Beyond the Hierarchy:
System-Wide Rearrangement as a Tool to Eliminate Iteration

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Abstract

A primary tenet of axiomatic design theory is the first axiom, stating that independence of functional requirements should be maintained throughout the design process. As the high level requirements are decomposed into greater detail, and information added to the design with the goal of creating a realizable system, the designer creates subsystems that satisfy the first axiom. While higher level decisions imply an intent that should be maintained as detail is added, this is often not done. When a system is designed that results in some unintended interactions between design elements, it is possible to achieve a non-iterative design process by rearranging the leaf level elements as a collective set. This is shown for a subset of elements from the design of a chemical mechanical polishing (CMP) machine tool.

Introduction

The reader is assumed to be familiar with the axiomatic design process. All terms used in this paper are consistent with those presented by Suh [1]. Axiomatic design begins with the most general requirements of the system, and decomposes these into sub-requirements, which are then mapped to design parameters in the physical domain. The hierarchical collection of functional requirements (FRs) and design parameters (DPs) generated during the zigzagging process is termed the system architecture, and elements which require no further decomposition are leaf level elements. Zigzagging is repeated until it is possible to construct the system from the information contained in the system architecture.

When systems are designed with axiomatic design, high-level design equations represent conceptual choices made by the designer, and the intent carried with those choices. In order to realize any system, information must be added. Information is added to the system through the decomposition process, which expands FR/DP pairs into sub requirements which are in turn mapped to the physical domain. As this zigzagging process continues, adding information, the decisions must remain consistent with those at higher levels if the original intent is to be maintained. Although this is the goal of the design process, it is not so easily accomplished. Particularly when designing large systems, which must satisfy a large number of functional requirements, it is likely there will be unconsidered influences, or emergent properties that may not be intended, but can not be avoided.

When the full system matrix is created of all leaf level design elements, interactions that fall outside of the original design intent may be uncovered, and serve to contradict the original intent. Elements in a design matrix that fall in the upper triangle represent iteration in the design process. While iteration does involve an increase in the design effort, it is often considered inherent to the design process [2]. The conventional solution in axiomatic design would be to rework the design, and develop a set of design parameters that do not result in a coupled system. Such practice would result in a desirable system that avoids all undesirable interactions.

Rather than search for a design solution which altogether avoids any of such small scale interactions, it is proposed that it is possible to rearrange the full system matrix, or any subset of leaf level FR/DP pairs beyond the structure that is defined by the hierarchy of decomposition, to reach a design sequence which does not require iteration.

Rearrangement of design elements beyond the structure defined at each level of the decomposition process has not been shown within the axiomatic design methodology, and has potential to reduce iteration to the minimum necessary. Another matrix based analysis method, the design structure matrix (DSM), does demonstrate resequencing of design elements, but does not generally keep the hierarchal structure once the matrix has been formed [3]. This is a strength of the DSM method that may be incorporated into the axiomatic design method as demonstrated in this paper. The DSM method acknowledges that iteration is going to exist in the design process and attempts to manage the iteration as necessary [4].

The DSM and axiomatic design matrix are very similar, and have been considered identical [5]; However, there are differences. The design matrix of axiomatic design often includes design parameters that are not strictly physical components. This ability to utilize features of components rather than components themselves is a particular strength of axiomatic design. Also, axiomatic design preserves the concept of FRs in the design matrix, assigning a DP to each FR. FRs and DPs are paired together, linking the rows and columns in the design matrix just as in the DSM, but the matrix information may be different. The design matrix represents the effects of DPs on functions, as opposed to the effects of physical components on each other, as in the DSM.

Case Study: Chemical Mechanical Polishing (CMP) machine

As an example for the utility of system wide rearrangement, the design of a chemical mechanical polishing machine will be used. This machine was developed as part of a research program at MIT, and has demonstrated advanced capabilities to polish silicon wafers for semiconductor fabrication. The system was developed within the axiomatic design framework, and provides a full system matrix with approximately 100 leaf level elements. While the full matrix should be investigated as a whole to insure a properly sequenced design, much may be learned by looking at a smaller subset of FR/DP pairs. This may be useful, for instance, as a way to collect elements that are relevant to a particular piece of hardware.

