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# Quantifying the emergence of modularity trap

# Case of Hard Disc Drive industry.

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#### Abstract:

With increasingly competitive markets and technological advances driving the world towards a "converging commonality", adopting "modularity" seems to be more and more appealing for companies and businesses wishing to adapt to various market conditions and to benefit from decentralized innovations. However, the decision to adopt a modular product architecture often comes with a need to deeply analyze the current market state and to predict the future technological shifts. Thus, minimizing the risk of falling into the "organizational traps" that comes in as a reason to a "misalignment" between the product architecture and the organizational structure of a firm. This paper proposes a way to quantify the modularity trap, using the 'coupling index' as a measure to the interdependencies and inter-connections between product's components, and applying the hypothesis to the Hard Disc Drive industry.

Keywords: Modularity, modularity trap, DSM, coupling index, Hard Disc Drive, product architecture.

### I- Introduction

The concept of modularity is gaining popularity among various fields of industries, since the year of 1964 where the first modular computer IBM 360 was born. The IBM 360 was the first product to allow consumers to swap out older modules for new ones without having to replace the entire system, as the interfaces between the modules were well documented. This been said, it reflects the definition of modularity itself. In fact, "modules have been defined as units in a larger system that are structurally independent of one another, but work together. The system as a whole must therefore provide a framework (an architecture) that allows for both independence of structure and integration of function" (Baldwin & Clarck 2000).

Modularity in product architecture has a lot to do with interdependencies between components, when these interdependencies are well defined and translate into a 'design rule' then we can start talking about 'modules'. In simple terms, it allows the components to work together while being structurally independent. On the opposite side, an integral system or product, is one where components are structurally and functionally integrated making the functioning of one components, dependent and highly 'sensitive' to a change in another component.

Researchers argued that the "technology of the firm shapes the organization of that firm" (Nonaka & Teece 2001). Thus, a firm adopting a modular (integral) product architecture, must adopt a decentralized (centralized) organizational structure, respectively. This been said, when a firm's organizational structure is not aligned with its technological structure then that firm might fall into what is referred to as "organizational traps". The motivation behind this research is to present a sufficient mathematical condition for the emergence of modularity trap. We base on the coupling index which allows for a measure of how strongly linked the components of the products are, i.e. how much a change in a component can affect, and to the extreme case, will require a change in other components.

## **II-** Literature review:

## A. Technological shifts

Chesbrough and Prencipe (2008) argued that in most complex industries, when the technology first emerges in the market, it is usually in its integral state. This state is referred to as pre-modular integral state. Ernest (2005) concludes that "many scholars share the assumption (at least implicitly) that every technology will proceed from a less modular, more integrated state towards a more modular state". When the interdependencies between the product's components begin to be clear and well understood by the market players the technology might shift to a modular state. Chesbrough (2003).

Although there is a growing tendency<sup>1</sup> to assume that modularity can become the "stable end state for technology evolution irrespective of the specific characteristics of diverse industries and technologies" Ernest (2005), many scholars oppose to the assumption, and some studies of the technological evolution throughout industries, have shown that the technology can shift back to an integral state, following the emergence of

<sup>&</sup>lt;sup>1</sup> For example, Sanchez (2000) emphasizes that, "once component interface specifications are fully defined in a modular product architecture, there is little or no need for the traditional development management function of adjudicating interface issues among teams developing interdependent com".

modularity. Chesbrough and Prencipe (2008) define this state as the postmodular integral state.

## **B.** Organizational traps

Sanchez and Mahoney (1996) attests that modularity can be a characteristic to both product architecture and to the organizational structure. Ernest (2005) argued that the organizational structure of the firm should be in line with its technological structure. i.e. a firm must adopt a decentralized organizational structure when the technology is in its modular phase, and a centralized organizational structure when the technology is in its integral phase.

Sanchez (2000), explores "how the design rules an organization adopts for creating product architectures fundamentally constrain the feasible organization designs an organization can adopt for creating, producing, and supporting its products". Within the same lines, Chesbrough and Kusunoki (2001) claim that "as the technology shifts from one phase to the other, the optimal organizational configuration of the firm must also shift if it is to continue to capture value from its innovation activities".

