2011

Co-evolution in Manufacturing Systems Inspired by Biological Analogy

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by

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A Dissertation
Submitted to the Faculty of Graduate Studies
through Industrial and Manufacturing Systems Engineering
in Partial Fulfillment of the Requirements for
The Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada

2011

Co-evolution in Manufacturing Systems Inspired by Biological Analogy

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Declaration of Co-Authorship / Previous Publication

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I hereby declare that this thesis incorporates material that is result of joint research of the author and his supervisor Prof. Hoda ElMaraghy. This joint research has been published / submitted to numerous Journals that are listed below.

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I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

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This thesis includes [7] original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Thesis Chapter	Publication title/full citation	Publication status
3, 4, 5	AlGeddawy T ,ElMaraghy H, 2010, A Model for Co-evolution in Manufacturing Based on Biological Analogy, International Journal of Production Research, DOI: 10.1080/00207543.2010.497780	Published Online
3, 4, 5	AlGeddawy T ,ElMaraghy H, 2010, Co-evolution hypotheses and model for manufacturing planning, CIRP Annals - Manufacturing Technology, 59/1: 445-448	Published
5	ElMaraghy H, AlGeddawy T ,Azab A, 2008, Modelling evolution in manufacturing: A biological analogy, CIRP Annals - Manufacturing Technology, 57/1:467-472	Published
4, 5	AlGeddawy T ,ElMaraghy H, 2011, Manufacturing Systems Synthesis Using Knowledge Discovery, CIRP Annals - Manufacturing Technology, 60/1	In Press
4, 5	ElMaraghy H ,AlGeddawy T, 2010, Co-evolution of Products and Manufacturing Capabilities and Application in Automotive Assembly, Flexible Services and Manufacturing Journal	In Press
6	AlGeddawy T ,ElMaraghy H, 2010, Design of Single Assembly line for the delayed differentiation of Product Variants, Flexible Services and Manufacturing Journal, 22/3: 163-182	Published
6	AlGeddawy T ,ElMaraghy H, 2009, Assembly systems layout design model for delayed products differentiation, International Journal of Production Research, 48/18: 5281 – 5305	Published

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ABSTRACT

The artificial world experiences continuous changes that result in the evolution of design features of products and the capabilities of the corresponding manufacturing systems similar to the changes of species in the natural world. The idea of simulating the artificial world, based on the analogy between the symbiotic behaviour of products and manufacturing systems and the biological co-evolution of different species in nature, is expressed by a model and novel hypotheses regarding manufacturing co-evolution mechanism, preserving that co-evolution and using it for future planning and prediction.

Biological analogy is also employed to drive the mathematical formulation of the model and its algorithms. Cladistics, a biological classification tool, is adapted and used to realize evolution trends of products and systems and their symbiosis was illustrated using another biological tool, tree reconciliation. A new mathematical method was developed to realize the co-development relationships between product features and manufacturing capabilities. It has been used for synthesizing / predicting new species of systems and products.

The developed model was validated using machining and assembly case studies. Results have proven the proposed hypotheses, demonstrated the presence of manufacturing symbiosis and made predictions and synthesized new systems and products. The model has been also adapted for use in different applications such as; system layout design, identifying sustainable design features and products family redesign to promote modularity.

The co-evolution model is significant as it closes the loop connecting products and systems to learn from their shared past development and predict their intertwined future, unlike available unidirectional design strategies. The economic life of manufacturing systems can be extended by better utilizing their available capabilities, since the co-evolution model directs products - systems development towards reaching a perfect co-evolution state.

This research presents original ideas expressed by innovative co-evolution hypotheses in manufacturing, new mathematical model and algorithms, and demonstrates its advantages and benefits in a wide range of applications.

DEDICATION

To my mom who raised me up

To my wife who kindled my life

To my supervisor who always supported my thoughts and encouraged my steps

Thank you wonderful ladies.

ACKNOWLEDGEMENTS

The author wishes to extend his appreciation to the sincere guidance of Professor Hoda ElMaraghy. The inspiration of her discussions, comments and follow-up has driven so far the ideas and hypotheses of this research. Not to mention the huge amount of her devoted effort and time, and her support and confidence for new ideas and propositions.

The author also wishes to honor the sincere and helpful feedback from all of his committee members specially the in-depth discussions of Professor Waguih ElMaraghy and his valuable suggestions regarding research publications and presentations. The author also thanks the Ph.D. supervisory committee members: Professor Fritz Reiger and Professor Richard Caron as well as past members, Dr. G. Zhang and Dr. F. Moro, for their support and advice.

The author acknowledges the great role of the Intelligent Manufacturing Systems Centre (IMSC). The academic meetings of the centre exposed the author to the most recent research topics and advances in the field of industrial engineering. Fresh material has been regularly presented by the centre professors, researchers and invited speakers. Those meetings allowed discussing Ph.D. research ideas and results with professors and other researchers through a series of formal presentations. Through the excellent communications between IMSC and industry; it was possible to identify real industrial problems and collect data from plant floors to validate proposed research models. This research atmosphere in IMSC motivates to excel, innovate and collaborate. IMSC also provided a great exposure to the CIRP (International Academy for Production Engineering) community through attending CIRP assemblies, conferences and presentations, which provided valuable learning experience and continuous feedback that greatly benefited Ph.D. research.

The author also gratefully acknowledges the funding provided by the Canadian Natural Science and Engineering Research Council (NSERC) and Canada Research Chairs program as well as the University of Windsor tuition scholarship and Research Assistantship provided by Dr. Hoda ElMaraghy; which gave the author a great opportunity to focus solely on his research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Motivation

New artifacts are constantly introduced to the market to satisfy customer needs and functional requirements. Those artifacts are the products of their manufacturing systems, which get their capabilities built to produce the features of those products. Nevertheless, products usually get redesigned and upgraded with full cognizance of the available manufacturing technologies and systems.

That close association of both products' design and manufacturing capabilities is evident, since those capabilities should include all the necessary required hardware to produce these products. The lifecycle of manufacturing systems are becoming shorter; since the lifecycle of products are enduring the same symptom. This urged manufacturers to adapt their systems to the frequent products changes, while designers are challenged to utilize all available manufacturing capabilities before introducing features that require additional or different facilities. Therefore, planning the progressive development of manufacturing systems to cope with the changing requirements is becoming not only essential, but also very complex in the uncertain world of rapidly varying customer requirements and processing technologies.

1.2 The Need for a new Model

Previous research work related manufacturing systems current configuration design to the requirements of products; but only few considered the transition of manufacturing systems design and configurations over several planning periods, yet with no clear association rules between the evolution of products and manufacturing systems. However, manufacturing systems experience clear cycles of change regarding both their capabilities and the produced products design, throughout their life.

The objective of this research is to recognize the symbiosis mechanism of intertwined changes between products and manufacturing systems, and forecast future symbiosis based on their related history. To achieve this goal, this research introduces a model that represents the association between products and manufacturing systems in the artificial world, plans the new products' designs to exploit most of the available manufacturing capabilities, and introduces only the necessary capabilities to perform the manufacturing process of those products. This research perceives the good managing and planning of manufacturing capabilities simultaneously with product design as a part of the solution to handle the persistent symbiotic change of artifacts design and manufacturing technology. That symbiosis is noticeably similar to biological co-evolution in nature, where different species affect each others' evolution.

The portrayal of the artificial world as similar to natural systems is familiar in literature. In Systems Thinking area; manufacturing systems and enterprises have been depicted as similar to living beings that have lifecycles of a biological pattern, which starts with 1) conception - the system is not yet existing, through 2) birth - system synthesis, 3) childhood - system value recognition, 4) adolescence - exhausting surrounding resources, 5) maturity - next generation system idea starts to emerge, 6) decline - new system is starting to replace the existing one, and finally 7) death - total old system replenishment (Slocum and Lundberg 2001). That pattern is commonly represented by a biological S-curve graph (Figure 1.1), showing the changing characters of the system vs. time (Zlotin *et al.* 2002).

