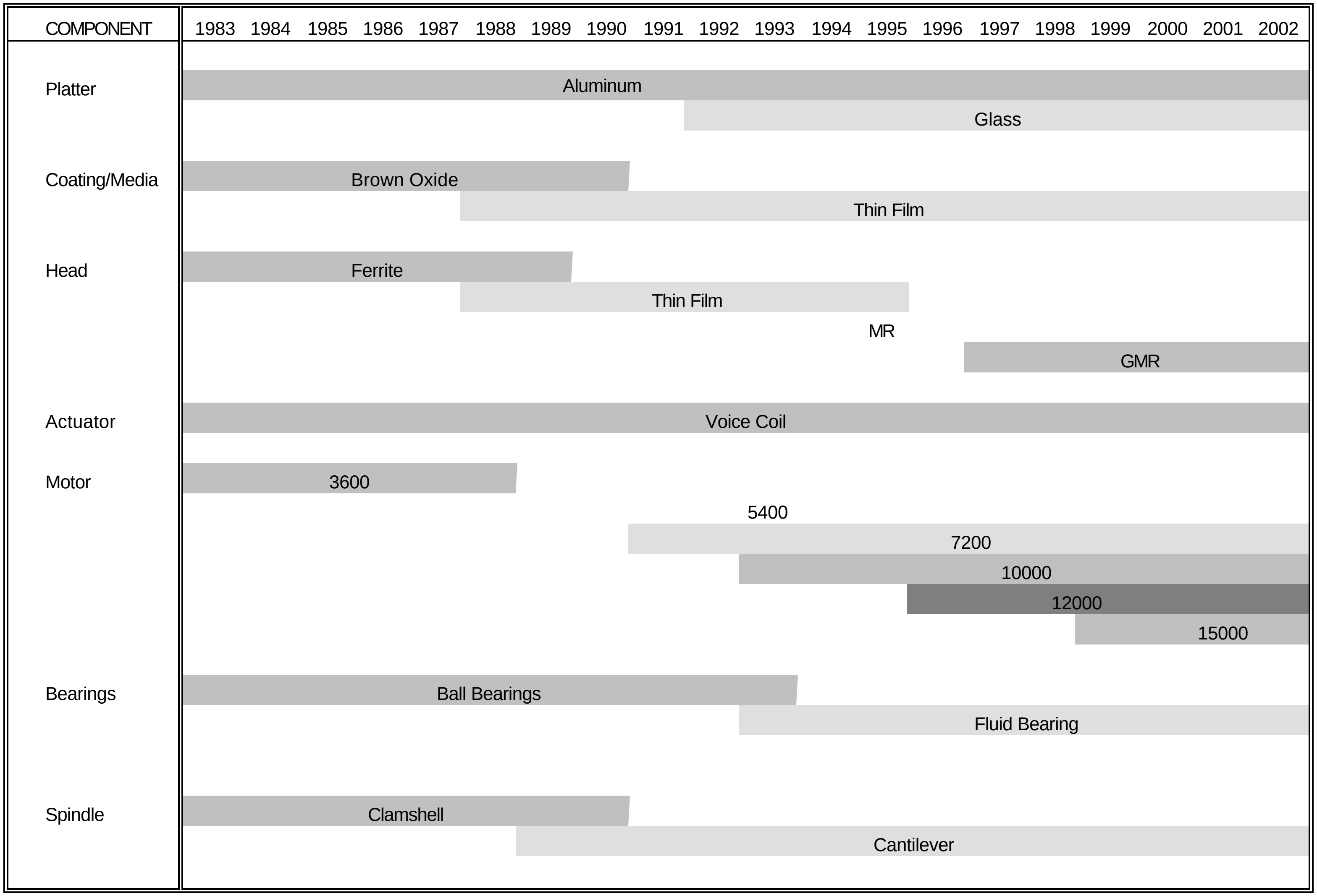
COMPONENT	Variations			
A	A_1	A_2	A_3	3 alternatives
B	B_1	B_2		2 alternatives
C	C_1	C_2	C_3	3 alternatives
D	D_1	D_2	D_3	3 alternatives
E	E_1			
F	F_1	F_2	F_3	3 alternatives
G	G_1	G_2		2 alternatives

The product needs one of each of the seven components. Each component has a number of alternative designs as shown. With this set of variations in components a total of 324 (3*2*3*3*1*3*2) varieties of final product can be produced.