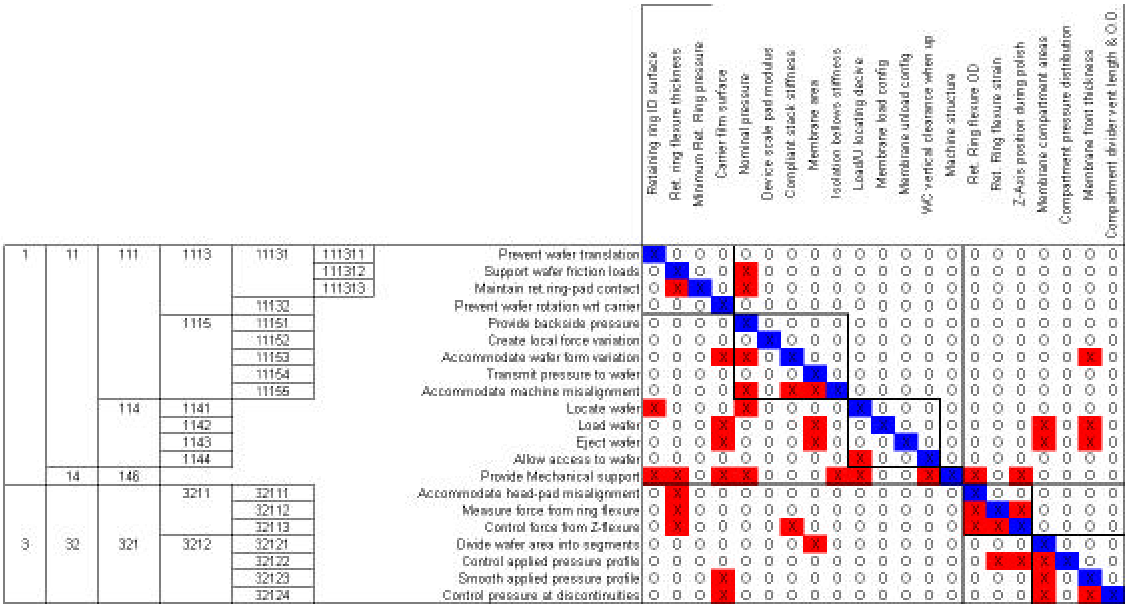
For the following example, the design elements that are relevant to the wafer carrier will be presented. The wafer carrier is the physical component of the machine that holds the wafer during polishing. As will be shown, FR/DP elements from various parts of the decomposition are embodied in the hardware of the wafer carrier. Therefore, the elements for this piece of hardware may be clustered together and then investigated as a part of the whole design. The relevant levels of decomposition are presented in Appendix A, along with some description of what the design parameters represent. Here, the collection of elements will be shown in matrix form, and the benefits of rearranging the matrix demonstrated.

Wafer carrier design matrix

If the leaf elements described in Appendix A are combined into a matrix, the result is shown in Figure 7. These are those elements that are relevant to the wafer carrier hardware. Also included in the matrix, but not discussed in detail is FR/DP 1.4.6: Provide mechanical support-Mechanical structure. The mechanical structure is part of the machine support systems, those systems which are necessary to enable other systems.

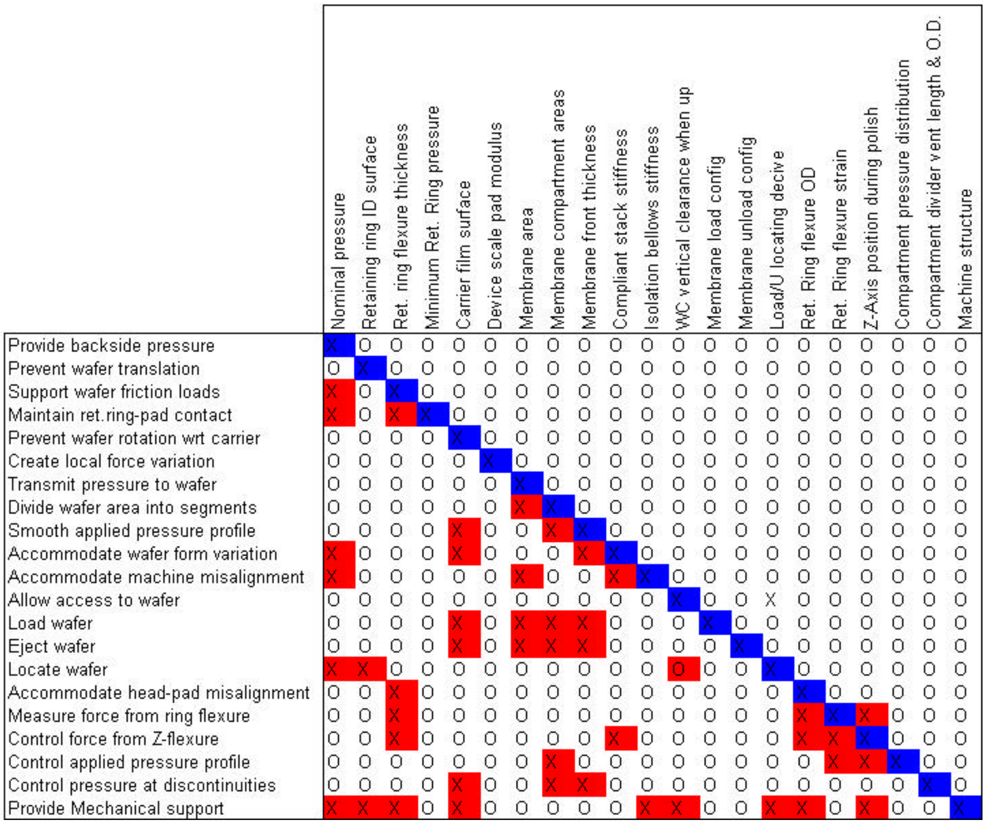
As is evident by inspecting the matrix, it is not lower triangular. During each stage of the decomposition, a lower triangular matrix was reached. Therefore, the full matrix shown in Figure 7 should be lower triangular. Unfortunately, it was not possible to maintain the intent of the higher level decisions in the strictest sense. The result is a matrix with some elements in the upper triangle. This will result in iteration during the design process, and therefore added time and expense during the design cycle.

One important characteristic is the nature of leaf level design elements. Since the leaf levels may be combined to make the parent (branch) levels, they are the elements of the design which must be individually set. Once this is accomplished, the structure of the hierarchy may be followed from the bottom of the top to realize the system. Because all the leaf levels must be determined, it is reasonable to consider them as the necessary and sufficient set of information to realize a system. In the matrix of Figure 7, only leaf levels are represented. Therefore, they may be reordered to reach an appropriate sequence for design. The result of such reordering is shown in Figure 8. As may be seen, the matrix is now lower triangular, to the extent that it can be. There is a fully coupled block that represents the closed loop control system of the retaining ring vertical motion, as discussed above. This is handled with a real time controller that iterates the solution during operation of the machine, guaranteeing FR satisfaction.



