

Symbiotic Design of Products and Manufacturing Systems Using Biological Analysis

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Abstract

Changes in manufacturing systems are often driven by product design variations that exist at specific points in time, and gradual product design changes that appear over time. Further interactions take place to fully utilize established manufacturing system capabilities when considering product future designs. This is common in eco-systems when two or more different species co-evolve simultaneously, and it has inspired the development of a new model to capture the symbiotic relationship between products and their manufacturing systems based on Cladistics which is commonly used in biology. The obtained hierarchical order was analyzed in depth to track the product changes record and guide the next design steps to benefit from system capabilities.

Keywords:

Design Change, Evolution, Symbiosis, Cladistics Analysis

1 INTRODUCTION

This research is motivated by the belief that some clues from nature can help explain products development and find parallels between their progression and that of the manufacturing systems used to produce them. One of these clues and parallels can be found in biological evolution. Evolution in nature is considered the source of life diversity on earth; it causes both gradual change overtime and brings about distinct variations at specific times. Different species in nature do not live in isolation; they interact, change and together produce new varieties [1]. It is believed that this kind of co-evolution is not limited to nature, but it can also be observed in manufacturing environments, albeit with different mechanisms, since products design and manufacturing systems are dynamic and dependant on each another.

Products design *changes* and *variations* are two main drivers that affect the manufacturing system design and capabilities. In nature; change and variety accompany evolution of species, while in manufacturing they accompany the co-evolution of products and systems. In nature, species that do not adapt and evolve fade away and become extinct. Similarly, in manufacturing, systems that do not accommodate the products changing processing requirements become less useful and are eventually phased out.

Products evolution modeling that follows the biological evolution definition was developed [2] as a first step towards a more comprehensive design framework, described in this paper, that considers not only changes in products design but also the corresponding manufacturing systems design changes. Cladistics is a mathematical technique that is commonly used in biology to visually help understanding the theories behind different species taxonomies, and eventually how they evolve and vary. That method was utilized to identify how manufactured products evolve and to illustrate the

potential knowledge and information that can be gained from the developed model.

In this paper, the developed classification method [2] for products instances is extended to include the wider view of product / system design inter-dependency and symbiotic relationships. In addition, a methodology is proposed for recommending the type and direction of logical product design modifications in order to increase the life span of a current manufacturing system and to exploit its full capabilities. An innovative in depth cladogram analysis is presented, which utilizes the historical data set of a product to shed light on its possible future design steps taking into consideration the manufacturing system capabilities.

2 SYMBIOSIS IN MANUFACTURING

Most design methodologies of manufacturing systems found in literature are uni-directional [3], where the needs are identified in terms of functional requirements, and the system components are expressed as design parameters and are best expressed in the 'Axiomatic Design' process terms [4]. However, the flow of the design tasks is normally in one direction, from functional requirements through to definition of the system components and their relationships and design parameters.

The overall view of a manufacturing system design methodology has to change to account for the noticeable mutual influence between products and manufacturing systems. In view of the apparent symbiotic relationship between changes in products and those in their manufacturing systems, where change of characteristics over time and emergence of variants at specific instances, a corresponding two way flow should exist in the design process that relates both products and systems components designs and changes. That loop is meant to capture the natural progression of products design, or technology break throughs by expressing and

