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DEVELOPING AN OBJECTIVE FORMULATION FOR MOTORCYCLE ARCHITECTURE

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Abstract

Though an objective formulation is available for building and IT architecture, no such formulation is available for architecture of automobiles, which characterizes the relationship between various elements of the design of a vehicle. This paper attempts to provide a mathematical formulation for engineering and visual architecture of motorcycles, define and quantify the complexity of architectural change to help the designer form the architecture strategy. This has been done by applying domain modeling concept to design data of motorcycles, scanning through the history of motorcycles in terms of architecture and applying the formulation to see how it helps the designers to understand the complexities of design changes. It concludes that major evolutions in motorcycles result in a drastic shift in architecture, visual architecture is a reflection of technological shifts and designers need to evolve architecture strategies for innovation.

Keywords: Product architecture, Complexity, Product structuring

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1 INTRODUCTION

ISO/IEC/IEEE 421010 (2011) defines architecture of a system as "fundamental of a system in its environment embodied in its elements, relationships and in the principles of its design and evolution". A fundamental feature unique to consumer oriented engineering systems is its visual design, which is not present in the case of software systems. Eilmus et.al. (2011) argue that a product program needs an analysis of tearing forces towards differentiation and standardization. Thus, vehicle architecture can be defined as the aspect of design which characterizes the relationship between various elements of the design of a vehicle. If the quantitative aspect fundamentally changes the relationship, it changes the architectural character in a significant way. Though the parallels between building and automobile architecture have been studied (Ristic, 1988), we don't find an objective formulation to describe and analyze it. For a motorcycle designer, the concepts of architecture are to be applied to parameters of motorcycle design to find an objective formulation, which helps the designer in addressing the complexities of architectural change.

2 OBJECTIVE

The high level design decision regarding modularity and platforms are based on concrete objective facts leading to concrete objective results. But, the architectural decisions which impact the design and the business in most profound way are mostly based on subjectivities. So, it becomes essential to not only find an objective formulation but to study the impact of this formulation on the architectural decisions as well. This paper attempts to: - (1) provide a mathematical formulation for engineering and visual architecture of motorcycles (2) scan through the history of motorcycle architecture in terms of the mathematical formulation and (3) find patterns through the historical data to establish how the formulation can help the designer in forming the design strategy for the motorcycle

An objective formulation (Wynes.et.al., 1996) helps the designer by: - (1) defining the complex dynamic systems in terms of simple models (2) focusing only on the areas requiring major change during redesign hence reducing the impact of changes to few models (3) indicating the most vital system components and constructs that should not be violated and (4) providing the means of communication during design or redesign process.

3 LITERATURE REVIEW

Jiao.et.al (2001) defines the architecture of product family in terms of three elements- common base, differentiation enabler and configuration mechanism. But, our challenge is to define the architecture of a product in such a way that it signifies the commonality and differentiation over wider range. Moreover Jiao's model does not account for visual architecture. Ulrich (1995) defines product architecture as (1) the arrangement of functional elements (2) the mapping of functional elements and (3) the specification of interfaces among physical components. This definition applies to automobile architecture suitably except for the fact that visual architecture is not accounted for as an independent criterion. Ristic (1988) provides a parallel with building architecture which includes visual architecture as well but it does not provide adequate basis for domain modeling as explained by Jacobsen (1999) and Millard.et.al (2008). Fractal analysis method attempts to quantify the complexity of visual architecture (Vaughan and Ostwald, 2014), but in context of building architectures. On the other hand methods for developing standardized and modularized platform architectures have been devised (Martin and Ishii, 2002). But, what we cannot find is an objective formulation combining visual architectures specific to the context of automobiles in general and motorcycles in particular. For research method Baxter.et.al (2008) provide us with exploratory and multiple case study methods.

4 METHODOLOGY

Based on the nature of the problem, we chose case study method and domain modeling technique for our research. Table 1 shows the research questions, data collection methods and the type of data.