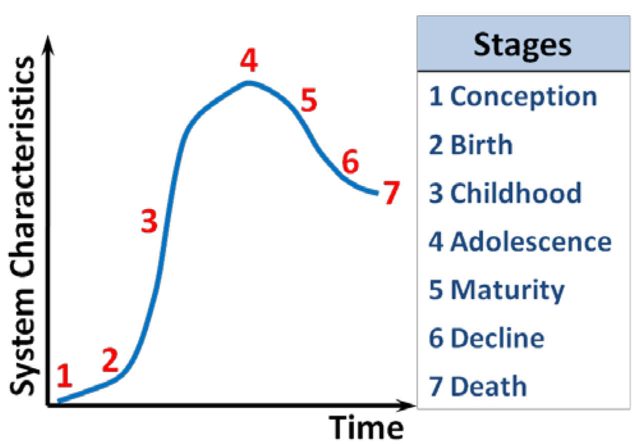


Figure 1.1 The S-curve of a system's natural lifecycle (According to Zlotin *et al.* 2002)

Manufacturing systems are not isolated systems; since they exchange effects back and forth across their boundaries. Their components can only tolerate the change of product design and processing technologies to a certain extent, resulting in the synthesis-to-replenishment lifecycle. This series of lifecycle phases is more collective than an individual living being lifecycle, the actions and reactions within and across the manufacturing systems boundaries indicate a resemblance to evolutionary trends of species in nature, starting with speciation - emergence of new species - and ending with extinction, a pattern that was long observed in financial, industrial and service organizations (McCarthy *et al.* 2000). Evolution and adaptation of species in nature are intertwined; species must have the required level of adaptability to tolerate changes, causing their characteristics to transform and eventually the whole species to evolve. Successful species are those which conquered the challenges and could adapt and evolve to avoid extinction (Ridley 2007). Prolonging the life of manufacturing systems is similar to avoiding extinction by any species.

1.3 Scope of Research

A model has been developed in this research to present a closer integration between manufacturing systems and the manufactured products; not only in the current planning horizon, but also throughout the course of their progressive development, evolution and interaction. This model establishes and demonstrates the analogy between the co-development of products and manufacturing capabilities and the co-evolution of biological species which have common evolution courses. The co-evolution model is based on a set of hypotheses that are believed to drive the postulated co-evolution of products and manufacturing capabilities. It promotes the strong association between both sides, throughout their shared evolution courses and potential future developments. The co-evolution model is mathematically established using Cladistics, which is a classification tool that is used extensively in Biology. It performs a nested commonality analysis that uses the different features of classified entities for their aggregation and segregation. A further mathematical elaboration is performed through reconciling the resulted classification trees from cladistics to obtain the present co-evolution state of the studied manufacturing systems and corresponding products.

The model and its driving hypotheses are validated by data sets from real industrial examples for machining and assembly environments. Results suggest directions for the future planning and development of the manufacturing facility and potential new features, products and variants that would further sustain and prolong the useful life of the current manufacturing capabilities and systems.

1.4 How this Research is organised

In *chapter 2*, previous literature work is reviewed to point out how manufacturing systems are synthesized, how they are connected to product variants, and how those variants are managed in industry. This chapter aims to identify the lack of change association between products and manufacturing systems and the uni-directionality of system synthesis and product design activities.

In *chapter 3*, the main proposed co-evolution hypotheses are presented. Observations from industrial history are also used to support the idea of products/systems change symbiosis. In this chapter, the analogy to biological co-evolution is established, and the theoretical and mathematical fundamentals of co-evolution process in manufacturing are introduced and discussed.

In *chapter 4,* manufacturing co-evolution hypotheses are translated into a mathematical model of several activities including: 1) realizing the independent evolution histories of the studied products and manufacturing systems based on their historical data; 2) establishing the association between the histories of those entities to decide the state of their co-evolution; 3) keeping their perfect co-evolution state - if it exists - for future planning of product variants design and manufacturing systems synthesis; and 4) perfecting products/systems co-evolution state, if it is out-of-equilibrium, by introducing new species of manufacturing systems and products.

In *chapter 5*; co-evolution model hypotheses are validated by several case studies from machining and assembly examples. Data are extracted from machine-tools catalogues (Seiki 1970-2008); parts classification codes (Opitz 1970); manufacturing systems classification codes (ElMaraghy 2006); and shop floor observations.

In *chapter 6*; the main co-evolution model idea of products/systems symbiosis is extended to other applications such as; designing and balancing assembly system layout to delay products differentiation; improving design sustainability by recognizing evolution-proven design features; and recognizing potential modules and integrated sub-assemblies in products families for a better family design platform.

In *chapter 7*; the validity and benefits of the introduced co-evolution model are discussed and final remarks and conclusions are deduced.

CHAPTER 2

MANUFACTURING SYSTEMS SYNTHESIS AND PRODUCTS DEVELOPMENT

2.1 Manufacturing System Components

A manufacturing system is a complex adaptive system (McCarthy 2003, McCarthy *et al.* 2006) that consists of other subsystems and components interacting with each other to deliver the required products with the right specifications. To recognize the scope of this research; manufacturing system components and their relationships are abstracted and the manufacturing system environment and boundaries are drafted.

According to Harrington (1984) a manufacturing enterprise (Figure 2.1) consists of four main subsystems:

1) **Manufacturing System** that consists of four components;

   a) *Product Development* is responsible for product design in terms of layout drawings (showing the total product with its component parts in working relation to one another of detail drawings) one for each individual part, and also of a list of all the parts required for the assembly, arranged in hierarchical array showing the sequence of assembly and the number required (Bill of Material BOM).

   b) *Production System* is responsible for the product transformation from just raw materials and purchased BOM into a finished product based on the product design received from product development. Production system incorporates the resources and personnel necessary for the transformation such as; production control, inspection and manufacturing capabilities of facilities, machines, material handling systems and equipment. Design changes or extra manufacturing capabilities requests may be issued to make transformation process feasible, more effective, faster, or less costly.

c) *Product Service* gathers information from the other three subsystems and issues guidelines and instructions for customers regarding product servicing, installation tools and needed spare parts.

d) *Manufacturing Management* orchestrates the other three components by giving directives.

2) **Management System** is responsible for administering the other subsystems and pursuing the objectives of the whole system by issuing appropriate directives and administering their execution throughout the other system components.

3) **Marketing System** incorporates advertising, sales and customer service subsystems. This system component promotes, sells, delivers and installs the finished product. It also collects market data about competition and customer needs, sending these pieces of information back to management to issue more policies and change objectives in corresponding.

4) **Support System** contains system components that are responsible for legal and financial services, personnel management (employing, training) and data processing when needed by the other components and subsystems.

The focus of this research is on modeling the relationships between manufacturing capabilities presented by machines, material handling systems and equipment on one hand and product features on the other hand. Therefore the boundaries of the studied manufacturing system in this research are only enclosing the manufacturing capabilities of the production system and product development. More details of the system components that are within focus of this research are shown in Figure 2.2.