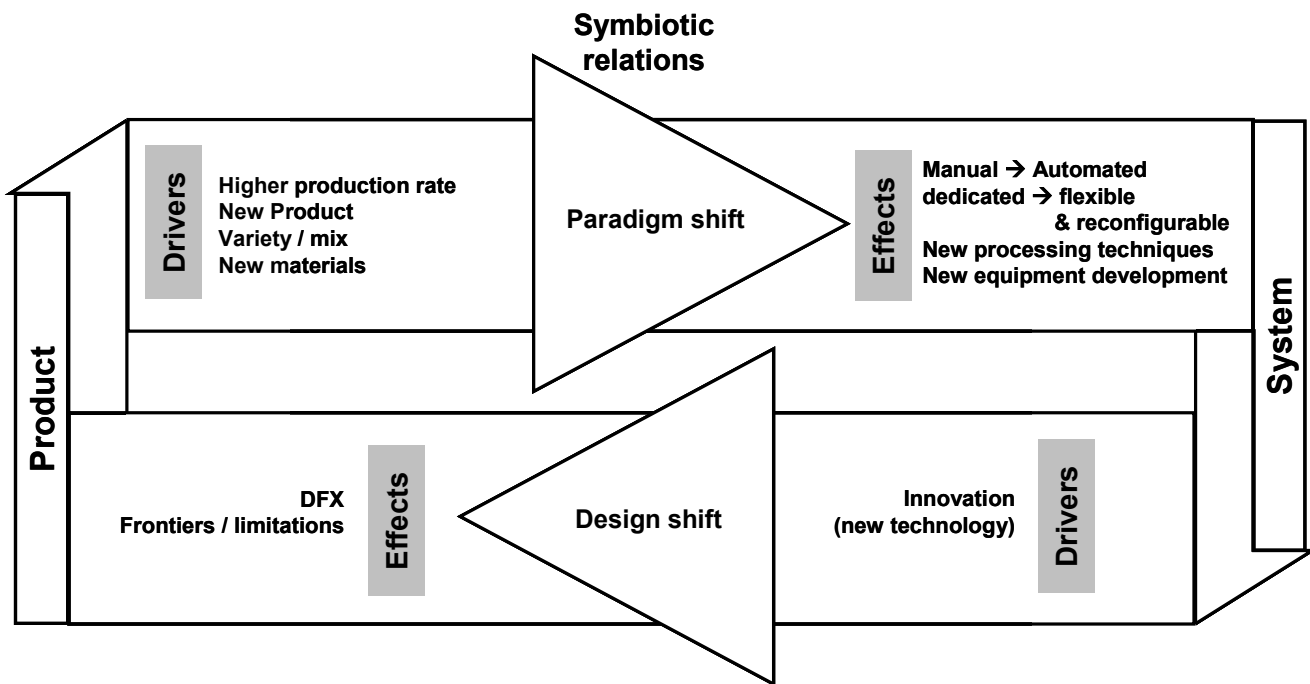


Figure 1: Disruptive Symbiosis in Product / System Relationships.

modeling their close inter-dependence and symbiotic relationship. A change or a variation in product design would change the processes needed to produce it, which would require changes in the manufacturing system design, unless the current system capabilities are sufficient to accommodate the product changes. The modified system capabilities in turn would present new opportunities for processing additional features that may be introduced over time as the products change or vary.

The symbiosis between products design and manufacturing systems may be characterized as either *disruptive* in the case of innovations and inventiveness or *steady* to account for gradual effects exchange between products and manufacturing systems.

2.1 Disruptive symbiosis

Drivers exist for any change; those drivers might be sufficiently strong to infuse a series of milestone effects. These influential strong drivers do exist in the domain of products and manufacturing systems. They don't just result in minor tweaks on both sides, but they introduce total renovation. Some examples of these powerful drivers and their effects are shown in Figure 1. They may include on the product side the need for higher product production rate, introducing a totally new product, and moving to a product family concept, as well as the introduction of new technologies and processes on the system side. All of these drivers are massive in their effects. They often lead to a major production paradigm shift affecting the manufacturing systems and often cause complete re-assessment of products design. Changing from manual operation to automation, dedication to flexibility, applying principles of design for automation, assembly, and manufacturability (DFX) all represent possible twists in the original conditions. It should be mentioned that this kind of symbiosis is impulsive and disruptive where innovation and creativity in producing new solutions are part of the symbiosis process.

2.2 Steady symbiosis

The other type of symbiosis between products and manufacturing systems can be considered gradual and steady; it does not involve big leaps, or major changes on either side. This kind of symbiosis is the main concern of this paper; it is the type of influence that needs to be

perfectly directed with the least effort and careful pre-planning to gain the most benefit from the changes. Introducing a new product variant to an existing product family, making a product design update, or installing additional manufacturing capabilities in a system, are all common change drivers that do not require massive change in either domain, they rather need new vision to direct these changes and their consequential effects in a clear and streamlined design process flow (Figure 2).

Few examples are found in literature to illustrate the selection of the appropriate product design from a given set of solution options to best suite a current configuration in a Reconfigurable Manufacturing System (RMS) [5], and reconfiguring machines layout according to a current configuration plan to minimize cost [6, 7]. However, the notion of cyclical and bi-lateral interactions between products and manufacturing systems does not exist. A manufacturing system structure can be adjusted based on processes needs and constraints and the products design can be modified and optimized given the current system capabilities. Both *change* and *variety* are present in the two dimensional symbiotic relationship between products and manufacturing systems.