Table 1. Research Methodology

Type of Case Study	Research Question	Type of Data	Data Collection Method	Remarks
Exploratory	What are the most important objects in context of motorcycle design and their inter-relationship.	(a) Elements of motorcycle design (b)Variations available for each element ©Design calculation methods indicating relationships between them	Data available from published sources and classified sources.	Domain modelling technique applied for formulating the mathematical model
Multiple case study	How did manufacturers formulate the architectural strategy and handle the complexities	Element-wise design data for Harley Davidson, Ducati, Honda and Hero	Through classified sources	Architectural complexity calculated and correlated with historical context

5 FRAMEWORK DEVELOPMENT

Engineering Architecture: Building on the definition by Ulrich, we define the four main systems which define a motorcycle as – frame, front suspension and wheel, rear suspension and wheel and engine. Going through the historical evolution of the design of these elements, an exhaustive list of various variations of these elements was prepared. Another list was prepared for the types of interfaces between the elements e.g. functional, dynamic, kinematic, and structural. Engineering architecture can be expressed as a combination of two matrices- one consisting of various elements and the second consisting of the relationships. Figure 1 shows a schematic representation of engineering architecture, where the four basic elements of a motorcycle are related through 6 lines each representing a specific type of relationship.

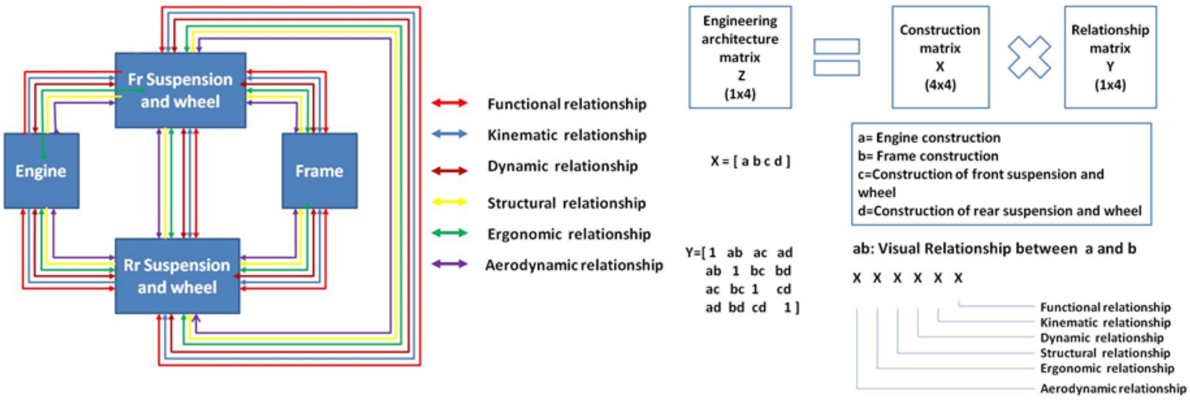


Figure 1. Schematic and Mathematical Overview of Engineering Architecture of Motorcycles

This scheme of engineering architecture lead us to define it as the product of two separate matrices- construction matrix (1x4) and relationship matrix (4X4). The resulting matrix will be a 1x4 matrix. The way to construct the construction matrix is shown in following four figures Figure 2 and Figure 3, where each element is broken into sub-elements and each element in the matrix is shown as a matrix constructed by its sub-elements. These sub-elements are the various constructs which define the elements. For example the architecture of a motorcycle is defined by its cylinder arrangement, no of cylinders, strokes, sparks/cylinder and valves/cylinder etc. Similarly, the architecture of frame is defined by its construction, material (here material does not represent the metallurgical property, but the raw material shape like sheet, tube etc.