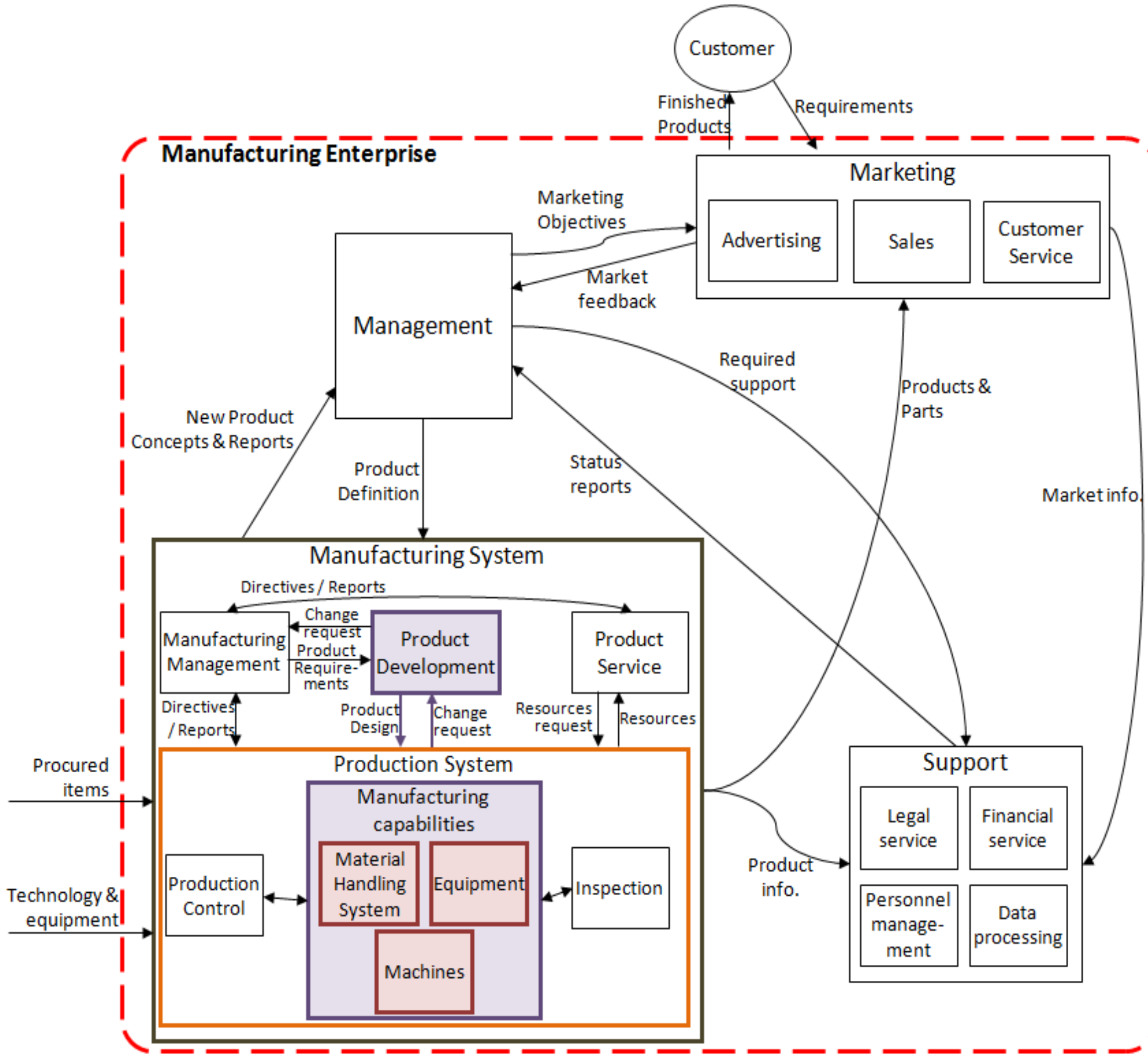


Figure 2.1 Components of a Manufacturing Enterprise (According to Harrington 1984)

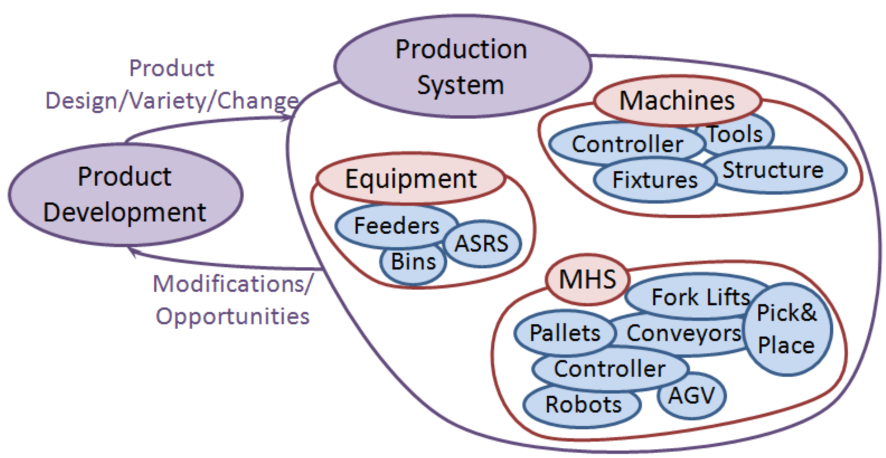


Figure 2.2 Manufacturing System Components and Relationships within Research Scope

2.2 Manufacturing System Synthesis

The term ‘synthesis’ means putting separate components or elements together to form a whole system, to convert simple into complex concepts. Synthesis activities are always related to human activities for creating artifacts. The needed knowledge for synthesis of manufacturing systems has traditionally been provided by human expertise regarding a specific product class (Ueda 2001).

The level of synthesis process is relative to the level of system design abstraction, such that detailed system design requires specifying system components, parts and elements. Producing a system framework is the highest synthesis level that specifies the main departments needed to satisfy the requirements of a certain type of manufacturing paradigm (Dedicated, Flexible and Reconfigurable).

Many manufacturing systems frameworks exist in literature with different approaches and goals, such as an iterative decision making process in a two-layers framework (Bonney 2000) to integrate ergonomics, health, and safety implications of design decisions within the overall decision making process, Unified structural–Procedural Approach (USPA) (Macedo 2004) to include the four steps of the life cycle process for designing a system; specification of system requirements (product portfolio and desired efficiency), conception (generating target values for structural parameters and target forms for structural relationships), design (generating satisfying values for structural parameters and satisfying forms for structural relationships) and implementation of system improvements, an expert system (Mellichamp *et al.* 1990) for designing Flexible Manufacturing System (FMS), using heuristics to address the problem of system bottlenecks, and Requirements Driven Design (RDD) language (Alford 1992) devoted to rapid prototyping environment.

Axiomatic design (Suh 2001) is a powerful tool used to determine the functional requirements of manufacturing systems. Yien (1998) identified five axiomatic design domains in a manufacturing system framework;

1. Customer Domain: at which customer requirements are specified.
2. Functional Domain: at which customer requirements are characterized.

3. Product Domain: at which product specifications are described (Design Parameters).
4. Process Domain: at which means are specified to introduce design specified in the physical domain.
5. System Domain: at which system components are selected according to process variables

Axiomatic design was also used to address extra system functional requirements; such as maximizing the return on investment while providing products at minimum cost (Suh *et al.* 1998), increasing the flexibility in FMS (Babic 1999, Gu *et al.* 2001), considering product quality (Liu 2004) while getting best diagnosability, and introducing a Toyota Production System and Lean Manufacturing (Cochran and Reynal 1996).

To construct system frameworks for Reconfigurable Manufacturing System (RMS) paradigm; many methods were introduced in literature such as; Analytical Hierarchical Process (AHP) approach (Abdi and Labib 2003), holistic enterprise approach (Vaughn and Shields 2002), computer aided design environment (Wu 2000), collaborative manufacturing platform (Sluga *et al.* 2005), network approach (Cunha *et al.* 2003), Supply Chain Management to account for resources planning, sales and service management (Tang and Qiu 2004), database management (Graul and al. 2003).

More detailed system synthesis activities were also investigated in literature at the factory and machines levels. Some of those activities are discussed in the next sections.