2.3 Changeable boundaries of products families

Innovative ideas about how families of products evolve to form new species, which are closely related to the essence of biological evolution, were presented and the new term "Evolving Parts / Products Families" was coined [8]. The changes occurring in those product families over time were described as mutations, with features losses and gains through generations leading to the appearance of new families of products. Novel models and methodologies for "Evolvable and Reconfigurable Process Plans", which are capable of responding efficiently to both subtle and major changes in "Evolving Parts and Products Families" and "Changeable and Reconfigurable manufacturing systems", were developed [9, 10]. In this approach, the sequence of features / operations, which represent the Macro-process plan, is thought of as a genetic sequence and the added new features / operations in the reconfigured process plan would represent mutation of that sequence by optimally inserting new genes (features / operations). This is consistent with the concept of evolving parts families and

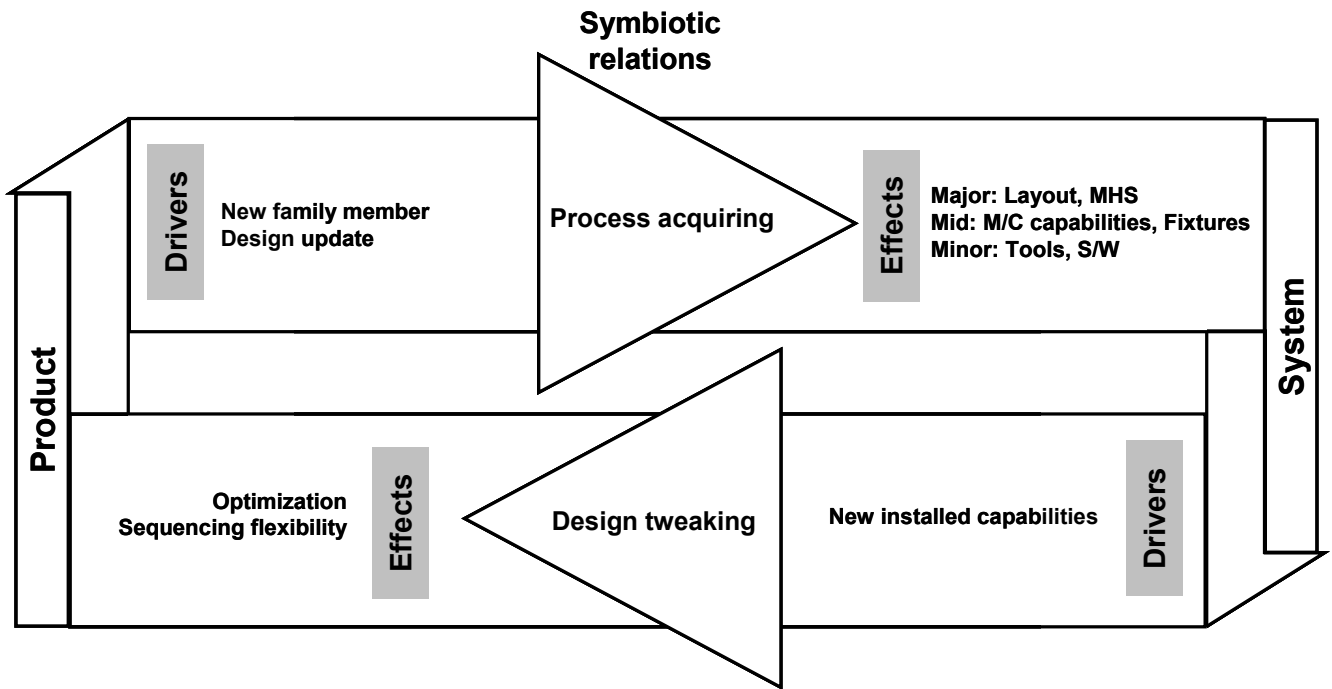


Figure 2: Steady Symbiosis in Product / System Relationships.

the biological evolution context. Such evolving families with dynamic changeable boundaries need a manufacturing system with higher adaptation capabilities, which led to introducing the notion of changeable manufacturing and emphasizing the importance of building change enablers into the system [11]. However, the benefits from changeability enablers, such as reconfigurable process plans, in manufacturing systems are not fully utilized yet. Two-way links should be established to reflect the inter-dependence of products families and the manufacturing systems capabilities.