TABLE IV

Component Technologies

95 mm Hard Disk Drives



Derived from Data Trend Reports on Hard Disk Drives.

TABLE V
COMPONENTS OF A HARD DISK DRIVE AND THEIR INTERFACES[5]

No.	COMPONENT	INTERFACE	FIXED PARTS	CHANGEABLE PARTS
1	Case	Size, shape, locators, mountings	All for a given form factor	Minor
2	Cover	Size, shape, locators, mountings	All for a given form factor	Minor
3	Platter	Size, information transfer mode	Size	Information transfer mode
4	Coating	Information transfer mode		Information transfer mode
5	Read Head	Size, attachment to actuator, attachment to write head, information transfer mode, height above platter	Size, attachment to write head attachment to actuator,	Information transfer mode, height above platter
6	Write head	Size, attachment to actuator, attachment to read head, information transfer mode, height above platter	Size, attachment to read head, attachment to actuator	Information transfer mode, height above platter
7	Actuator	Size, speed of movement, damping characteristics	Size	Speed of movement, damping characteristics
8	Motor	Power input, spindle size, speed	Spindle size	Speed, power input
9	Bearings	Size, load capacity	Size	Load capacity
10	Connectors	No. of connections and type, speed of data transfer	No. of connections	speed of data transfer
11	Software	Seek speed, speed of coding, read and write		Seek speed, speed of coding, read and write
12	Power supply	Voltage, current	Voltage	Current

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[5] Not a comprehensive list.

TABLE VI
COEFFICIENT OF MODULARITY
Hard Disk Drive*

No.	Component	1	2	3	4	5	6	7	8	9	10	11	12	Comp.Mod	Wt.
1	Case	**1**	1											0.5	0.083
2	Cover	1	**1**											0.5	0.083
3	Platters			**1**	1	1	1		1					0.2	0.083
4	Coating			1	**1**	1	1	1						0.2	0.083
5	Read Head				1	**1**	1	1						0.25	0.083
6	Write Head				1	1	**1**	1						0.25	0.083
7	Actuator			1		1	1	**1**						0.25	0.083
8	Spindle motor			1		1	1	1	**1**	1			1	0.17	0.083
9	Bearings								1	**1**				0.5	0.083
10	Connectors					1	1	1			**1**			0.25	0.083
11	Software/Hardware					1	1	1				**1**		0.25	0.083
12	Power supply	1						1	1		1	1	**1**	0.17	0.083
														3.49	0.083
	Coefficient of Modularity													**0.29**	

Coefficient of Modularity = 3.49* 0.083 (as all weights are equal)
= **0.29.**

*Based on discussions with a Design Executive of a HDD manufacturer. Only the impact of redesign is considered, and not the costs of redesign; the weights of all components are assumed to be equal. The design of the disk drive, by this measure, has a low modularity coefficient.
The coefficient of modularity could be higher if the actual weights are included.

The modularity can be increased by reviewing components with lower component modularity. In this case, it appears that the motor and power supply are the leading contenders. Next are the Platters, Coating, Connectors and Software. Looking at the nature of the components we have identified, it appears that these components should be made more robust, and independent so that they do not need to be redesigned as often as they are done now.
The actual components to be considered for a modular redesign could be different based on actual costs of redesign. The weights as well as the component modularity will change, resulting (usually) in a higher coefficient of modularity for the product.