2.2.1 Factory level

Facility layout represents a long term commitment decision, which needs to be well studied and analyzed before being taken. Therefore facility layout is an important component of the system's structure, both in terms of maximizing the effectiveness of the production process and meeting the needs of humans. The basic objective of a good layout is to ensure a smooth flow of work, material, and information through the system. Facility layout design is usually dependent on rough estimates and figures for market demands, inventories, and management policies; however, new issues of market dynamics, adaptability to environment, and system flexibility and reconfigurability have been recently addressed in literature.

System reconfigurability is a system property that is reacting to the changes of the product, either in design or demand. A reconfigurable facility layout should be able to relocate its departments across its space. System reconfigurability was promoted by identifying the best layout for the present manufacturing planning interval, and the easiest to be reconfigured for the next interval (Yang and Peters 1998). Similarly, a dynamic facility layout methodology was introduced (Kochhar and Heragu 1999), taking into consideration material handling system reconfiguration cost and relocation of layout cost. Also a four-phase approach was introduced for the reconfigurable layout problem for multi-planning periods (Meng *et al.* 2004) to connect the plan of product variety mix with the design of cellular manufacturing layout.

Machine location and arrangement handles the relative positions of machines in each single department or production cell. System flexibility affected this problem, since the optimization method depends on the type of machines layout either in a line or in a cell (Heragu and Kusiak 1988), also depending on either robotic, linear or rotary parts motion between machines is used; a different mathematical model to handle machine location (Chaieb *et al.* 2001).

System reconfigurability also affected the problem, since system reconfiguration can be performed through reconsidering machines location in each cell (Hu and Koren 2005). Abdi (2005) used an AHP model to validate reconfiguring machines location; while Youssef and ElMaraghy (2007) used a GA model for optimizing the multiple aspect, multi-part RMS configurations. These aspects included arrangement of machines (number of stages and number of parallel machines per stage), equipment selection (machine type and corresponding machine configuration for each stage) and assignment of operations (operation clusters assigned to each stage corresponding to each part type). Depending on the projected product mix, a system configuration is suggested.

2.2.2 Machine level

Equipment selection considers the basis and procedures used to choose among the variety of machine selection presented from machine tools manufacturers. The strategic plan for machine selection can be described in six steps (Chick 2000); Strategic goal setting, Selection-process stage, The pre-bid stage, The post-bid stage, The option selection stage, The post-selection stage. Axiomatic Design was also used (Kulak *et al.* 2005) with the objective of making the selection to decrease structural complexity of the manufacturing system by increasing the overlapping of both design and system ranges. Analytic Hierarchal Process (AHP) was suggested to support the selection process to handle uncertainty of judgments (Manassero *et al.* 2004). An expert system was developed to evaluate selection by both qualitative (reliability, safety, impact on environment and maintainability) attributes (Guldogan 2010). Other mathematical models were suggested to make a selection from a pool of machines taking into consideration the dynamics of demands (Bard and Feo 1991, Chen 1999), and combining the two problems of assigning type and quantities of machines together at each production stage (Kumar and Herrmann 2003).

Machines capabilities in a changeable environment determine the structures, attributes, and designs needed to allow change, in order to satisfy the required jobs. A concept for a 3D reconfigurable machine structure was proposed by Murata (1998), where a six-way like structure was introduced as the base building block, then similar building blocks can be stacked together in numerous ways to build up the required structure, which was proposed to take effect autonomously and remotely, in case of hazardous environment. This concept of building small blocks into whole machines is further tuned into modularity concept. A general framework to introduce modularity in RMTs was proposed by Perez (2004), based on the knowledge of the requirements of the machine builder. A generalized Kinematic model for a Reconfigurable Machine Tool (RMT) modular design was introduced by Moon and Kota (2002), where modules are selected according to requirements from a library of module. A selection framework to optimize module selection for a RMT was presented by Chen et al. (2005).

Scalability of RMT was introduced by Spicer *et al.* (2005) where a validating architecture was proposed to build up scalability in machines. Machine capabilities determination could be also mixed with equipment selection in a conjugate operations clustering generation and a machine assignment model that assigns the minimum needed machining capabilities per product features (Shabaka and ElMaraghy 2007). The final assigned machine is presented in a kinematical schematic presentation that shows the used machining axes and their structure on the machine. An Ant Colony model was introduced to optimize the configuration path of the RMTs encompassing the whole product lifecycle (Zeng *et al.* 2010). The optimization ensures that each configuration is economics, and a configuration can be cost-effectively converted into another configuration.

2.3 Manufacturing System Adaptation to Change

There are several system paradigms that were introduced to define the workspace of manufacturing system so that a certain degree of adaptation to product changes. These paradigms consist of the physical and logical enablers for system adaptation to take place.

2.3.1 Hard Adaptation

Flexible manufacturing systems (FMS): In the eighties of last century the concept of flexible manufacturing was introduced in response to the need for mass customization and for greater responsiveness to changes in products, production technology, and markets. Flexible manufacturing systems (FMS) were also developed to address mid-volume, mid-variety production needs. Similarities between parts in design and/or manufacture were used to achieve economy of scope. Flexible manufacturing systems anticipated these variations and built-in flexibility a priori; hence they are more robust but have high initial capital investment cost. The flexibility attributes are sometimes underused. In the nineties, optimality, agility, waste reduction, quality, and lean manufacturing were identified as key drivers and goals for ensuring survival in a globally competitive market (ElMaraghy 2005). When it comes to a definition, FMS can be defined as a machining system configuration with fixed hardware, but programmable software to handle changes in work orders, production schedules, part-programs, and tooling for several types of parts with the objective to make possible the cost-effective manufacture of several types of parts, that can change overtime, with shortened changeover time, on the same system at the required volume and quality (Mehrabi *et al.* 2000), which indicates the great effect of electronics advancement on that paradigm. This paradigm is widely used in industry through the millions of Computer-Numerical-Control (CNC) machine tools and sophisticated material handling systems sold around the world nowadays. The problem within FMS is defining its scope at initial investment step, too tight scope means less ability to adapt to demands, too wide scope means huge waste of unused processing capabilities. Consequently, FMS is a pre-determined fixed capabilities manufacturing system that is suitable for producing a pre-determined variety of products. If the scope of these products changes, the whole system becomes obsolete. The idea of designing the system upfront, with no considerations for improvements upon product design un-projected change defies the notion of adaptation through evolution, and hinders FMS chance for survival.

Reconfigurable manufacturing system (RMS): is introduced in the nineties to address the rapid changes in market nature, products variety, and the need for agility. The paradigm is based on the keyword ‘Reconfigurability’, which is a terminology that defines the ability of a manufacturing system to switch reactively and with minimal effort and delay to a particular number of work-pieces or subassemblies through the addition or removal of single functional elements (Koren 2002). Reconfigurability is associated with the ability of a physical change; however different physical change types may be present. Reconfigured machines layout, capacity scalability, and adding new machine elements are some of the changes types of which Reconfigurability is capable of. Even with the ability to reconfigure; there is a need to introduce a model that links both product development with the structure of RMS, advising the optimum stream of changes and configurations in both product and system.

Changeable manufacturing: ‘changeability’ has been proposed as an umbrella concept that encompasses many aspects of change on many levels within the manufacturing enterprise. Changeability can be defined as the needed characteristics to accomplish early and foresighted adjustments of the factory's structures and processes on all levels, due to change impulses, economically (ElMaraghy and Wiendahl 2008). Flexibility and reconfigurability are among other classes that form a changeable manufacturing umbrella such as; the ability of a machine to switch-over a different product (change-over-ability) and the strategic capacity of an enterprise for the switch-over process (agility). Modularity and scalability are the main guidelines for having changeability from the process planning level to the manufacturing system level (Wiendahl *et al.* 2007). While modularity addresses the structure of objects; scalability advocates the size, when together; a changeable format can be obtained, it can be a machine-tool extra axis of motion or a whole factory that is different but consistent with the rest of the enterprise. The enablers of changeability are so much similar to some factors in the biological evolution process; since size and shape are also two characters that favor certain living beings to others in survival.