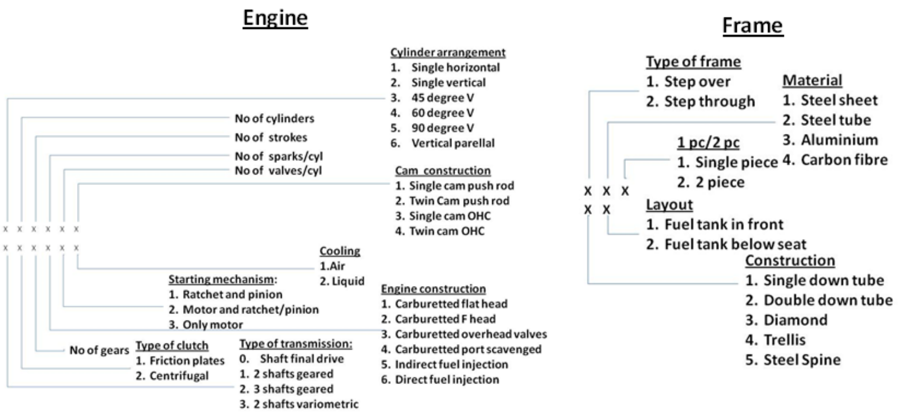


Figure 2. Engineering Architecture of Engine and Frame

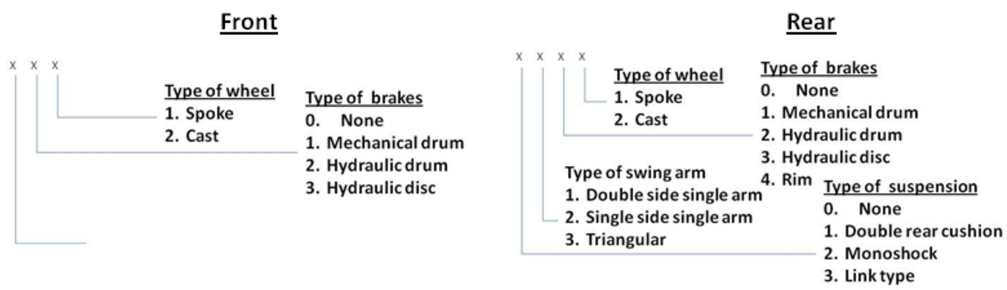


Figure 3. Engineering Architecture of Front and Rear Suspensions with Wheels

Now, these elements are related to each other in various ways to make the motorcycle function and the relationship matrix is constructed by 6 relationships ab, ac, ad, bc, bd and cd. Each of these elements of the relationship matrix is constructed by a sub-matrix constructed by 6 sub-elements, each representing the different type of relationships. These sub-elements are defined by Table 2.

Table 2. Sub-elements for Relationship Matrix

	ab (engin-frame)	ac(engine-front suspension)	ad (engine - rear suspension)	bc (frame-front suspension)	bd (frame-rear suspension)	cd (front suspension-rr suspension
Functional relationship	No of mountings	0:None	1: Chain drive 2: Belt drive	1: Castor agle decided by frame 2: Castor angle not decided by frame	0: None	1: Individual braking 2: Combination braking
Kinematic Relationship	Digree of freedom	0: None	1: Swing arm on frame 2: Swing arm on engine	1. Head light movable with handle bar 2. Fixed head light	0: None	0: None
Dynamic relationship	0: No significant impact on CG 1: CG in first quadrant 2: CG in 2nd quadrant 3: CG in 3rd quadrant 4: CG in 4th quadrant	0:None 1: Weight of engine significantly impacts the load deflection curve	0:None 1: Weight of engine significantly impacts the load deflection curve	1. High rake and high trail 2. Medium rake and medium trail 3. Low rake and low trail	0: None	0: None
Structural relationship	1: Engine not a stressed member 2: Engine stressed member	0:None 1: Significant impact of engine wt on axle loads	0:None 1: Significant impact of engine wt on axle loads	0:No significant variation	0:No significant variation	0:None
Ergonomic relationship	1:gear shift on left, kick on right 2: gear shift on right, kick on left	0: None	0: None	0: None	0: None	0: None
Aerodynamic relationship	1: Air flow restricted by body 2: Air flow not restricted by body	1: Air flow significantly restricted by fr fork 2: Air flow not significantly restricted by fr fork	0: None	0: Low frontal area 1: High frontal area with low Cd 2: High frontal area with high Cd	0: None	0: None

Visual architecture: A motorcycle has five visual elements and these elements have visual relationships in form of continuity of elements, unity of form and unity of lines. Besides these five, the holistic view of the overall construction itself can be considered the sixth element. Again the visual architecture can be expressed in terms of two matrices- one consisting of elements and the second consisting of relationships (Figure 4).