Further, Chesbrough and Prencipe (2008) assert that when a firm fails to align its organizational structure with its technological structure, an organizational trap occurs as a consequence to that misalignment. The authors then specify two types of organizational traps: modularity trap and integrality trap. The modularity trap is defined as a kind of organizational misalignments that occurs when a decentralized firm fails to shift to a centralized one when the technology of its product shifts from a modular to an integral phase. In other words, if a firm remains decentralized when the technology shifts to an integral phase, and finds it difficult to see through the interdependencies in the new integral product that has emerged in the market then we talk about 'modularity trap'.

Similarly, a firm with a centralized organization might fall into the integrality trap when the modularity emerges in the market. Nonaka and Teece (2001) explored the Hard Disc Drive industry and detected both modularity and integrality traps along the evolution of the industry. Ernest (2005) studied the Chip design industry, and talked about the occurrence of modularity trap, referred to as 'modularity limits'.

## C. Product architecture and the coupling index:

Ulrich (1995) defines product architecture as "the scheme by which the function of a product is allocated to its physical components". The definition suggests a double perspective, including the mapping from functional elements to physical components and the specification of the interfaces among physical components. Hence, the notion of change in product architecture represents any modification to one of the architecture' parameters, i.e. the mapping between functions and components, and/or the interactions between the components. In their effort to develop a method that helps create designs taking into account eventual future design changes, Martin and Ishii (2007) defined the coupling index as a way to capture the weight by which a change in a component would affect another component coupled to it. The coupling index was first introduced by Ulrich (1995) to measure or weight up the interdependencies between components. "Two components are considered coupled if a change made to one of the components can require the other component to change."

Modularity in product architecture is a fertile ground research for many researchers wishing to understand the dynamics of modularity and its benefits. And a large body of scholars has examined the advantages and disadvantages of modularity in product architecture. However, fewer researches examined the limits of modularity, or the emergence of modularity trap, and the ones who did have tended to focus on particular cases studies from specific industries. In this paper, we propose a quantifiable measure to the emergence of modularity trap. We base on the coupling index to build a sufficient mathematical equation to the emergence of modularity trap, and we propose an illustration of the method using a case from the Hard Disc Drive industry.

# III- Coupling index hypothesis:

## A. Stating the hypothesis

The coupling index was introduced to measure or weight up the interdependencies between components. "Two components are considered coupled if a change made to one of the components can require the other component to change." (Robertson, K. Ulrich 1995).

Building upon this definition, comparing the coupling indexes of two products can be an effective way to tell which one of the two has a higher degree of component' interdependencies.



Figure 1: Modularity trap in the time line of technological shifts

Accordingly, and based on the concept of technological shifts among industries and the definition of Modularity trap (Figure 1), we built our hypothesis concerning the emergence of modularity trap as follows:

If the coupling index of the newly introduced product, referred to as the Post-Modular Integral product is greater than the coupling index of the Pre-Modular Integral product, we can say that the new integral product has some new interdependencies that didn't exist in the integral product the technology has started with. This means that the now-decentralized<sup>2</sup> firms might not be able to clearly detect these new interdependencies, and thus might fall into the modularity trap.

<sup>&</sup>lt;sup>2</sup> With the assumption that, when modularity emerged in the market, the firms has adopted a decentralized organizational structure.

We introduce the Coupling index ratio as follows:

$$CI^{*}(p) = \frac{1}{p} \Sigma CIni/CIi \qquad (1)$$

Where p is the number of components, CIni is the coupling index of component "i" in the Post-Modular integral product, and CIi is the coupling index of the component "i" in the Pre-Modular Integral product.

Our hypothesis supposes that if  $CI^*>1$ , in other words, CIin > CIi, the firms might fall into the modularity trap. Since the emergence of modularity trap depends in a great part on the organizational structure of the firm as well as the technological structure of the market, we add two conditions to the coupling index hypothesis, as follows:

 $\begin{cases} Decentralized organizational structrure \\ Integral technology newly emerging in the market \rightarrow \\ CI * > 1 \end{cases}$ 

Modularity trap (2)

The coupling index of each component is calculated using the weighting system in Table I, considering the inter-dependencies between the components and the functions first, and then weighting up the "distance" of each component to the specific function.

	component suppliating to functions weighting system
9	The functionality of the component depends directly on the function.
6	The function is necessary for a functionality of a directly coupled component.
3	A directly coupled component is coupled with a component for which the functioning is dependent on the specification (three degrees' dependency)
1	The component is directly coupled to at least one component with three degrees' dependency.
0	The component doesn't depend on the function in any way.