							Retaining ring ID surface	Ret. ring flexure thickness	Minimum Ret. Ring pressure	Carrier film surface	Nominal pressure	Device scale pad modulus	Compliant stack stiffness	Membrane area	Isolation bellows stiffness	Load/U locating decive	Membrane load config	Membrane unload config	WC vertical clearance when up	Machine structure	Ret. Ring flexure OD	Ret. Ring flexure strain	Z-Axis position during polish	Membrane compartment areas	Compartment pressure distribution	Membrane front thickness	Compartment divider vent length & O.D.
1	11	111	1113	11131	111311	Prevent wafer translation	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
					111312	Support wafer friction loads	O	X	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
					111313	Maintain ret.ring-pad contact	O	X	X	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
				11132		Prevent wafer rotation wrt carrier	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
			1115	11151		Provide backside pressure	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
				11152		Create local force variation	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
				11153		Accommodate wafer form variation	O	O	O	X	X	O	X	O	O	O	O	O	O	O	O	O	O	O	O	X	O
				11154		Transmit pressure to wafer	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O
				11155		Accommodate machine misalignment	O	O	O	O	X	O	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O
		114	1141			Locate wafer	X	O	O	O	X	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O
			1142			Load wafer	O	O	O	X	O	O	O	X	O	O	X	O	O	O	O	O	O	X	O	X	O
			1143			Eject wafer	O	O	O	X	O	O	O	X	O	O	O	X	O	O	O	O	O	X	O	X	O
			1144			Allow access to wafer	O	O	O	O	O	O	O	O	O	X	O	O	X	O	O	O	O	O	O	O	O
	14	146				Provide Mechanical support	X	X	O	X	X	O	O	O	X	X	O	O	X	X	X	O	X	O	O	O	O
3	32	321	3211	32111		Accommodate head-pad misalignment	O	X	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O
				32112		Measure force from ring flexure	O	X	O	O	O	O	O	O	O	O	O	O	O	O	X	X	X	O	O	O	O
				32113		Control force from Z-flexure	O	X	O	O	O	O	X	O	O	O	O	O	O	O	X	X	X	O	O	O	O
			3212	32121		Divide wafer area into segments	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	X	O	O	O
				32122		Control applied pressure profile	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	X	X	X	O	O
				32123		Smooth applied pressure profile	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	X	O
				32124		Control pressure at discontinuities	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	X	X

Figure 7: Matrix of wafer carrier design elements



	Nominal pressure	Retaining ring ID surface	Ret. ring flexure thickness	Minimum Ret. Ring pressure	Carrier film surface	Device scale pad modulus	Membrane area	Membrane compartment areas	Membrane front thickness	Compliant stack stiffness	Isolation bellows stiffness	WC vertical clearance when up	Membrane load config	Membrane unload config	Load/U locating decive	Ret. Ring flexure OD	Ret. Ring flexure strain	Z-Axis position during polish	Compartment pressure distribution	Compartment divider vent length & O.D.	Machine structure
Provide backside pressure	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Prevent wafer translation	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Support wafer friction loads	X	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Maintain ret.ring-pad contact	X	O	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Prevent wafer rotation wrt carrier	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Create local force variation	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Transmit pressure to wafer	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Divide wafer area into segments	O	O	O	O	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O
Smooth applied pressure profile	O	O	O	O	X	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O	O
Accommodate wafer form variation	X	O	O	O	X	O	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O
Accommodate machine misalignment	X	O	O	O	O	O	X	O	O	X	X	O	O	O	O	O	O	O	O	O	O
Allow access to wafer	O	O	O	O	O	O	O	O	O	O	O	X	O	O	X	O	O	O	O	O	O
Load wafer	O	O	O	O	X	O	X	X	X	O	O	O	X	O	O	O	O	O	O	O	O
Eject wafer	O	O	O	O	X	O	X	X	X	O	O	O	O	X	O	O	O	O	O	O	O
Locate wafer	X	X	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O
Accommodate head-pad misalignment	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O
Measure force from ring flexure	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	X	X	X	O	O	O
Control force from Z-flexure	O	O	X	O	O	O	O	O	O	X	O	O	O	O	O	X	X	X	O	O	O
Control applied pressure profile	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	X	X	X	O	O
Control pressure at discontinuities	O	O	O	O	X	O	O	X	X	O	O	O	O	O	O	O	O	O	O	X	O
Provide Mechanical support	X	X	X	O	X	O	O	O	O	O	X	X	O	O	X	X	O	X	O	O	X

Figure 8: Rearranged matrix of wafer carrier design elements.

Full design matrix

Similarly to the subset of elements that make up the matrices in Figures 7 and 8, the entire collection of leaf level elements may be investigated and restructured. The full design matrix created by the decomposition for the CMP machine is shown in Figure 9. As before, the full matrix is reordered, and the result is shown in Figure 10. The matrix in Figure 10 represents an improved sequence for the design elements to be set, in a manner that will reduce the iteration required in the design. As may be seen in the figure, some elements remain in the upper triangle of the design matrix. These represent iterative loops that may not be eliminated.