2.3.2 Soft Adaptation

Evolvable manufacturing systems (EAS): This is a business model introduced by Onori (2002) to sustain competitiveness in micro and mini assembly environments that imply a highly dynamic lifecycle for shop floors. Micro and mini assembly units are expensive and require a lot of expertise, therefore the idea of having reusable modules by companies at different times would improve the return on investment (ROI) for each module and would increase the competitiveness, rather than accomplishing all of the envisaged assembly needs within a closed FMS unit. EAS is based on a multi-agent control solution (CoBASA) to manage and combine assembly modules to form 'coalitions' of modules that serve a 'contract' (the targeted aggregated functionalities) (Barata *et al.* 2005). However, EAS assembly system layout, monitoring and re-configuration in case of failure are done manually (Frei *et al.* 2008), consequently it is not autonomous or self-reconfigured.

Biological manufacturing systems (BMS): It is a manufacturing system model that was designed to adapt dynamically to non-pre-deterministic changes in both internal and external environments based on biologically-inspired ideas such as; self-organization (inspired by the unification of biological information), adaptation (using Genetic Algorithms GA), and learning (using Instance-Based Classifier Generator method) (Ueda 2007). The quoted ideas are executed within the larger framework of the emergent synthesis theory. Due to the incomplete nature of system surroundings and the system structure itself, the model of the system starts with the relationships between the different system components, and as time passes, more knowledge about those entities and their structure is built up. This philosophy of realizing the unforeseen nature of manufacturing systems as well as other systems was referred to as 'Emergent synthesis' by Ueda (2001). Examples of AGVs routing and supply network simulations were presented as applications to emergent synthesis theory, using relationships modeling between entities as some analogies from nature (attraction-repulsion forces, ant colony behaviour and pheromone trails). BMS is merely a system modeling technique; using emergent synthesis philosophy of modeling, makes it a very generic model umbrella that encompasses any other intelligent modeling tools. In this case, using a Complex Adaptive System (CAS) model and multi-agents for manufacturing systems modeling will also lie within the same scope of BMS and emergent synthesis theory. Because the emergent synthesis theory is a way of system modeling, other system paradigms emerged from the same origin of BMS. For example, the Multi-Agent Manufacturing Systems (MAS) is an agent model that personifies various objects in the manufacturing environment using agents on the different levels (Monostori *et al.* 2006). Using agent-based approach offers autonomy, responsiveness, modularity and openness, and is able to use distributed and incomplete sources of information and knowledge, thanks to emergent synthesis thinking. BMS depends on computer simulations to pursue the emergence of the system behaviour, without a formal system model or analysis.

Holonic manufacturing system (HMS): That was suggested as a highly distributed control paradigm, which is needed to be able to handle uncertainties in system environment (product changes), and uncertainties within the system itself (technology changes, and manufacturing processes uncertainties. HMS is based on autonomous cooperating agents called holons, which means that it is a multi-agent model that comprehends the characteristics of Complex Adaptive Systems (CAS) such as; aggregation and specialization. There exist four types of holons in an HMS; order information processing) holons, product holons, resources holons and staff (support) holons (Van Brussel *et al.* 1999) . HMS is defined as a holarchy (a system of holons) that integrates the entire range of manufacturing activities from order booking through design, production and marketing to realize the agile manufacturing enterprise (Cheng *et al.* 2001). HMS model was used to present a control system that predicts the near future while accounting for changes and disturbances, using an ant colony behaviour control mechanism to ensure the process plans are properly executed and emergently forecasts the workload of the manufacturing resources as well as lead times and routings of the products (Valckenaers *et al.* 2009). HMS is adequate with the notion of adaptation for agility and responsiveness, however it is merely a control model that attempts to avoid the flaws of hierarchal and heterarchical control systems of being distributed and complex in the same time. A control model does not change the physical structure of the system; consequently it does not comply with the notion of evolution.

Fractal Factory: This term and also the term of "factory with a future" were coined by Warnecke (1993). The idea refers back to the geometry of objects with nontrivial scaling behaviour. Analyzing these objects according to the principles of fractal geometry resulted in the insight that complex structures occurring in various forms in nature are built from few self-similar elements, called fractals. That basic concept was transformed to manufacturing enterprises from the demand arises for introducing the same self-similarity in an enterprise. Consequently, enterprises can form units aligned with a common target system. Those units are largely autonomous in the manufacturing, assembling and dispatching of the parts and components of a product. Through the decentralization of product and process responsibility and by integrating supportive activities into the semi-autonomous units or fractals, it is possible to launch a continuous improvement process in an enterprise (Westkämper *et al.* 2000). Fractal Factory is an integrating system design approach, where complex organization solutions were arrived at by using self-imitating elements/fractal objects, considered to be the central structural elements of a company, which behaved dynamically and independently in a self-organizing, self-optimizing and goal-oriented manner (Warnecke 1993). The model is delivered through directives and rules of thumb rather than mathematical foundations, leaving a big chance for misinterpretations. The model is also communicating with the high level of the enterprise and how information is transferred, rather than the in-depth manufacturing system details and components.

2.4 The Uni-directionality of System Synthesis

The reviewed manufacturing synthesis approaches in system frameworks, factory and machines levels succeeded in make one-time decisions before the initial investments of the next planning interval or system reconfiguration are taking effect. All system requirements and product changes have to be known in advance.

A continuous action and reaction dynamic model between ‘what is needed’ by products and ‘what should be’ in a machine or on the shop floor was not yet introduced. The investigated models in the literature - though they are mostly analytical hence decisive – they neither keep track of historical achievements of the system nor the product. Historical track of change in both the system and the product can illuminate a wider view of their dependency and mutual balance, hence having a long term plan for both sides, rather than waiting for the next change to come, and react to it correspondingly. In this context, the flow of these models can be described as uni-directional. The continuous feedback for a better understanding is lacking.

Moreover, the surveyed manufacturing systems models to adapt to change show that there are two classes of these models; the first one constitutes a physical paradigm where the system philosophy has a physical effect on the system components and vice-versa, such as the actions and reactions between machine design and FMS or RMS. The other class is a way of system modeling through simulation to manage or control system components, without a physical addition to the system structure itself, mostly following the ideas of natural adaptation and evolution incorporated in Complex Adaptive Systems theory and multi-agent modeling. BMS, EMS, HMS and others fall into the later class. The first class is found to be uni-directional in terms of design activities flow. A system is initially designed to handle perceived (FMS) or hidden (RMS) challenges ahead of time. FMS can't handle challenges beyond its pre-designed scope. RMS can be modified frequently for reconfigurations of its components; however, this is done reactively in response to the emerging challenges in products and markets, as needed when needed. The other class may have the potential for an active link that updates both sides but currently it does not have input to the physical structure of both product design and system components, besides, it does not have capacity for an analytical model. This research establishes the missing link between the two classes. It opts to use the findings of FMS, RMS and changeable manufacturing and incorporate that into an analytical model which should be able to integrate both product design and manufacturing capabilities. To address adaptation in manufacturing systems, the notions of flexibility, reconfigurability and changeability were introduced with their physical enablers - soft and hard (ElMaraghy 2008) - to increase system adaptation.

2.5 Product Development

2.5.1 The Proliferation of Product Variety

Manufacturers are getting more interested in producing more product variants, since markets are neither homogeneous nor demands for products are stable; consequently, targeting profit from many market niches became a need, which means increasing products variety through production. There are many reasons for that instability; such as the existence of different regional requirements due to cultural or geographically related factors that require a product to have many models and variants. Even within the same regional market, several distinct market segments may exist, requiring different functionalities or capabilities for the same product (Pine 1993). Therefore, in the past few decades manufacturing enterprises started to switch their economies to benefit from the economy of scope instead of the economy of scale. That paradigm switch shifted manufacturing systems from mass production and dedicated systems to mixed-model transfer lines and flexible manufacturing.