 TABLE I

 Component's dependency to functions' weighting system

#### B. Steps of calculating the coupling index:

#### Step I: Quality Function Deployment matrix

Before diving into the calculation of the coupling index, it is necessary to first state the functions (specifications) of the product, and the way they are mapped to the physical components. These mappings are depicted in a Quality Function Deployment matrix (Figure 2), where the components are represented in the columns and the specifications in the rows. When a component j enables a function i, the element Dij is represented by 1. In the case where the component i doesn't enable the function j, Dij takes the value of 0.

			Components										
		<b>C1</b>	C2	C3	C4	C5	C6	<b>C7</b>	<b>C8</b>				
	F1	0	0	0	0	D51	D61	0	D81				
	F2	D12	0	0	D42	0	0	D72	D82				
	F3	0	0	0	D43	0	D63	0	0				
Functions	F4	D14	0	0	0	D54	0	0	0				
	F5	0	0	D35	0	0	D65	0	0				
	F6	0	D26	0	0	D56	0	0	0				
	F7	0	0	0	0	D57	0	0	D87				

Figure 2: Example of the Quality Function Deployment matrix

#### Step II: Graphical representation of specification flows

In order to illustrate the specification flow between the components, we will use the concept of closeness centrality. This concept first appeared in Social network theory and was adapted to product architecture, "using the notion of distance between components, such that the more distant a component is from the other components, the further its design dependencies have to propagate" (Sosa & Eppinger 2007). Thus, in order to illustrate the closeness centrality in the Graphical representations, we draw the components (control volumes) taking into account the concept of "distance" between the control volumes. In other words, two components are directly linked in the Graphical representation if the functioning of one is directly dependent on the specification of the other. In this case, the latter is said to be "supplying" the specification to the former. The Graphical representation is then the illustration of theses "supplies" (flows) of the specifications from the components.

## Step III: Design Structure Matrix

In order to capture the criticality or weight of each dependency we use a 5points scale represented in Table 1. Accordingly, a component that is directly dependent for its functionality, on a specification of the component will have a higher dependency' weight on that specification, than that of a component that is indirectly dependent on the same specification. The design structure matrix (Figure 3) depicts these dependency' weights in two directions, namely: supply and requirement of specifications. i.e. when the functioning of a component i depends on the specification (a metric) of another component j, then the component j is said to be "supplying" the specification to the component i while the component i is said to "require" that specification. The supply of the specifications is represented as the columns of the DSM matrix and the requirements as the rows.

		Components									
		<b>C1</b>	C2	C3	C4	C5	C6	C7	C8		
	C1		C22		C42	C14		C72	C81		
	C2	C12				C56		C72			
	C3						C65				
Components	C4	C12	C22				C63	C72			
	C5	C14	C26				C61		C81 C87		
	C6			C35	C43	C51			C81		
	C7	C12	C22		C42						
	C8	C12	C22		C42	C51 C57	C61	C72			

Figure 3: Example of Design Structure Matrix

In the Figure 4, the example highlighted shows the dependency between the function F2 and the component C4. In other terms, we can see from the matrix functions-components that there are four components that can enable the function F2: C1 C4 C7 and C8. Each dependency is given by the coefficient Di2 with i referring to Ci and 2 referring to F2.

Moving on to the components-components matrix, we can now look at the interdependencies between the components i and j, measured as a distance of component i to the function enabled by the component j.

Following the example highlighted in the Figure 4, we can spot the coefficient C42 in each of the cases notifying the interdependency between the components that enable<sup>3</sup> the function 2.

Once the interdependencies between each component to every other component are determined, we move on to weight up these interdependencies. Usually, it is the work of the system experts to determine these weights, but for the sake of convenience, we base our weighting on the analysis behind the functioning principle of the hard disc drives, for our illustration in the following chapter.



Figure 4: Illustrating interdependencies using DSM and QFD

<sup>&</sup>lt;sup>3</sup> In the example of a hard disc drive, the 'head' is considered to be the main component 'delivering' the specification 'seek time' which is the period between the moment the head receives a read/write signal from the control-circuit to the moment it finds the track it is requested to read/write from. In the example show above, we suppose that the component 4 is the main component that enables or delivers the function 2.