Conclusion

As has been shown with the CMP case study, although design intent may be for a purely uncoupled or decoupled system, details of the implementation can lead to unpredicted interactions. Due to these interactions, iteration is required in the design process. If the full system matrix, or even a subset of it, is rearranged to create the desired lower triangular form, iterations in the design process may be reduced or eliminated. It would be useful in this process to use an algorithm that would efficiently structure the matrix.

While the method described here does show promise for improving the design process, it does carry with it some potential issues. By redefining the correct sequence for design, iteration is reduced; however by ignoring the structure of the hierarchy, other useful concepts of axiomatic design are challenged. For instance, the flow diagram representation of a system architecture relies on the hierarchal nature of the system architecture to form an efficient representation [6]. The ideal case would be to maintain the uncoupled or decoupled intent of the design as decomposition proceeds, in which case the method described here would not apply. It is presented as a tool that may be used to help a design where such undesired interactions present themselves.

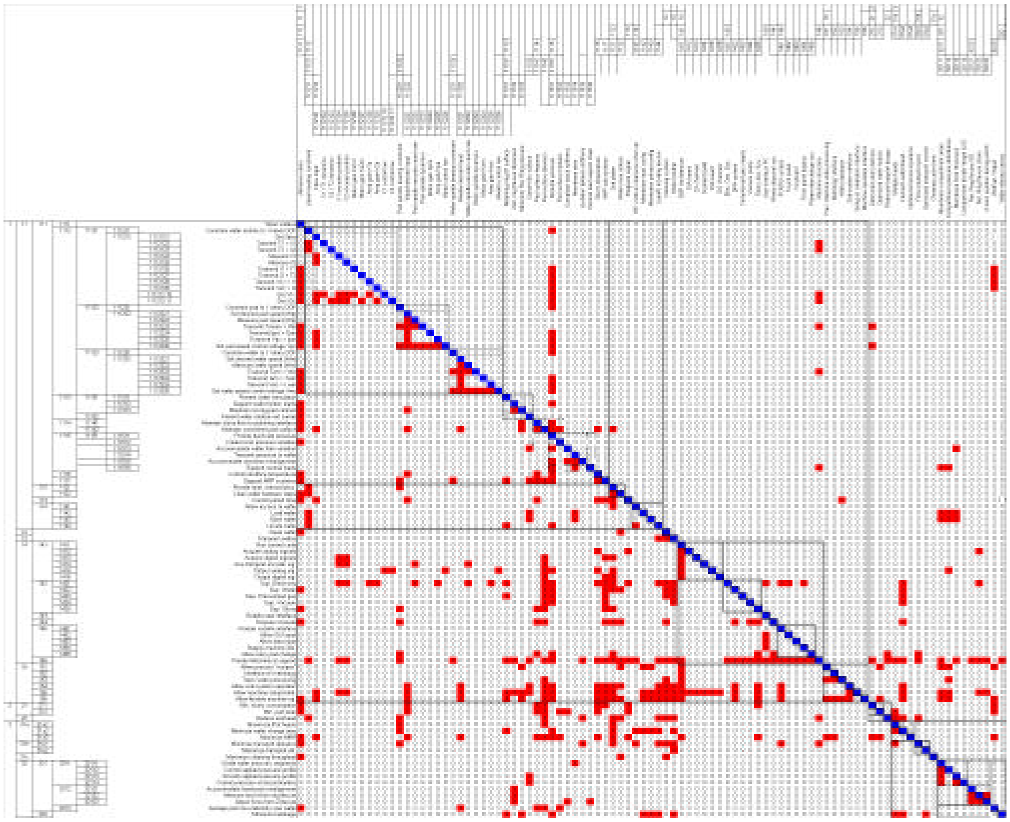


Figure 9: Full system matrix from the CMP machine as decomposed

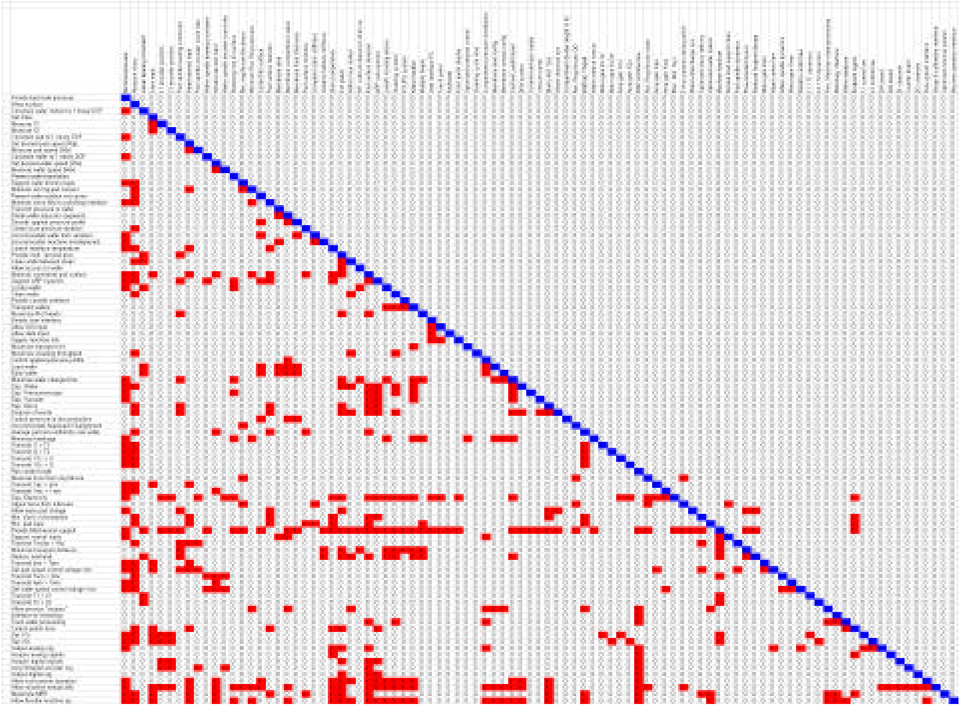


Figure 10: Rearranged system matrix for the CMP machine

Appendix A: Decomposition of selected CMP machine elements

FR/DP 1.1.1.3 Maintain wafer position-Wafer retention system

It is necessary to hold the wafer in position during the polishing cycle. This requirement is satisfied by the wafer retention system. The decomposition of FR/DP 1.1.1.3 is shown in Table 1. The wafer must be restricted to not move in the horizontal plane, and not to rotate in that plane. A schematic is shown in Figure 1, and the associated design equation is Equation 1.

Table 1: FR/DP 1.1.1.3 decomposition

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
1.1.1.3.1	Prevent wafer translation	Wafer locating system
1.1.1.3.2	Prevent wafer rotation relative to carrier	Wafer carrier surface

$$\begin{Bmatrix} FR21131 \\ FR21132 \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP21131 \\ DP21132 \end{Bmatrix} \qquad (1)$$

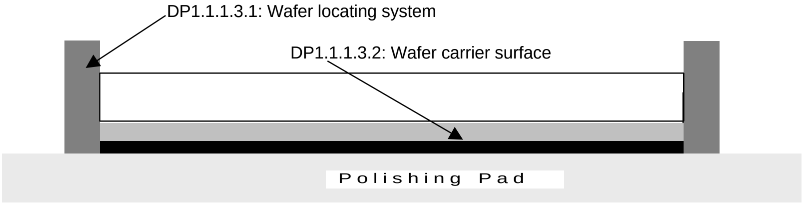