New business strategies also started to emerge to reap the benefits of economy of scope, such as mass customization and product personalization, but at the cost of a huge increase in product variety. This increase is meant to match up the wide scope of customer's requirements, which could be functional (Purpose, Performance, Reliability, Serviceability), environmental (using Safe materials, Fuel efficiency, Lower energy consumption, Recyclability), ergonomic (human–product interface, ease of use, user fit), aesthetic (visual and acoustic impact on human senses) and emotional (Feeling of satisfaction, intimacy, Luxury) (Hopkinson *et al.* 2006).

Offering a wide range of product variants can lead to a considerable expansion in the number of sub-assemblies and amounts of raw materials that must be kept in stock to satisfy the full range of possible variations in product configurations (Bragg 2004). In addition, customer service cost increases when many product variations exist. For example, managers attempt to stock as much as possible of the finished products under the pressure of maintaining good customer service quality, while eventually those stocks might become obsolete in a relatively short time due to rapid technology changes (Lee and Billington 1994). Increasing the product variety means increasing manufacturing complexity, which eventually leads to higher managerial burdens in order to handle all the previously discussed symptoms of increasing products varieties, and associated escalating administrative cost.

2.5.2 Variety Management

Continuous research efforts were made to handle and improve product data and development in a way that allows manufacturing process easier and less costly. Such efforts permitted products to survive longer through tiny design tweaks, or small core design reconfigurations. Arranging products into families, increasing design modularity, or adopting a product platform are some of the followed guidelines to implant intelligence in product design. These methods are meant to manage the challenges of product change and variety proliferation, which reduce drastically the lifecycle of any manufacturing systems. Some of these guidelines are further constituted into product design methods. Using - directives, rules of thumb or some fill-able tables - are the way by which those design methods are working, giving the directions to designers onto how to build such intelligence into product design. Weather it is an assembly environment, a machining environment or else, those design methodologies advise the best design practices to introduce a product that is adequate with the manufacturing processes in hand.

The persisting need for multiple-product along with small lot size demand in manufacturing was the main driver of the classical flexible manufacturing and group technology concepts emergence. These concepts constituted the physical arrangement and structure of manufacturing systems in the near past until now. Consequently, there was a necessity for managing the proliferated number of product variants into product families. A product family was simply defined as a group of products that have some specific sameness and similarities in design features or production processes (Ham *et al.* 1985).

The simple definition of product families was widely expanded over time to comprehend a broader scope of similarities. A product family definition might focus on process planning; hence grouping is based on similar overall routing and process sequencing. A definition might address functional similarities, consequently product variations result from optional components or the differences in the secondary functions. That definition could also be stretched to address products of related set of market applications (Abdi and Labib 2004).

There are many classical methods for forming a product family, which engineers used during the past few decades such as the manual / visual search, the functional grouping, production flow analysis classification, and coding/classification and clustering techniques (Groover 2001). The last method was vastly used; but each research group in each country developed their own coding system that could fit their uses. These system ranged from the widely used OPITZ (Germany), to the less known - SALFORD (UK), BUCCS (USA) and KK1-3 (Japan) – coding systems (Ham *et al.* 1985). The famous OPITZ (Germany) coding system (Opitz 1970) is a collection of small number of poly-codes. Digits in poly- codes are self-contained, and the order of the digits may be reversed without any loss of generality; which is an advantage over mono-codes in which the meaning of a given digit depends on the meaning of preceding digits in the code string (Groover 2001).

The physical emergence of reconfigurable and changeable manufacturing made it clear that the goodness of a product family formulation is the key to a better management of a manufacturing system; especially if it has the ability to frequently reconfigure. The previous notion was emphasized by Abdi and Labib (2004), and they pursued with their own grouping model, which was specially devoted to RMSs. Their model promotes a single product family for each system configuration stage using AHP technique to identify it amongst the several candidates, where grouping itself is based on operational similarities. More inclusive similarities were used by Galan *et al.* (2007) to perform family grouping. Those similarities include modularity, commonality, compatibility and reusability of parts. But the model ignored a basic input; the cost of system reconfiguration of each period. That left product family choice - from the offered ones by the model - to designers.

Not only the definition of a product family has progressed, but its classical view of the rigid boundaries has also changed. ElMaraghy (2008) introduced a new class of "*Evolving Parts/Products Families*", where the boundaries of those families are no longer rigid or constant. The features of new members in the evolving families of parts/products overlap to varying degrees with some existing features in the original families; they mutate and form new and sometimes different members or families similar to the evolution of species witnessed in nature (Figure 2.3). Such a metaphor fuels the potential to an intended analytical model - in this research - which uses that biological analogy as its own backbone. A model that keeps track of those ever reforming family boundaries, and more importantly relate that change to the manufacturing systems components, which similarly keep changing structure and capabilities.

The need for more inclusive classifications – rather than the simple product family class - grew both; over time due to the desire of design changes fulfilment; and over space due to the expansion of product variants to the point of products mass customization. Therefore, it is both meaningful and informative to capture and classify the expanding products differentiations in an illuminating hierarchy. Such classification would lead to outline concisely the types and degrees of variation that occur at the different hierarchy levels and consider ways of modeling them and their consequential effects on change enablers - especially for products and systems modeling and design.

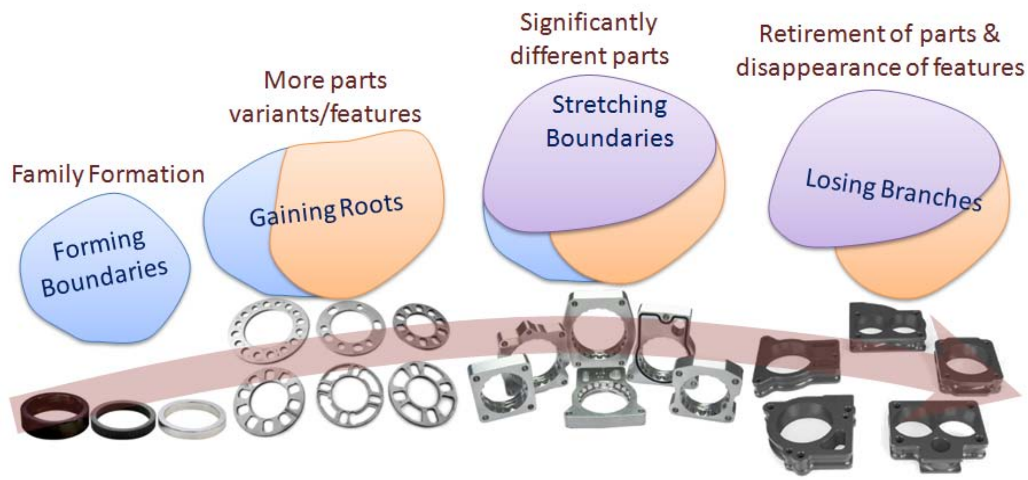


Figure 2.3 Family of products evolves into different products / species after n generations (Adapted from ElMaraghy 2008)

In the next chapter (3); the uni-directionality of previous literature work regarding system synthesis and product design is resolved by introducing the notion of products/systems symbiosis. The idea of manufacturing co-evolution of products/systems akin to co-evolution of different species in nature is also introduced. Chapter 3 introduces 'Cladistics' as a more effective classification tool that is borrowed biology, and is used in this research to unfold the history of products and systems evolution, since they are noticed to change and evolve from real world examples (chapter 3) and from literature review (chapter 2). In addition; observations from nature and manufacturing worlds are combined into a series of hypotheses that are used to construct the mathematical co-evolution model.