## IV- Case study: Toshiba's modularity trap, disc drive industry

In order to illustrate the hypothesis proposed in this paper, we will use a case study from the Hard Disc Drive industry, since the industry had noticed rapid and disruptive changes in a 'relatively' short period of time (Figure 5).



Figure 5: Time line of technological shifts in the disc drive' head industry

"Those who study genetics avoid studying humans, because new generations come along only every thirty years or so, it takes a long time to understand the cause and effect of any changes. Instead, they study fruit flies, because they are conceived, born, mature, and die all within a single day. If you want to understand why something happens in business, study the disk drive industry. Those companies are the closest things to fruit flies that the business world will ever see." (Christensen 1997)

In this paper, we will focus on the disk drive's head technology, and particularly the emergence of the magneto-resistive technology, in order to prove the coupling index hypothesis, testing it on Toshiba's response to the emergence of this at-the- time-new modular technology.

## A. Technological shifts in the disc drive's technology:

Since their introduction by IBM in 1956, disc drives used ferrite head technology up until late 1970's, when IBM introduced a new technology using 'Thin Film Inductive heads' in 1971 (Figure 5). With this new technology came new interdependencies between the head and the other elements of the drive, announcing a technological shift to an integral phase. A few years later, specifically in 1992, and after the thin film head technology shifted towards a modular phase, as the interdependencies

became well understood by the market' players, developmental limits to this technology started to be felt, which gave birth to a new technology using Magneto-resistive (MR) heads.

During the modular phase of the technology, i.e. the thin film technology, Toshiba had adopted a decentralized organizational structure. Once the MR heads emerged in the market, causing the technology to shift back to an integral phase, Toshiba was faced with a challenge to communicate its requirements and specifications to its head suppliers, which suggests that Toshiba appears to have fallen into the modularity trap.

## B. Hard disc drive's operation principle:

Testing our Coupling Index hypothesis on Toshiba's 'modularity trap' in the early 90's will require comparing the coupling index of the thin film heads technology when it was in its integral phase to the coupling index of the MR heads technology when it had first emerged in an integral state as well.

• Disc drive operation principle:

The hard disc drive is an electronic device for which the main function is to write, store and read computer data from a rigid/hard rapidly rotating disc. In addition to the turning disc (platter), the drive also contains a magnetic head flying over the disc to write data on the surface and read from it. (Christopher & Bajorek 2014)

• Main differences between TFI technology and MR technology:

In the Thin film inductive technology, the read head consists of a ferromagnetic material wrapped with wire. The operation principle follows Faraday's law: when the head passes over magnetized sections of the disc, the change of the magnetic flux induces an EMF, generating a current flow in the wire.

On the other hand, the magneto-resistive technology is based on the simple fact that the electrons move easier when their magnetization is aligned with the magnetization of the layer they are moving into. Thus, the MR head is composed of a tiny electrical resistor, when the head is reading data from the disc, the changes in the magnetic flux emanating from stored bits, induce changes in the electrical resistance in the head.

This been said, we can already point out some interdependencies' differences between the two technologies. The change of the resistance of the MR head doesn't depend on the disc velocity (rotational speed), which

means that the read-back signal captured by the head is independent of the speed. In other words, there is more weight to the specification "read-back signal" in the interface head-disc in the TFI drive than that in the MR drive. Other major differences can be derived from the challenges that the MR heads presented when they first emerged in the market, namely: ESD: Electrostatic discharge, and TA: Thermal Asperities<sup>4</sup>. Overcoming these challenges suggested redesigning the pre-amplifier, to be able to recover from the distorted signal by TA. The pre-amplifier had to also ensure a near 0Volt potential for the MR sensor to avoid ESD.

Since these challenges didn't exist in the era of thin film head, we can say that the MR head drive came with new specifications, leading to new interconnections between the drive's components<sup>5</sup>.

## C. Coupling index for the hard disc drive

• Quality Function Deployment Matrix: QFD

The Quality Function Deployment matrix for the Thin film drive and the MR drive are displayed in (TABLE II) and (TABLE III), respectively.