Figure 1: FR/DP 1.1.1.3 decomposition schematic

DP 1.1.1.3.1: The wafer locating system is a means for surrounding the wafer and trapping it between the polishing pad and the carrier film, so that polishing pressure may be applied.

DP 1.1.1.3.2: The surface of the wafer carrier that contacts the wafer is designed to provide a high friction with the wafer back surface. This friction will prevent the wafer rotation.

FR/DP 1.1.1.3.1 Prevent wafer translation-Wafer locating system

To prevent wafer translation during polishing, the wafer locating system is used. This system is decomposed as shown in Table2, and the design matrix is Equation 2.

Table 2: FR/DP 1.1.1.3.1 decomposition

	Functional Requirements (FRs)	Design Parameters (DPs)
1.1.1.3.1.1	Provide barrier	Ring ID – compliant
1.1.1.3.1.2	Support friction loads	Lateral load support
1.1.1.3.1.3	Maintain barrier contact with pad	Minimum ring contact pressure

$$\begin{Bmatrix} FR1.1.1.3.1.1 \\ FR1.1.1.3.1.2 \\ FR1.1.1.3.1.3 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ O & X & O \\ O & X & X \end{bmatrix} \begin{Bmatrix} DP1.1.1.3.1.1 \\ DP1.1.1.3.1.2 \\ DP1.1.1.3.1.3 \end{Bmatrix} \qquad (2)$$

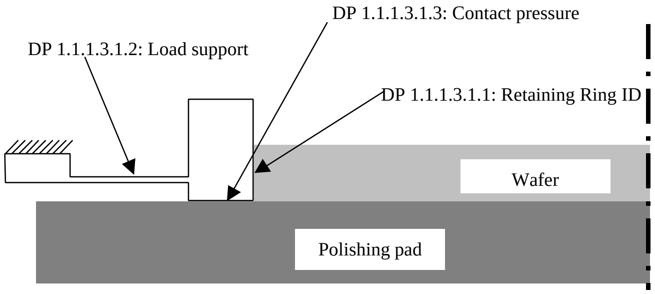


Figure 2: FR/DP 1.1.1.3.1 decomposition

DP 1.1.1.3.1.1: The ring ID is the inner surface of the retaining ring, which contacts the edge of the wafer. It is this surface which provides the support to prevent wafer translation.

DP 1.1.1.3.1.2: The Ring flexure is a continuous ring of material that will support the frictional loads of polishing while minimally influencing the contact pressure. The ring flexure affects FR 1.1.1.3.1.3 because the influence of the loads and other factors on the contact pressure is affected by the design of the ring flexure.

DP 1.1.1.3.1.3: The minimum contact pressure is the interface conditions around the bottom surface of the ring. To maintain contact with the pad, the contact pressure must be maintained above a certain value. This value will be determined experimentally.

FR/DP 1.1.1.5: Apply Normal Pressure-Interface pressure

The decomposition of FR/DP 1.1.1.5 is shown in Table 3. The associated design equation is shown in Equation 4, and a schematic of the DPs is shown in Figure 3. Following is a description of each of the DPs, and their relationships with other FRs, explaining the off-diagonal elements in the design matrix.