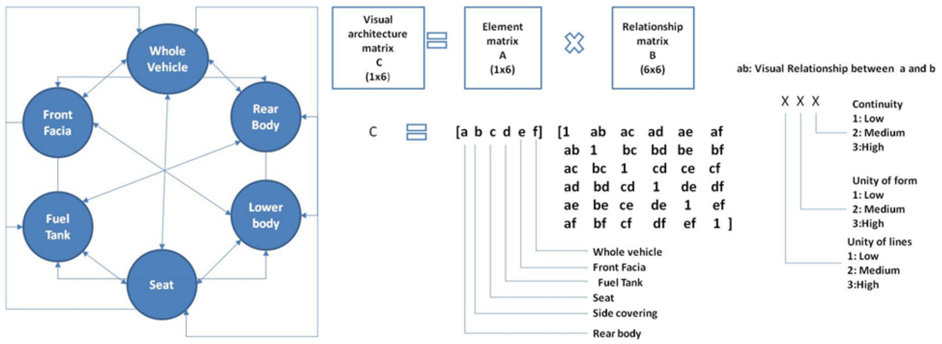


Figure 4. Schematic and Mathematical Overview of Visual Architecture of Motorcycles

The holistic view of the whole body architecture has many elements. The visual construction of bikes has seen many variations like two box, three box, whole cowl etc. Besides, the other elements like bulkiness, dynamism, length to height ratio, visual balance are illustrated in Figure 5 and remaining five elements in Table 3. These terms (visual balance, unity and dynamism) are objectively definable and quantifiable (Chandra and Atreya, 2012).

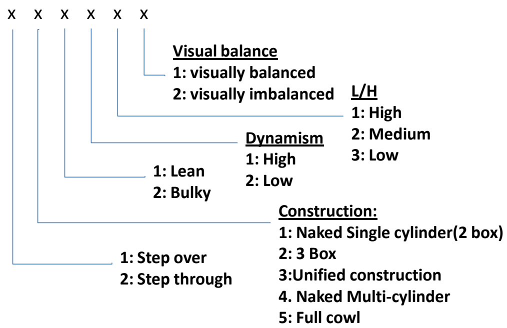


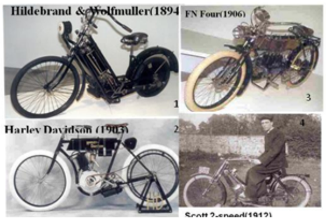
Figure 5. Sub-elements for Visual Architecture of Whole Body

Table 3. Sub-elements for Visual Architecture of Visual Elements

Matrix Code	Fuel Tank	Seat	Fr Facia	Side Covering	Rear Body
1	Single side surface with slow curvature	Single straight	Only round head light	Single box plain	Tail light and winker separate
2	Single side surface with fast curvature	Single inclined	Only rectangular head light	Two box separate	Tail light flush with rear winker separate
3	Mild negative space with sharp character lines	Single curved	Only trapezoidal head light	Two box unified	Tail light and winker flush with rear
4	Deep negative space with sharp character lines	Straight+mild curve	Round head light+visor	Unified from fuel tank to	
5	Deep negative space with generous character lines	Inclined+mild curve	Rectangular head light+visor		
6	Positive cuves with sharp character lines	Straight+deep curve	Trapezoidal head light+visor		
7		Inclined+deep curve	Round head light+visor and windshield		
8		Mild step (straight+straight)	Rectangular head light+visor and windshield		
		Mild step (straight+inclined)	Trapezoidal head light+visor and windshield		
		Steep step (straight+straight)	Twin head light+visor and windshield		
		Steep step			
		Single seater			

5.1 History of Motorcycle Architecture:

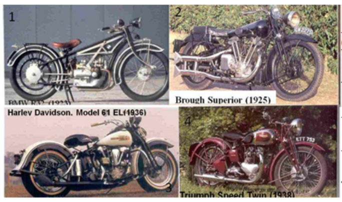
A brief and cursory look at the architecture of motorcycle (since its commercial inception in 1894) helps us in understanding how the architecture evolves.