2.4 Evolution in Biology

In nature, organisms are always changing, their properties and characters are altered and transformation in their form and behavior is observed through the generations. These changes are described as the biological evolution of life forms. Evolutionary modification in living things has some distinctive properties; evolution does not proceed along some grand, predictable course, instead, the details of evolution depend on the environment that a population happens to live in and the genetic variants that happen to arise in that population.

Biological evolution does not just indicate an individual temporary change in attitude or in morphology of a group of entities, but rather describes the wider inheritable changes transferred to successors from their ancestors. That is why the main characteristic of evolution process is not only the occurrence of the change, but rather the ability to preserve and transfer that change over time. This emphasizes the fact that evolution as described in biology is gradual and steady compared to the spontaneity of creation and innovation.

2.5 Cladistics for manufactured products change analysis

As evolution is a process of change for the involved entities, if a classification is linked to this change process, it is postulated that groups of manufacturing entities can be formed based on similar technological and behavioral attributes, and that there will exist an ideal model or solution for the group. This group reference model will then help reduce the time and costs associated with developing solutions (e.g. design procedures, process plans, tooling and fixturing methods, etc.) for individual

entities within that group. The existence of a manufacturing classification is based on the process of comparative study, which enables the storage and retrieval of information to facilitate the application of generalization points. This process enhances the knowledge and understanding of entities in the manufacturing environment and enables early predictions about their behavior [12].

Cladistics is an important classification approach in biology that establishes a classification scheme based on commonalities. Cladistics is a method of classification that groups entities hierarchically into discrete sets and subsets, in order to organize their comparative data. Cladistics is used mainly in the field of biological Systematics, however, it was also used in the field of organizational Systematics [13]. It was recently used by the authors to study evolution in manufacturing [2] and to construct a layout of an assembly line that follows a delayed product differentiation strategy [14]. In this paper, Cladistics is used to extend the earlier product evolution study to capture the steady symbiosis between products and manufacturing system(s) due to gradual changes.

Cladistics was originally developed by Hennig [15], where the systematic construction process begins with choosing end-taxa, which are the variants to be investigated and placing them at the end of a cladogram (tree-like

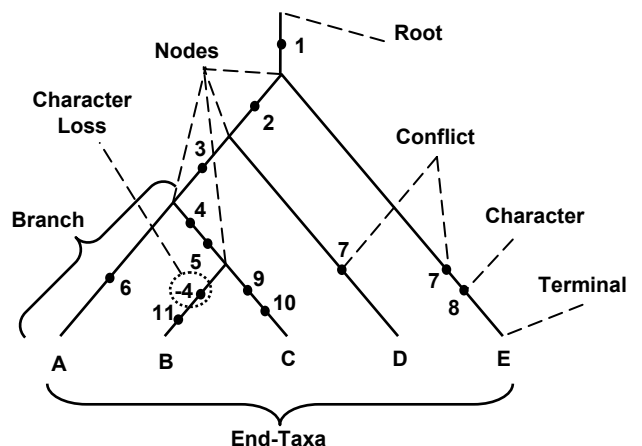


Figure 3: Cladogram Shape and its Related Terms.