CHAPTER 3
MODEL HYPOTHESIS

3.1 Establishing the Analogy

Humans have always mimicked nature, seeking inspiration for innovations in their life. Nature has always provided mechanisms and capabilities that helped humans to engineer new designs and accomplishments through understanding natural phenomena. Bio-mimicry is a very rich source for inspiration, from cell structure inspired nano-technology to imitating social and biological behaviors in robotics (Bar-Cohen 2006). Evolution in nature was also mimicked; it inspired humans with the mechanism of experimenting effective solutions, which for example can be noticed in using Genetic Algorithms (GAs) in mathematical optimization of complex problems.

In nature, organisms are always changing, their properties and characters are altered and transformation in their form and behavior is observed through the generations, which consequently lead to the huge variety of life forms that can be distinguished in nature. These changes over generations 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.

Evolution can be defined in more specific biological scientific terms as the process of change with time in the characteristics of organisms. Heritable traits are encoded in the genetic material of an organism. Evolution results from changes in this genetic material, and the subsequent spread of these changes within a population of a species, and inheriting these changes through the generations, resulting in new different species (Ridley 2007). The famous "Charles Darwin" defined evolution as "Descent with Modification" (Darwin 1859), and the word "Descent" refers to the way evolutionary modification takes place in series of populations that descended from one another.

Moreover, evolution is always attributed to progression; however, not everything attributed to evolution is progressive. When it comes to the level of fitness and adaptability, then evolution is progressive in that way. Organisms are very evolvable, placed in a new environment, or deliberately chosen for certain characteristics; selection will always tend to modify the population appropriately. Progress, however, is often taken to mean an advance in some subjective measure, such as complexity of organization. This usage is especially prevalent in the popular literature of the subject. Evolution does not in general cause progress in this sense. Selection will favor attributes such as beauty, strength, or wit only to the extent that they are associated with increased fitness, and this is not by any means necessarily the case. Organisms may readily be selected to become smaller, simpler, or less aesthetically appealing (Bell 1997).

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.

Same image is captured perfectly in the manufacturing environment; changes are always driven by a desire for adaptation. Industry never stopped developing; everyday thousands of new products, new techniques, and even new philosophies are introduced. The picture of the industrial world has evolved from the simple handicrafts to the extremely complicated microscopic chips, proclaiming same amount of evolution on both technologies and product sides. Technologies always evolve with correspondence to the new requirements of both customers and manufacturers, and to validate the needs of the competitive environment imposed on industry, which implies more responsive, quicker, and more precise manufacturing systems. That is why industry escalated its capabilities from handcraft, to man-operated, to man-programmed and now unattended-artificial intelligence technology.

Products are also evolving, motivated by innovations on one hand, and the available technologies on the other hand. It can be postulated that in modern manufacturing, designing new versions of existing products generally predominate over designing new products, as time to market has to continually be reduced, so product design is increasingly becoming a re-design task (Kryssanov *et al.* 1999), extending, manifestation and improving the existing product properties compared to newly innovated products. Therefore, the process of products evolution is also meaningful in the context of how products are developed nowadays (ElMaraghy 2008) .

3.2 Using Cladistics for Classification

The nature of the outlined product and manufacturing capabilities evolution, perceived to have similarities with evolving biological species, and the need for more in-depth and more informative classification pointed to some more powerful tools used in biological science. ‘Cladistics’ is a method of classification that groups entities hierarchically into discrete sets and subsets, in order to organize their comparative data based on commonalities (Kitching *et al.* 1998). While cladistics is mainly used in the field of biological classification, it has also been used in organizational classification (McCarthy and Ridgway 2000, Rose-Anderssen *et al.* 2009).

Cladistics was originally introduced and developed by Hennig (1966, republished in 1999), generating cladograms (tree-like structures). The generation process begins with choosing end-taxa (the variants to be investigated) placed at the end of cladogram terminals, such as taxa A, B, C, D and E shown in Figure 3.1, then determining the characters that will provide relationship evidence (1 to 11 in Figure 3.1). Next, all inherited character states by each taxon are identified. A character indicates a certain feature, and its states are its different values, ranges, shapes, phases, etc. A character state could be ‘primitive’, where a feature does not exist or presents a low profile state (0), or could be a ‘derived’ state, representing the existence of a feature, or a more advanced state (1). A cladograms length is the number of characters appearing on the cladogram tree, which is the total number of changes in character states that are necessary to support the relationship of the taxa in a tree, since cladograms are used to test the various hypotheses on the evolution process in those studied taxa. Fewer steps mean better cladogram with fewer assumptions and better representative hypothesis of the taxa relationship, or what is referred to as 'parsimony'. The objective of cladogram construction is to generate cladograms with the minimum length (best parsimony).

In Figure 3.1, the cladogram shown has a total length of 12 steps, while there are only 11 characters because character '9' is repeated, which represents a cladistic conflict that increases the length of cladogram. The objective is to always avoid these conflicts by maximizing the parsimony of the cladogram.

The proposed co-evolution model of product design and manufacturing capabilities uses cladistics as a classification tool to study the evolution of products in parallel with the capabilities of the manufacturing system, by investigating their historical development, and relating their postulated changes for co-adaptation. The idea is to expand the boundaries of the changeable manufacturing environment by relating the analytical and physical models of manufacturing capabilities to the methodologies of product design. This is done by not only classifying products variants but also by relating the history of change and reconfiguration of the corresponding manufacturing capabilities to that classification to gain a better understanding of the mechanics of the change process on both the products and manufacturing capabilities sides.

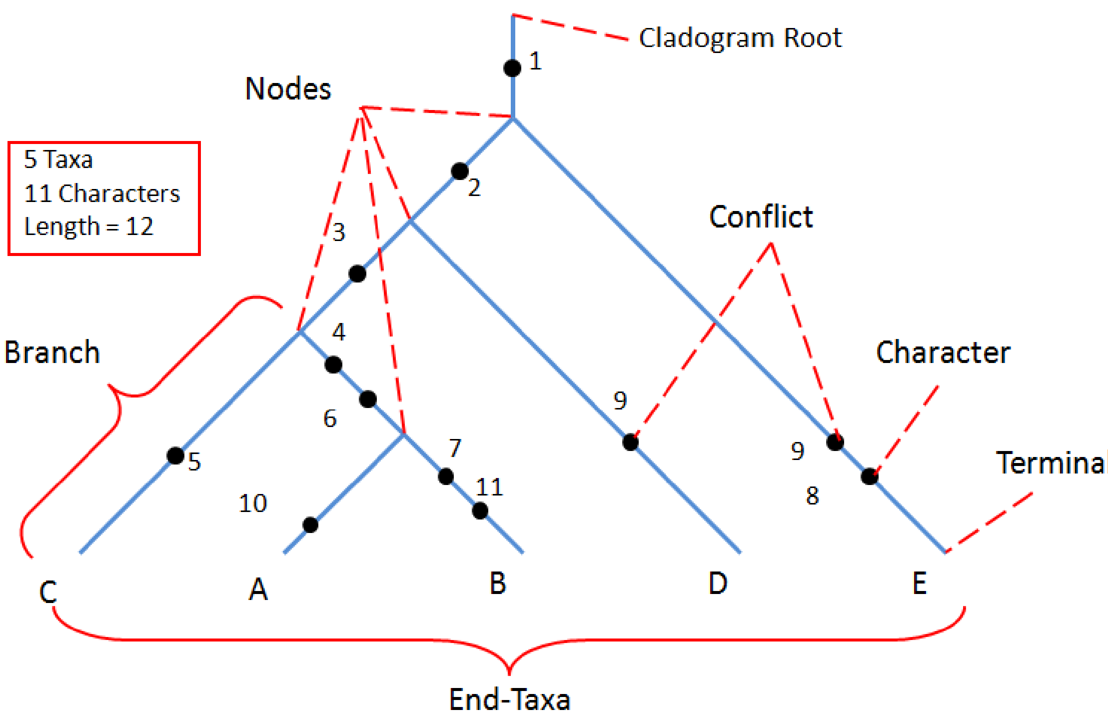


Figure 3.1 Classification by Cladistics and Parsimony analysis

3.3 The Symbiosis of Manufacturing Capabilities and Product Features

Products are designed to satisfy recognized needs. This motivates the development of techniques, processes or machines to produce products. This motivation can be clearly observed through the next example from the history of machine-tools development. This example is presented in support of the notion of manufacturing symbiosis; showing the back and forth interactions between product design features and manufacturing systems capabilities.