Table 3: FR/DP 2.1.1.5 Decomposition

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
1.1.1.5.1	Provide pressure	Nominal compartment pressure
1.1.1.5.2	Create local pressure variation	Pad surface modulus; $E_{PAD-TOP}$
1.1.1.5.3	Accommodate wafer form variation	Stack stiffness; $(Eh^4)_{mem} + (E_{bulk}/h)_{PAD}$
1.1.1.5.4	Transmit pressure to interface	Membrane area
1.1.1.5.5	Accommodate machine misalignment	Isolation bellows stiffness
1.1.1.5.6	Support normal loads	Normal load support chain

$$\begin{Bmatrix} FR\,1.1.1.5.1 \\ FR\,1.1.1.5.2 \\ FR\,1.1.1.5.3 \\ FR\,1.1.1.5.4 \\ FR\,1.1.1.5.5 \\ FR\,1.1.1.5.6 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ O & X & O & O & O & O \\ O & X & X & O & O & O \\ O & O & O & X & O & O \\ O & O & X & O & X & O \\ O & O & O & X & O & X \end{bmatrix} \begin{Bmatrix} DP\,1.1.1.5.1 \\ DP\,1.1.1.5.2 \\ DP\,1.1.1.5.3 \\ DP\,1.1.1.5.4 \\ DP\,1.1.1.5.5 \\ DP\,1.1.1.5.6 \end{Bmatrix} \qquad (3)$$

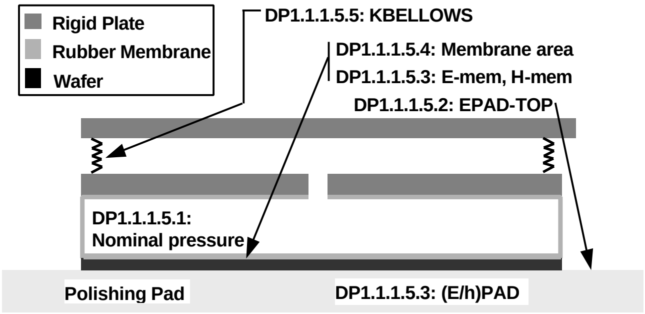


Figure 3: FR/DP 1.1.1.5 Decomposition Schematic

DP 1.1.1.5.1: Compartment pressure is the pressurized gas supplied to the bladder compartments. This pressure is controlled with a E/P valve, using a control loop within the valve.

DP 1.1.1.5.2: The pad surface modulus is what creates preferential removal of the high features compared to the low features. This is the process of planarization. The pad surface modulus affects FR 1.1.1.5.3 because a higher modulus will to some extent reduce the ability of the system to tolerate wafer form variation.

DP 1.1.1.5.3: $(E/h)_{PAD}$ is the stiffness of the pad in the vertical direction. The membrane modulus, E_{mem}, combined with the membrane thickness, h_{mem}, describes the bending stiffness of the planar membrane. The total stack stiffness of the pad and membrane controls how the pressure will respond to wafer form variation. A low stiffness will accommodate a large wafer form variation without creating large pressure variation. The stiffness affects FR 1.1.1.5.5 because low stiffness reduces requirements for misalignment.

DP 1.1.1.5.4 - Membrane area is the overall area of the membrane. It should match the wafer area. Area affects FR 1.1.1.5.6 because a change in area will change the applied loads that the system must support. The area does not change during operation of the machine, so creates no problem.

DP 1.1.1.5.5 - The isolation bellows stiffness is the tip-tilt stiffness of the bellows that loads the wafer against the pad.

DP 1.1.1.5.6 - The load support chain is the series of machine elements that allows a load to be present at the wafer-pad interface without undue deflection.

With the collection of FRs and DPs shown in Table 1 along with the rest of the necessary elements, the design satisfies the minimum requirements to polish wafers. It can supply pressure to the wafer, and does so in a manner that is tolerant of input variation. This type of design was reached in most commercial CMP equipment by the second or third generation. The desire in this project was to extend the capabilities of the machine past the current state-of-the-art. To realize these goals, an FR was added to minimize the amount of overpolishing when processing wafers.

FR/DP 1.1.4: Exchange wafers-Wafer exchange sequence

While polishing a wafer is the primary configuration of the machine, it is necessary to enable a flow of wafers through the polishing cycle. To accommodate this, one of the machine requirements is the ability to exchange wafers. The decomposition of FR/DP 1.1.4 is shown in Table 4 and the associated design equation is Equation 4.

Table 4: FR/DP 1.1.4 decomposition

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
1.1.4.1	Locate wafer	Wafer locating device
1.1.4.2	Load wafer	Membrane load configuration
1.1.4.3	Eject wafer	Membrane unload configuration
1.1.4.4	Allow access to wafer	Wafer carrier vertical clearance when lifted

$$\begin{Bmatrix} FR\,1.1.4.1 \\ FR\,1.1.4.2 \\ FR\,1.1.4.3 \\ FR\,1.1.4.4 \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ X & O & O & X \end{bmatrix} \begin{Bmatrix} DP\,1.1.4.1 \\ DP\,1.1.4.2 \\ DP\,1.1.4.3 \\ DP\,1.1.4.4 \end{Bmatrix} \tag{4}$$

DP 1.1.4.1: The wafer locating device is the device which aligns the wafer with the wafer carrier. Examples may be a robotic arm, or a known geometric constraint. The locating device effects FR 1.1.4.1 because the clearance required under the wafer carrier is determined by the device which locates the wafer for loading.

DP 1.1.4.2: The membrane load configuration is how the membrane is used to retain a wafer during the time between polish cycles. Generally, the membrane is used as a suction cup, and vacuum applied to the membrane to retain the wafer.

DP 1.1.4.3: The membrane unload configuration is the means of removing the wafer from the membrane surface. Due to surface tension of the water between the membrane and the wafer, there may be some attractive force that must be broken. By inflating the membrane with pneumatic pressure, curvature may be introduced that will cause the wafer to dislodge.