S.No	Cylinders	Type	Strokes	Valves	Cooling	Transmission	Frame	Fr /Rr Brake	Fr /Rr Susp	Wheel
1	2	parellal	4	2	Water	Direct	Steel-downtube	Fr Spoon/Bar	None	Spoke
2	1	In over Ex	4	2	Air	Direct	Steel-downtube	Tele/rigid	None/contracting bar	Spoke
3	4	In-line	4	2	Air	Direct	Steel-downtube	Tele/rigid	None/contracting bar	Spoke
4	2	parellal	2	2	Liquid	2-s chain	Steel-downtube	Tele/none	Sirrup/shoe on sprocket	Spoke

Figure 6. Motorcycle Architecture Before First World War

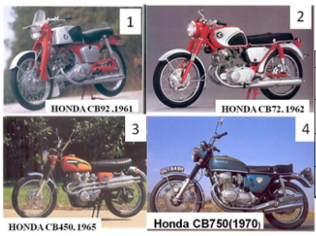
The first bunch of motorcycle till the first war (Figure 6), were all the motorized versions of a bicycle, without lights, without cushions at rear, with elementary brakes and a single horse-shoe seat. The next rush (Figure 7) surfaced after the war, when we had the fuel tank in the front as we know it today, wider tires, spring cushions at rear and lights at front. They still had, single seats and push rod mechanism for valve operation. The most important evolution was visual, where an architecture independent from bicycle had taken shape. The major reason for this evolution was technological and socio-economic. Technologically, metal processing had taken a great leap after the war and forming of sheet metal to desired forms was now possible. Socially, motorcycle had become the private mode of transport for those who could not afford cars.



o	Cylinders	Type	Strokes	Valves	Cooling	Transmission	Frame	Fr /Rr Brake	Fr /Rr Susp	Wheel
1	2	in-line	4	side-2	Air	Shaft final	steel-downtube	leaf spring/rigid	drum/rim	Spoke
2	2	v twin	4	ohv-2	Air	4s-chain	steel-downtube	Girder/twin spring	drum/drum	Spoke
3	2	v twin	4	ohv-3	Air	4s-chain	steel-downtube	springer/rigid	drum/drum	Spoke
4	2	parellal	4	push rod-2	Air	4s-chain	steel-downtube	Girder/rigid	drum/drum	Spoke

Figure 7. Motorcycle Architecture Between the Two World Wars

The post war situation saw two major shifts. The post war generation in US saw the baby-boomers graduating to the young age and cars getting as affordable as bikes. This resulted in bikes shifting from commuter to luxury segment which saw a major shift in visual architecture. Another factor was the Japanese manufacturers entering the scene in a big way. Technologically, the major impact of this was engines with overhead cams (Figure 8).



S.No	Cylinders	Type	Strokes	Valves	Cooling	Transmission	Frame	Fr /Rr Brake	Fr /Rr Susp	Wheel
1	2	parellal	4	ohv-2	Air	4s-chain	steel-downtube	Tele/twin shock	drum/drum	Spoke
2	2	parellal	4	ohv-2	Air	4s-chain	steel-downtube	Tele/twin shock	drum/drum	Spoke
3	2	parellal	4	ohv-2	Air	4s-chain	steel-downtube	Tele/twin shock	drum/drum	Spoke
4	4	in-line	4	ohv-2	Air	4s-chain	steel-downtube	Tele/twin shock	drum/drum	Spoke

Figure 8. Architecture of Japanese Motorcycles Before Seventies

The late century generation of bikes saw a revolution in terms of breadth, technological and visual architecture with Japanese manufacturers Honda, Yamaha, Suzuki and Kawasaki leading the march. On one hand, they expanded in South-Asia with single-cylinder two-box or three-box architecture; on the other hand they dominated US and Europe with in-line multi-cylinder super-bikes, both with naked and whole-cowl visual architecture (Figure 9).

S.No	Cylinders	Type	Strokes	Valves	Cooling	Transmission	Frame	Fr /Rr Brake	Fr /Rr Susp	Wheel
1	4	in-line	4	ohv-4	Liquid	5s-shaft	steel-twin downtube	Tele/twin shock	disc/disc	Cast
2	4	in-line	4	ohv-4	Liquid	5s-chain	Al twin spar	Tele/twin shock	disc/disc	Cast
3	4	in-line	4	ohv-4	Liquid	6s-chain	Al twin spar	Tele/twin shock	disc/disc	Cast
4	4	in-line	4	ohv-4	Liquid	6s-chain	Al twin spar	Tele/twin shock	disc/disc	Cast
5	4	in-line	4	ohv-4	Liquid	6s-chain	Al twin spar	Tele/twin shock	disc/disc	Cast
6	4	in-line	4	ohv-4	Liquid	6s-chain	Al twin spar	Tele/twin shock	disc/disc	Cast