	Arm actuator	Head	Platter	DC motor	Pre- amplifier	Control- circuit
Seek time "Seek.T"	1	1	1	1	0	1
Settle time "S.T"	1	1	0	0	0	1
Media rate	1	1	1	0	0	0
Areal density "AR"	0	1	1	0	0	0
Cylinder switch time "CST"	0	0	1	1	0	0
Rotational latency "RL"	1	1	1	1	0	1
Rotational speed "RS"	0	0	1	1	0	1
Command process time "CMT."	0	1	1	0	0	1
Power supply	1	0	0	1	0	1
Signal-to-noise rate "STN.Rate"	0	0	1	0	1	1

TABLE II QFD for the thin film head' drive

<sup>&</sup>lt;sup>4</sup> TA is defined as physical defects caused when the head flies too close to the disc causing physical defects and distortion of the signal in the part of the disc where the head inadvertently touches.

<sup>&</sup>lt;sup>5</sup> We tried to use control volumes: components (or in some cases sets of components) at approximately the same level of complexity as the "head". For example, the DC motor contains in itself many components (Stator, Rotor, Shaft, Logic Controller and a power supply inverter), but since the objective of this paper is to prove the Cl hypothesis and to test it on the disc drive's heads industry, we ignored the interactions between components inside our control volumes.

For example: the arm actuator, the head, the platter, the DC motor and the control circuit all have an impact of the specification "Seek time<sup>6</sup>". For the MR drive, the head, the platter and the pre-amplifier can affect the specification of "avoiding ESD".

QFD for the MR head' drive											
	Arm actuator	Head	Platter	DC motor	Pre- amplifier	Control- circuit					
Seek time	1	1	1	1	0	1					
Settle time	1	1	0	0	0	1					
Media rate	1	1	1	0	0	0					
Areal density	0	1	1	0	0	0					
Cylinder switch time	0	0	1	1	0	0					
Rotational latency	1	1	1	1	0	1					
Rotational speed	0	0	1	1	0	1					
Command process time	0	1	1	0	0	1					
Power supply	1	0	0	1	0	1					
Signal-to-noise rate	0	0	1	0	1	1					
Avoiding TA	0	1	1	0	1	0					
Avoiding ESD	0	1	1	0	1	0					
TA Recovery	0	1	1	0	1	0					

TABLE III QFD for the MR head' drive

• Graphical representation of specification flows

We draw the graphical representation of specification flows for the thin film head HDD (Figure 6) and the MR head HDD in (Figure 7). The squares indicate the components (control volumes), and the arrows indicates the dependency' directionality. An arrow in the same color with control volumes indicates a specification supplied from that component.



Figure 6: Graphical representation of specification flows of the TFI drive

<sup>&</sup>lt;sup>6</sup> The seek time measures the time the head needs to access the data on the drive.

For example, the cylinder switch time CST<sup>7</sup>, is a specification proper to the platter. Thus, the specification flow is represented by an arrow emanating from the control volume "platter" and of the same color of the control volume: orange. On the other hand, the functionality of the platter is directly dependent on the DC motor controlling the rotation of the platter. If the DC motor was to stop supplying the specification "rotational speed RS" to the platter, the platter will lose its functionality. This is represented by a direct link from the DC motor to the platter, supplying the specification "rotational speed RS".



Design Structure matrix: DSM

The main differences between the two technologies reside in the specification flows from the pre-amplifier. The interface head-platter has also changed, and the weight of the head's dependency on the media rate (read-signal) has changed from 9 in the thin film drive (Table 4) to 6 in the MR head (Table 5). This is due to the fact that in the MR head the change in the resistance does not depend on the velocity of the platter, making the signal independent from the platter's rotational speed.

<sup>&</sup>lt;sup>7</sup> CST is the time it takes the platter to switch from one cylinder to another.