DP 1.1.4.4: The wafer carrier vertical clearance when lifted represents the space that is required between the wafer and the loading structure. During polishing, the wafer carrier is pressed against the polishing pad, precluding the ability to load or unload a wafer. Between polishing cycles, the wafer carrier may be lifted for access by a robot, or lifted and moved to a location for exchange at a loading station.

FR/DP 3.2.1: Minimize overpolish percentage-Uniformity control mechanisms

To minimize the overpolishing of wafers, the only option is to improve uniformity. This decision is made with the assumption that the optimal endpoint is correctly used, meaning that some areas on the wafer are correctly polished, and some are overpolished.

The decomposition of FR/DP 3.2.1 is shown in Table 5, along with the associated design matrix in Equation 5, and a schematic of the elements in Figure 4. Following is a description of the DPs and their relationships to the FRs, explaining the off diagonal element in Equation 5.

Table 5: FR/DP 3.2.1.1 Decomposition

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
3.2.1.1	Control edge effects	Retaining ring pressure
3.2.1.2	Control polish rate as a function of radius	Radial pressure distribution

$$\begin{Bmatrix} \mathrm{FR}\ 3.2.1.1 \\ \mathrm{FR}\ 3.2.1.2 \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP}\ 3.2.1.1 \\ \mathrm{DP}\ 3.2.1.2 \end{Bmatrix} \qquad (5)$$

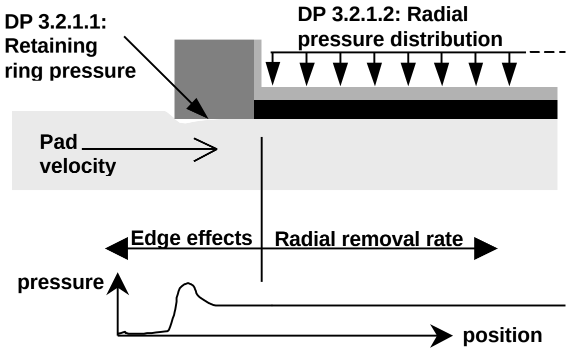


Figure 4: FR/DP 3.2.1 Decomposition Schematic

DP 3.2.1.1: The retaining ring is an element of the machine which originally satisfies the functional requirement to maintain the wafer position during polishing. When the DP for uniformity control mechanisms is introduced, the existing hardware element of the retaining ring is used to control the edge effects, by controlling the normal pressure against the polishing pad. This pressure has no effect on the ability of the retaining ring to maintain the wafer position during polishing, so functional independence is maintained. By making the retaining ring pressure approximately equal to the pressure at the polishing interface, the edge effects which would have occurred near the wafer are pushed out onto the retaining ring, a non-critical surface. The retaining ring pressure affects FR 3.2.1.2 because if it is too low or too high, the edge effects influence the wafer, and may be partially compensated by a mechanism to control the radial

DP 3.2.1.2: The radial pressure distribution directly affects the removal rate on the wafer. Since the wafer is rotating during polishing, the removal tends to be axisymmetric, and control is only needed in the radial direction.

The children of FR/DP 3.2.1 are primarily conceptual, so further decomposition is necessary. Each will be expanded in the following sections.

FR/DP 3.2.1.1: Control edge effects-Retaining ring pressure

The pressure under the retaining ring is controlled by connecting the retaining ring to the machine spindle through a flexure. By monitoring the strain in the flexure during polishing, and adjusting the vertical position of the spindle, the force on the retaining ring may be controlled. The decomposition of FR/DP 3.2.1.1 is show below, in Table 6, along with the associated design matrix in Equation 6 and a schematic of the system in Figure 5. Following is a description of the individual DPs, and the interactions they have with the FRs.

Table 6: FR/DP 5.2.1.1 Decomposition

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
3.2.1.1.1	Accommodate head-pad misalignment	Retaining ring flexure O.D.
3.2.1.1.2	Measure force from flexure	Retaining ring flexure strain
3.2.1.1.3	Control force from flexure	Z-Axis position during polish

$$\begin{Bmatrix} \text{FR } 3.2.1.1.1 \\ \text{FR } 3.2.1.1.2 \\ \text{FR } 3.2.1.1.3 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & X \\ O & X & X \end{bmatrix} \begin{Bmatrix} \text{DP } 3.2.1.1.1 \\ \text{DP } 3.2.1.1.2 \\ \text{DP } 3.2.1.1.3 \end{Bmatrix} \qquad (6)$$

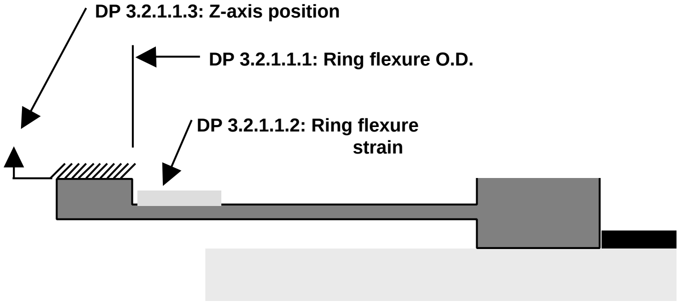


Figure 5: FR/DP 3.2.1.1 Decomposition schematic

DP 3.2.1.1.1: The retaining ring flexure O.D. is the outer diameter of the annular flexure. The inner diameter is constrained to fit the retaining ring, which surrounds the wafer. By controlling the O.D. of the flexure, sufficient tip-tilt compliance can be incorporated to tolerate some misalignment. Since the ring flexure is part of a precision machine, even one degree of misalignment would be a large amount, so the requirement is relatively easy to satisfy. The flexure O.D. influences FR 3.2.1.1.2 because the O.D. changes the relationship between force and strain, and therefore must be designed before the appropriate range of strain is known.