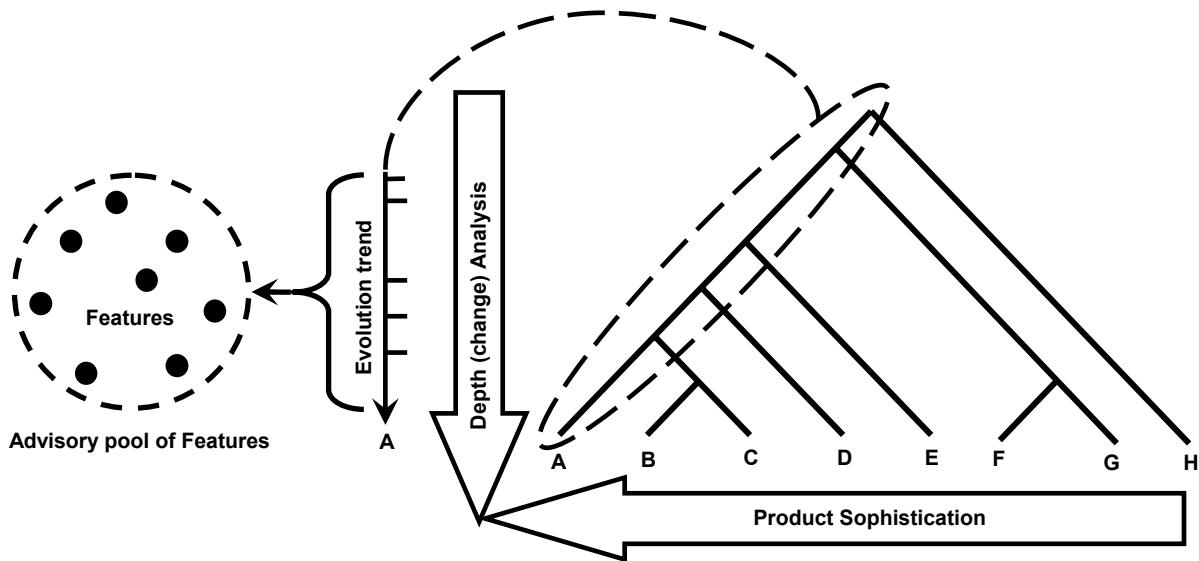


Figure 4: Cladistics' Depth Analysis to Manage Change in Products.

structure) terminals (Figure 3). Next, each character states inherited by each taxon are identified. While a character means a certain feature, its states are its different values, ranges, shapes, phases...etc. A Cladogram length is the number of steps appearing in the cladogram, which is the total number of character state changes necessary to support the relationship of the taxa in a tree. Fewer steps mean a better Cladogram and better representative hypothesis of the taxa relationship, or what is referred to as 'parsimony'.

3 DIRECTING PRODUCT DESIGN TRENDS USING CLADISTICS ANALYSIS

While Cladograms are meant only to be a visual aid for clarifying concepts in biological science regarding organisms' taxonomies, some additional and beneficial information can be derived from them using the innovative and new analysis introduced in this paper for managing products change with respect to manufacturing system capabilities. A depth Cladogram analysis is performed for managing products change (Figure 4), which can be described in the following steps:

- Identify the features that impose design differences among studied product entities.
- Gather the needed historical data about the different product entities (data about product entities from different competitors may enrich the analysis, and reveal more perspective).
- Perform Cladistics analysis and obtain the most parsimonious Cladogram.
- Search for the Cladogram branch that contains the most evolutionary twists (largest number of character states – it represents product evolution trend).
- Retrieve existing characters on the found branch.
- Establish an advisory pool of features using those characters.

Examination of the Cladogram tree can easily identify the branch that contains the most nodes and other branches that are splitting out of it. An example of this kind of branching is shown in the far most left side of the cladogram in Figure 4, however its location can be anywhere on the tree depending on the layout of the resulted cladogram, yet, the identification criterion, being the highest number of splitting nodes, remains the same.

Identifying that branch corresponds to recognizing the trend of product design evolution, since usually the most sophisticated product in the entire studied set of products would be located at the end of that branch, as an end-taxon (terminal entity). Such innovative analysis was not originally attributed to Cladistics; however, it promises to be useful as a planning, managing and analyzing tool for the historical progression and evolution of a product.

Since this analysis considers nodes, it is called "Depth" analysis - as the number of splitting nodes increases the Cladogram branches get longer and deeper. The analysis reveals a design trend that represents the evolutionary twists exhibited in the history of the most sophisticated product entity in the studied set of products. Furthermore, the features that appear along that branch (trend) can be retrieved and stored in an advisory pool of features. As the product changes gradually, the manufacturing system changes accordingly and new capabilities may be added as needed. However, in the subsequent product design changes, some of these product characters / features may be lost / eliminated, while the manufacturing system continues to possess the related capabilities. The advisory pool of features then represents a design boundary. If the next product design lies with that boundary; it would be compliant with the current capabilities of the manufacturing system, and no further system changes would be needed to produce the new designed product.

The use of the advisory pool of features would also exclude the undesirable product features that were proven not to hold against change and design requirements (i.e. that did not survive). Less sophisticated products appear as end-taxa of the right hand side branches of the Cladogram where some features that don't appear on the evolution trend branch are found. This indicates their lack of survival and adaptation ability; hence they are excluded from the advisory pool of features.

A case study that shows how data can be analyzed to derive an advisory pool of features for further product development is presented in the next section.