									Arm	or	Head		Platter	DC mot	or Cont	rol-circui	Pre-	Ber
							1	Arm			Seek.T	6	CST 6		Seel	.Т9	unipin	
								actuator			ST 6		RL 6		ST 9		1	
									Seek.1	6			RL 3		CPT	9		
									ST 6				MR 9		Seel	.V6		
								Head					CST 3	-	SV 6		SNT 9	
													AD 3		Read	i signal 9	-	
															Writ	e signal 9		
											Seek.T	3			CPT	9		.
								Platter			MK9			10.9	RL	6	SNIT	°
							l I		_				RL 6		RS	9		-
								DC motor			Seek.T	1	RS 9		1	-	1	
													CST 6					
								Control			Seek.T	9						
								circuit			ST 9		RL 9				SNT (	5
									_		Read-s	ignal 6						_
								Pre-							STN	rate 9		
	Arm				Pre-	Contro		ampimer										
	actuator	Head	Platter	DC motor	amplifier	circuit								-				
Seek time "Seek.T"	1																	
	-	1	1	1	0		1											
Settle time "S.T"	1	1	1	1	0		1											
Settle time "S.T" Media rate "MR"	1	1	1 0 1	1 0 0	0 0		1 1 0	-										
Settle time "S.T" Media rate "MR" Areal density "AR"	1	1 1 1 1 1	1 0 1 1	1 0 0	0 0 0		1 1 0	-										
Settle time "S.T" Media rate "MR" Areal density "AR" Cylinder switch time "CST"	1 1 0 0	1 1 1 0	1 0 1 1	1 0 0 1	0 0 0		1 0 0	-										
Settle time "S.T" Media rate "MR" Areal density "AR" Cylinder switch time "CST" Rotational latency "RL"	1 1 0 0	1 1 1 1 0	1 0 1 1 1	1 0 0 1	0 0 0 0		1 0 0 0	-										
Settle time "S.T" Media rate "MR" Areal density "AR" Cylinder switch time "CST" Rotational latency "RL" Rotational speed "RS"	1 1 0 0 1 0	1 1 1 0 1 0	1 0 1 1 1 1 1	1 0 0 1 1	0 0 0 0		1 0 0 1 1	-										
Settle time "S.T" Media rate "MR" Areal density "AR" Cylinder switch time "CST" Rotational latency "RL" Rotational speed "RS" Command process time "CMT."	1 1 0 0 1 0 0	1 1 1 0 1 0 1	1 0 1 1 1 1 1 1	1 0 0 1 1 1 0	0 0 0 0 0		1 0 0 1 1 1											
Settle time "S.T" Media rate "MR" Areal density "AR" Cylinder switch time "CST" Rotational latency "RL" Rotational speed "RS" Command process time "CMT." Power supply	1 1 0 0 1 0 0 1	1 1 1 1 0 1 1 0 1 1 0	1 0 1 1 1 1 1 1 1 0	1 0 0 1 1 1 0 1	0 0 0 0 0 0		1 0 0 1 1 1 1											
Settle time "S.T" Media rate "MR" Areal density "AR" Cylinder switch time "CST" Rotational latency "RL" Rotational speed "RS" Command process time "CMT." Power supply Signal-to-noise rate "STN.Rate"	1 1 0 0 1 0 0 0 0 1 1 0 0	1 1 1 0 1 1 0 1 1 0 0 1 0 0 0 0	1 0 1 1 1 1 1 1 0 0	1 0 0 1 1 1 1 0 0 1 0	0 0 0 0 0 0 0 0 0		1 0 0 1 1 1 1 1											
Settle time "S.T" Media rate "MR" Areal density "AR" Cylinder switch time "CST" Rotational latency "RL" Rotational speed "RS" Command process time "CMT." Power supply Signal-to-noise rate "STN.Rate"	1 1 0 0 1 0 0 0 1 0 0	1 1 1 0 1 0 1 0 0 0	1 0 1 1 1 1 1 1 0 0 1	1 0 0 1 1 1 1 0 0	0 0 0 0 0 0 0 0 0 0		1 0 0 1 1 1 1	-										

	Arm actuator	Head	Platter	DC motor	Control-circuit	Pre- ampl	ifier
Arm		Seek.T 6	CST 6		Seek.T 9		
actuator		ST 6	RL 6	1	ST 9		
	Seek.T 6		RL 3		CPT 9		
	ST 6		MR 9		Seek.V 6		
Head		1	CST 3	]	SV 6	SNT	9
			AD 3	]	Read signal 9		
					Write signal 9		
		Seek.T 3			CPT 9		
Platter		MR 9		RS 9	RL 6	SNT	6
					RS 6		
			RL 6		RS 9		
DC motor		Seek.T 1	RS 9				
			CST 6				
Control		Seek.T 9					6
circuit		ST 9	RL 9			SNT	
circuit		Read-signal 6					
Pre- amplifier					STN rate 9		
	12	49	60	9	96	21	
							247

Figure 8: Coupling index of the Thin Film head drive

In the case of the 'seek time' specification, which is a specification proper to the head, the weight of dependency of the arm actuator on this specification is 6, since the arm actuator is directly coupled with a component: the head, which depends for its functionality on the seek time specification. And that the arm actuator doesn't depend on the specification "seek time" for its functionality.