Figure 9. Architecture of Recent Japanese Motorcycles

This brief journey through the history of motorcycles clearly illustrates how, the architecture has evolved with technological evolutions and demographic changes**.**

6 ARCHITECTURAL STRATEGY

Now the pertinent question, how this exercise in defining the architecture going to benefit the designer. After all, any kind of mathematical formulation makes sense only if it helps in reaching to a conclusion. The answer lies in formulating the design and development strategy. Any decision in design has different levels of implications varying from minor to huge ones. This mathematical formulation helps the designer and the project team in judging the complexities involved in any architectural decision. Sinha et.al. [10] have devised the topological complexity of the architecture of a system in terms of matrix energy. Using the same concept in context of motorcycles, we propose to define the complexity of engineering ($C_{\text{Engineering}}$) and visual changes (C_{Visual}) as shown in Figure 10 and the product of these factors gives the complexity of Architectural Change that expresses the enormity of the challenge involved in the decision.

$$C_{\text{Architecture}} = C_{\text{Engineering}} + C_{\text{Visual}}$$

$$C_{\text{Engineering}} = \Delta X \times \Delta Y$$

$$C_{\text{Visual}} = \Delta A \times \Delta B$$

$$\Delta X = [\Delta a\ \Delta b\ \Delta c\ \Delta d]$$

Δa, Δb, Δc, Δd =Impact of engine, frame, front and rear suspension architecture
0: No impact
1: Major change in toolings and infrastructure
2: Major change in supplier and OEM relationships
3: Major change in organizational structure

Figure 10. Complexity of Architectural Change

To illustrate an example, Harley Davidson was stuck with push-rod and air cooled engine architecture and low unity visual architecture, when it decided to affect a major architectural shift with V-Rod. A comparison of earlier generation of bikes and the resultant complexity in V-Rod is illustrated in Figure 11 to Figure 13.

Figure 11. V-Rod and Harleys before

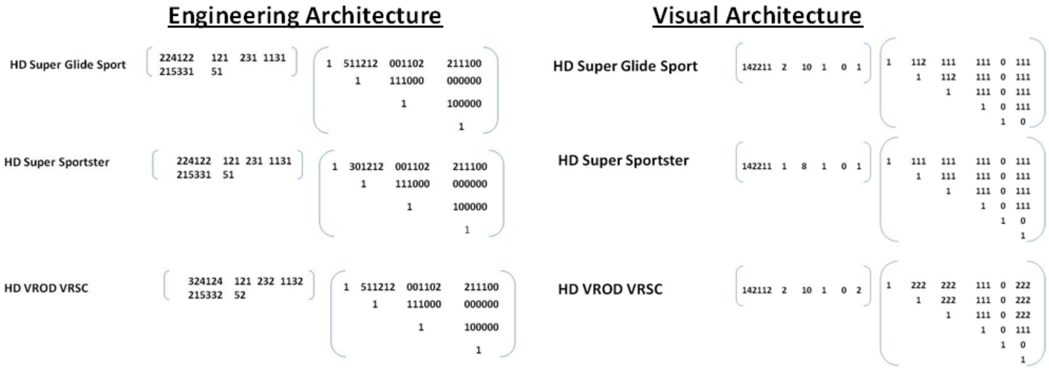


Figure 12. Engineering and Visual Architectures of Harley

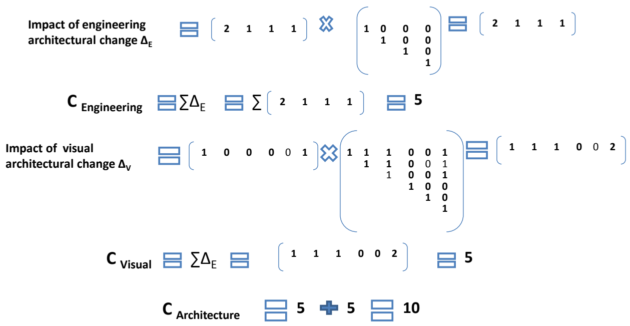


Figure 13. Complexity of Architectural Change for Harley V-Rod

Similar question was faced by Hero-Honda, when it launched its first above-100 cc bike CBZ. The comparison of architecture as illustrated in following diagrams (Figure 14 to Figure 16) shows that the complexity of architectural change involved was negligible. In fact, before the company launched its first beyond-200 cc bike Karizma, all the bikes launched by it had almost the same architecture, (barring Street, which had a step through architecture), with negligible complexity of change.