4 CASE STUDY - PLANNING FUTURE CYLINDER BLOCK CHANGES

A set of cylinder blocks that consists of six different instances is used as an example to demonstrate the use

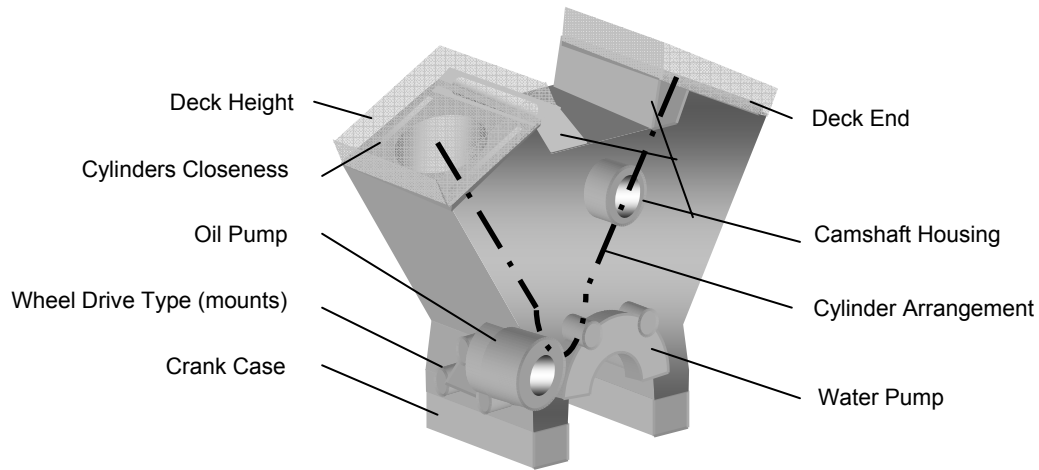


Figure 5: Cylinder Block with All-Derived Characters.

Characters		States	Description
1	Material	0	Aluminum
		1	Cast Iron
2	Cylinders Arrangement	0	Inline with $\varnothing=0$
		1	V-Banks with $\varnothing=60^\circ$ or 90°
3	Wheel Drive Type	0	Front- (transverse position engine)
		1	Rear- engine mounts are on block sides (longitudinal position engine)
4	Deck End	0	Open- block made by die casting
		1	Closed- block made by sand casting
5	Cylinders Closeness	0	Siamese cylinders
		1	Separated cylinders
6	Skirt (Crank Case)	0	Assembled to the block
		1	Integrated with the block
7	Camshaft Housing	0	Absent from block (over head cam)
		1	Camshaft and Pushrods housing exists in block (over head valve)
		1	Exists (Balance shafts overcome 2 nd harmonic vibrations in the engine)
8	Water Pump	0	Completely separable from the block
		1	Pump housing integrated in the block
9	Oil Pump	0	Completely separable from the block
		1	Mounted on the block
10	Deck Height	0	Low deck *stroke length<bore diameter
		1	High deck *stroke length>bore

Table 1: Identifying studied characters and their states.

Characters Variants	Characters									
	1	2	3	4	5	6	7	8	9	10
4A-GEU 1587cc	1	0	1	0	0	1	0	0	1	0
711 M 1691cc	1	0	1	1	1	0	1	0	1	0
QR20DE 1998cc	0	0	0	0	1	0	0	1	0	0
Mopar 2360cc	0	0	0	0	0	0	0	1	1	1
Buick215 2900cc	0	1	0	0	0	1	1	1	0	0
LS2 5967cc	0	1	1	0	0	1	1	1	1	0

Table 2: Characters' States in the studied cylinder blocks.

of the proposed Cladogram depth analysis and its merits. The cylinder block variants belong to automotive engines of different makes and materials (extended data of more

cylinder blocks and more features are published in [2]). The cylinder blocks are made of either Aluminum or Cast Iron. They belong to either inline or V-type, high-deck or low-deck, front or rear wheel drive, Over Head Cam (OHC) or Over Head Valve (OHV) engines. Table 1 identifies and summarizes the different characters, states variations, and their descriptions. In the character states column; (0) means that the cylinder block variant does not possess the character or it is absent or primitive (low profile state), and (1) means that the character exists or it is derived (high profile state). Figure 5 shows a composite part for the cylinder blocks representing the whole data set including all derived features. The six cylinder blocks are also presented along with their inherited characters in OTable 2.