DP 3.2.1.1.2: The retaining ring flexure strain is measured using a strain gage applied to the upper surface of the flexure, on the outer perimeter. The gage is temperature compensated for the material it is mounted on to minimize thermal drift, and calibrated before polishing is started, as the ring contacts the pad. The flexure strain affects FR 3.2.1.1.3 because a change in the strain necessitates a change in the control effort.

DP 3.2.1.1.3: The Z-axis position during polish directly controls the separation of the spindle from the pad, and therefore is used to maintain the desired force on the ring flexure. The Z-axis position influences FR 3.2.1.1.2 because when the spindle height changes, the strain is a measure of the change. During polishing, the machine software measures the value for strain and adjusts the Z-axis position to compensate for error from the desired value. This forms a servo feedback system, and thus, the apparent coupling in the design is managed.

FR/DP 3.2.1.2: Control radial polish rate-Radial pressure distribution

The other uniformity control mechanism in the decomposition of FR/DP 3.2.1 is the radial pressure distribution. The pressure distribution is controlled by dividing the membrane used in the FR/DP 1.1.1.5 decomposition into annular zones, and then controlling the pressure in each of the zones. The flexible membrane used to apply pressure is compatible with such an approach allowing integration of the hardware elements. The decomposition of the radial pressure distribution is shown in Table 7, with the associated design matrix in Equation 7 and a schematic of the elements in Figure 6. Following is a description of the DPs, and their interaction with the FRs.

Table 7: FR/DP 3.2.1.2 Decomposition

Element #	Functional Requirements (FRs)	Design Parameters (DPs)
3.2.1.2.1	Divide wafer area into segments	Membrane compartment areas
3.2.1.2.2	Control applied pressure profile	Compartment pressure distribution
3.2.1.2.3	Smooth applied pressure profile	Membrane thickness; h-mem
3.2.1.2.4	Control pressure at discontinuities	Compartment divider vent length & I.D.

$$\left\{\begin{array}{c} \text{FR } 3.2.1.2.1 \\ \text{FR } 3.2.1.2.2 \\ \text{FR } 3.2.1.2.3 \\ \text{FR } 3.2.1.2.4 \end{array}\right\} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ O & O & X & O \\ O & X & X & X \end{bmatrix} \left\{\begin{array}{c} \text{DP } 3.2.1.2.1 \\ \text{DP } 3.2.1.2.2 \\ \text{DP } 3.2.1.2.3 \\ \text{DP } 3.2.1.2.4 \end{array}\right\} \quad (7)$$

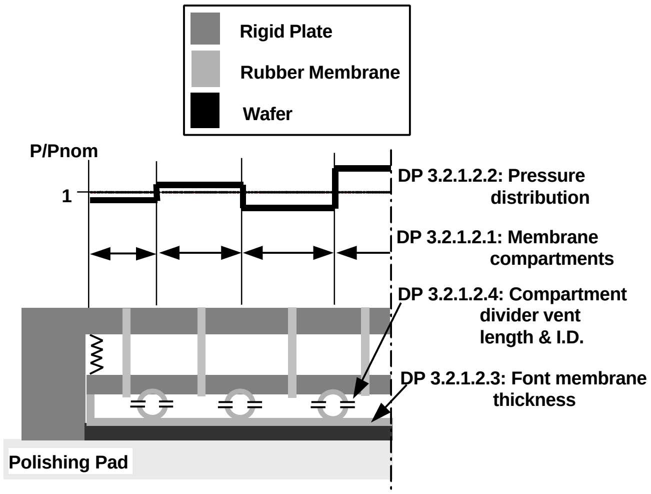


Figure 6: FR/DP 3.2.1.2 Decomposition schematic

DP 3.2.1.2.1: The membrane compartment areas are a means for applying a pattern of displacement in concentric rings to the wafer front surface. With this displacement, the wafer front side will see a variation if normal pressure due to the compression of the polishing pad. The membrane compartments affect FR 3.2.1.2.2 because the way the total area is divided into segments defines how the profile is controlled.

DP 3.2.1.2.2: The compartment pressure distribution is the pressure supplied to a particular bladder compartment to load the respective area of the wafer. Each individual compartment pressure is defined as a ratio to the nominal pressure. The pressure distribution affects FR 3.2.1.2.4 because the difference between adjacent compartments determines how much of a transition there is to smooth out.

DP 3.2.1.2.3: The front membrane thickness may be used to smooth the pressure distribution from the loading rings as it is transmitted to the wafer back surface. The front membrane thickness is coupled to the following FRs: 3.2.1.2.4: The membrane thickness will smooth out the discontinuities of pressure at the dividing walls, and so make the system more tolerant to such discontinuities. The maximum allowed variation across a transition from one compartment to the next is therefore influenced by the membrane thickness.

DP 3.2.1.2.4: The compartment divider vent length & I.D. are the characteristics that define flow through the vents into each compartment divider. The divider is formed of a tubular cross section, and therefore may contain a pressure that is an average of the adjacent compartment. The tubular cross section gives the divider a high compliance, so the pressure within it dominates the pressure applied to the wafer backside.

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