Figure 14. Hero-Honda Bike CBZ and Those before It

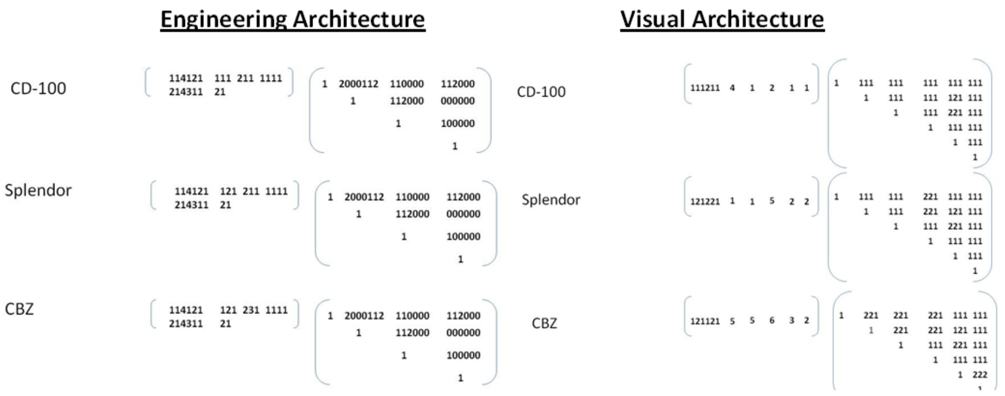


Figure 15. Engineering and Visual Architectures of Hero-Honda Bikes

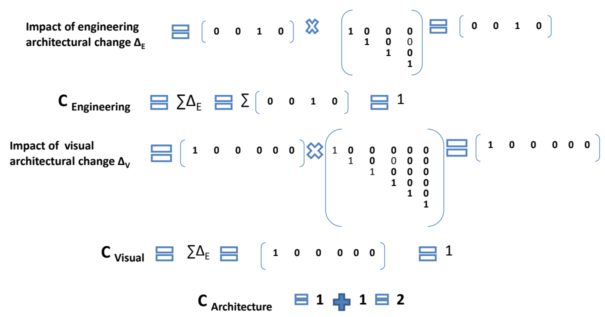


Figure 16. Complexity of Architectural Change for Hero-Honda Bikes

7 CONCLUSIONS

Product architecture, which has been defined earlier only in terms of engineering elements can be redefined to consider the visual scheme as well. More importantly, this framework can be used to establish the complexity of architectural change to help the designers. An evaluation of the results in this paper in light of the following observations leads to affirmation of the results:

Going through the history of motorcycles from pre-war era to today, throughout the evolution of motorcycles from basic to super-bikes, the architectures have seen major shifts depending on technology, geography and surrounding cultural changes. As the building architecture and fine-arts moved from modernism to post-modernism, the visual architecture of motorcycles has also moved from low unity to high unity bikes. Similarly the geographic shift of the centre of gravity of motorcycle production from US to Japan to India has also seen major shifts from V-twin engines to in-line cylinder engines to single cylinder motorcycles.

Technology has been a major driver for changes in architectural changes. Besides the above mentioned changes in engine architecture, we have seen how the world has moved from push-rod cams to overhead cams, air cooled to water-cooled engines, drum brakes and spoke wheels to disc brakes and cast wheels, steel frames to aluminium frames, front fuel tanks to below seat fuel tanks.

Visual architecture is a reflection of technological shifts. Again, the changes in engineering architecture for V-Rod resulted in the completely new visual idiom for Harley.

Designers need to evolve architecture strategies for innovation. As the V-Rod example shows, architectural strategy is the key to innovation. It is not my contention that, high complexity inhibits innovation. The point is that a realistic assessment of complexities prepares the organization for corresponding changes in manufacturing systems and developmental eco-system.

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