A commercial package ('WinClada') was used to perform Cladistics analysis on the given data set. The Cladogram in Figure 6 represents the hypothetical evolutionary path of the six presented cylinder blocks. The total length of this Cladogram is 17 steps, which is the most parsimonious for this set of data. The small solid circles represent derived character states, while the small hollow circles represent the disappearance of a character in further evolutionary steps, which was allowed in this Cladistics analysis as they simulate features lost due to design considerations along the product evolution history.

Depth analysis was performed on the obtained Cladogram. The '711M' engine branch contains most of the evolutionary twists and design changes among all other studied engines. That branch represents the evolution trend of the studied set of engines. The intended advisory pool of features can be established by retrieving the characters appearing along that trend (branch). It contains 8 characters (1, 3, 4, 5, 6, 7, 8 and 9) while two characters (2 and 10) are excluded as they appear in less sophisticated engines. Although characters 6 and 8 disappeared in later evolutionary steps in this trend, their corresponding manufacturing system capabilities remain. Hence, they can be used in a future product design especially that their disappearance occurred late in the evolution path of this trend.

5 CONCLUSIONS

Product design has always been the outcome of designers' innovative creation, however, that outcome needs to be managed and logically guided to benefit from the product past evolution and inform the next generation

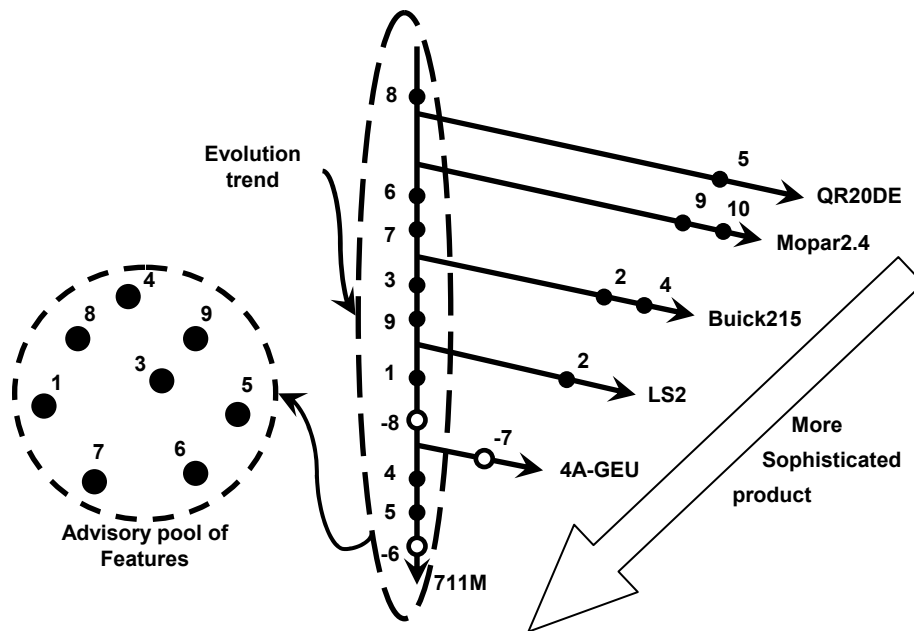


Figure 6: Depth Analysis of the Cylinder Blocks Cladogram.

product design. An innovative method of product design analysis based on Cladograms was introduced. The Cladistics technique is a way to logically order entities in a hierarchy according to their commonality. Hence it was used innovatively in this paper to reveal and analyze product evolution (change) using in depth Cladogram analysis to isolate the most evolutionary branch with the most evolutionary twists, which resembles the change trend in the studied set of products. The design features appearing along the change trend are used to form an advisory pool of features that defines the desired targeted boundary for future product designs. The features pool is consistent with the capabilities that already exist within the manufacturing system and excludes the features that were not required by the most sophisticated products.

The feedback to the product designer, based on this analysis, has the benefit of prolonging the life and utility of manufacturing systems and reducing the need for its reconfiguration, re-design, re-tooling or dismantling by advising the designer on the most promising products family boundary and existing factory resources. This feedback is one part of the proposed design framework that captures the symbiosis between products and manufacturing systems. The presented innovative framework of this symbiotic relationship is akin to the biological co-evolution model found in nature. It aims to manage product variation and change through enhancing the design process of both the product and the manufacturing systems.

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