	Arm actuator	Head	Platter	DC motor	Control-circuit	Pre- amplifier	
Arm		ST 6	CET 6		ST 9		
actuator		Settle.T 6	6310		Settle.T 9		
	ST 6		RL 3		CPT 6	SNT 9	
	Settle.T 6		MR 9		ST 9	ESD 9	
Head			CST 6	]	Settle.T 9		
			AD 3		Read signal 9		
				]	Write signal 9		
		ST 3			СРТ 9	SNT 9	
Platter		Read-signal	6	RS 9	RL 6	ESD 9	
					RS 6		
			RL 9		RS 9		
DC motor		ST 1	RS 9				
			CST 6				
Control		ST 9					
circuit		Settle.T 9	RL 6			SNT rate 6	
circuit		Read-signal	9				
Pre-		F5D 0	ESD 9		STN rate 0		
amplifier		50 9	TA.Recovery 9		STN race 9		
	12	58	75	9	99	42	
						295	

Figure 9: Coupling index of the MR head drive

## D. Result's interpretation:

Following the notations adopted in this paper, we can write:

CIni = 295 (3) CIi = 247 (4)  $\rightarrow CI *= 1.19 > 1$  (5)

This result shows the change in the coupling index, representing the weight of inter-dependencies between components, following the technology evolution from a pre-modular integral state, to a modular state, and then to a post-modular integral state. When Toshiba had fallen into the modularity trap, the company was adopting a decentralized organizational structure. When the new technology (the MR head technology) emerged in the market as an integral technology, Toshiba was not able to understand the new inter-dependencies between the components, and thus it was not able to clearly specify its needs to its suppliers, thus falling into the modularity trap.

Calculating the coupling index of the newly emerging technology, and comparing it with the coupling index of the integral technology that preceded the emergence of "modularity" in the HDD market, have shown that in this particular case, the post-modular integral technology contained new inter-dependencies that didn't exist in the product that preceded the emergence of modularity, which have caused Toshiba to fall into the modularity trap.

## V- CONCLUSION

To conclude, it is necessary to mention that, the coupling index we introduce is a "risk factor" translating the risk of falling into the modularity trap, for firms adopting a decentralized organizational structure, when the market shifts back to an integral state. In that case, and if the coupling index hypothesis is satisfied, i.e. if the newly introduced product brings in new interdependencies that didn't exist before, then those organizationally decentralized firms might face a high risk of falling into the modularity trap, should they not be able to quickly get an insight into the new interdependencies.

For the particular case of Toshiba, illustrating the steps of calculating the coupling index using the QFD and DSM matrixes, have helped us show the extent to which the inter-dependencies between the HDD components have changed along the technological shifts that the industry has noticed in a relatively short period of time. The fact that the MR head had a greater

coupling index than that of the TFI head explains the reasons behind Toshiba's modularity trap, as the company was not able to clearly see through the new inter-dependencies that emerged with the post-modular integral product.

Having a quantifiable measure to the emergence of modularity trap will be beneficial in a double dimension. First, relaying on the coupling index as a measure to the inter-dependencies between the components, and on the complexity managing tools (such that the DSM and OFD) to depict the change propagation within a product, might be of good help to firms and engineers wishing to keep track on the evolution of the technological structure of their product in terms of its component's interdependencies, along with the firm's organizational structure. On the other hand, this paper can serve for a basis to a future study, on modelling the emergence of the modularity trap. Having a mathematical condition to the emergence of modularity trap, can help building a computational model that simulates, and thus shows the conditions behind the emergence of the modularity trap. The next step of this research will consist of using a generative approach, that is building an Agent Based Computational Model, to simulate the emergence of modularity trap and show the conditions under which a firm can fall into the modularity trap.

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