3.3.1 Observing Co-evolution Mechanism in Manufacturing

- The development of industrial lathes and CNC Machine-Tools

Turning processes and the early use of lathes were introduced to satisfy the need for symmetric cylindrical products (e.g. eating plates, wheels); initially made of wood then later of metals. Up to the end of the 17th century the lathe was intended to work on wood, horn, ivory or soft metals. Then, there was a growing demand for more accurate metal parts than can be achieved by casting. The lathes created by 'Henry Maudslay' (1797 to 1800) mark the beginning of the modern industrial metal-working lathe of today (Lilley 1966). His lathes' structure was made wholly of iron and used a slide rest with a traversing tool, allowing machine structure rigidity and accurate depth of cut, hence parts' dimensional accuracy (Usher 1954). These lathes were the best known combination of lead-screw, carriage, and change gears; a machine-tool that held the work-piece in the spindle and rotated it allowing a cutting tool to machine the surface to the desired contour. The cutting tool was manipulated by the operator through the use of cranks and hand-wheels. Dimensional accuracy was controlled by the operator who observed the dials on the hand-wheels and moved the cutting tool by the appropriate amount. Each part that was produced required the operator to repeat the movements in the same sequence and to the same dimensions (Benes 1999).

The same lathe that generates different diameters on a work-piece can also produce face and internal turning, by using the cross-slide for feed towards the piece center at the face instead of using it for cutting the circumference. The tedious work of machining long shafts in different machining paths with manually controlled feed and depth of cut and the instability of fixation could be decreased by adding a gearbox to the main head-stock to control spindle speed and drive the feed rod automatically, in addition to a tail-stock with a center to fix the far end of the work-piece, and a hollow main spindle to allow insertion of long objects, and longer machine bed. The existence of a tail-stock allows twist drills to be used and a work-piece to be drilled adding a different feature to parts that can be produced by a lathe. To produce threads on a part, a lead screw is used in the machine and in turn thread standardization and accuracy was improved on the part side (Rolt 1965).

Since workpieces were clamped directly to the faceplates. Due to the limitations imposed by this mounting method fast mounting chucks were developed. It was first the 4-Jaw independent chuck in the early 20th century, consisting of four bolts passing axially through the body of the raw material. That was shortly followed by the introduction of the self-centering chuck, where chuck jaws move simultaneously towards the center, when tightening on the work piece, using key pinions that are meshed with a circular rack on a scroll plate (Bradley 1972). Though the independent chuck setting process is slow it is still useful to grip onto products like crank-shafts or coupling rods, where the part is needed to be eccentric at some points, or the work-piece itself is not originally or perfectly cylindrical.

There were also demands placed on turning machines that are not necessitated by new features in product design. Cutting down production cost to a minimum while also increasing production rates was urgently needed in production. This was first necessitated by nations' conflicts, which resulted in supplying armaments to fighting armies and then was further utilized by market competition. In 1812, a large weaponry order was placed with an American firm to be produced in a short time, which gave birth to lathes that are capable of repetitive and fast machining. A turret that carries several tools was added to the lathe. Turret lathes (turret is on the cross slide) were first developed for rapid production rates followed by the even faster production capstan lathes (turret is on a separate slide on the lathe's bed) (Bradley 1972). This advancement unleashed designers' imagination to pack parts with every possible turning feature knowing that it can be produced on a single machine, in a single setup. Nowadays a regular lathe can have literally an endless number of jigs, fixtures and tooling, allowing plenty of turning operations. Each one of them was developed to suite the required job, while a new product feature that was not initially feasible may become possible by using the new added capabilities.

Throughout the 19th century the production of general purpose machine-tools like lathes was undertaken by the early textile machine shops in response to the domestic requirements of their industry (shafts in textile mills). The more specialized high-speed machine tools like turret lathes grew initially out of the production requirements of arms makers and later by sewing machines manufacturers (Rosenberg 1963). Throughout the 20th century to the present day the automotive industry has been the biggest consumer of machine tools and has put the greatest pressure on their builders to develop and improve their designs. Machine-tools enabled automobile designers to introduce better bearings and gears and consequently more efficient and compact transmission systems. Shortly after this these improved transmission systems were adopted in the construction of the lathe headstock itself for its built-in change-speed mechanism (Rolt 1965). The previous discussion served to demonstrate the reciprocal cause and effect actions that can be easily observed between what was needed on the products side, what was developed on the machine side and the new features that can be incorporated into parts as a result (Figure 3.2).

In the second half of this century more companies focused on producing lower volume product batches but with higher quality, which required more flexible changeover in manufacturing systems. Advances in mechatronics enabled machine-tool builders to meet those requirements. Numerical control of machine-tools started in the 1950s with research work at MIT funded by the U.S. Air Force. The first commercial production-based numerical control unit was built by Bendix Corp. in 1954 for machine-tools introduced in 1955. Another significant development at that time was the development of direct numerical control, which paved the way for the first flexible manufacturing system (FMS). Numerical control allowed a machine tool to work fully unmanned, while keeping the essence of flexibility intact since a machine-tool is designed to handle a wide variety of parts inside a certain envelope of dimensions and specifications, which basically defines the boundaries of the family of products that can be produced by that machine. While the need for automated yet flexible manufacturing did not have a direct relevance to certain needs for parts features the newly introduced numerically controlled lathes had an impact on the parts that could be produced. Designers could freely use circular and semi-circular profiles on the parts (Figure 3.3), not fearing the inaccuracies that might be caused by a human controlled machine.

The Numerically Controlled era led the way to a more sophisticated technology which was dependent on the advancements made in the computers field. Computer Numerical Control (CNC) technology allowed easier and better control over machine tools. Cutting-tool-path computations were left to be done by the machine-provided software on the computer rather than in the machine controller unit. Accordingly, there was an impact on the allowed features in parts produced by a CNC lathe; more complex curves (not just circular features) started to appear on parts surfaces.

Numerical control also made it possible to introduce advances in the lathe structure; an ordinary lathe is kinematically a 2-axis (2 DOF) mechanism with a moving cutting tool in the X and Z directions. More working axes could be introduced through an extra tool turret, producing 4-axis lathes with a pair of cutting tools that could work simultaneously (Ferguson 1978). Of course the gain was mainly reflected in reduced machining time, however, more accurate parts could be generated by using this technology since the second tool would get what was missed by the first one, and this had an effect on product design, especially for long shafts and bars.

A dual-processing two-chuck 2-axis lathe is one of the CNC fruits, it allows swinging work-pieces over the two chucks, and therefore, a designer could add features on both ends of the designed parts, knowing that it is possible to make it seamlessly without interruption for a face flip-over.

It was also possible to convert a 2-axis CNC lathe into what is called a turning centre (Figure 3.3), since some of the milling tools stored in the tool turret had their own rotors and could be used to perform simple milling operations if the main-spindle rotation is synchronized and angle-controlled accurately. This might be looked at as the development that came about both due to the need for reduced production time (by not having to switch to different machines) and for parts with features requiring combined turning and milling.

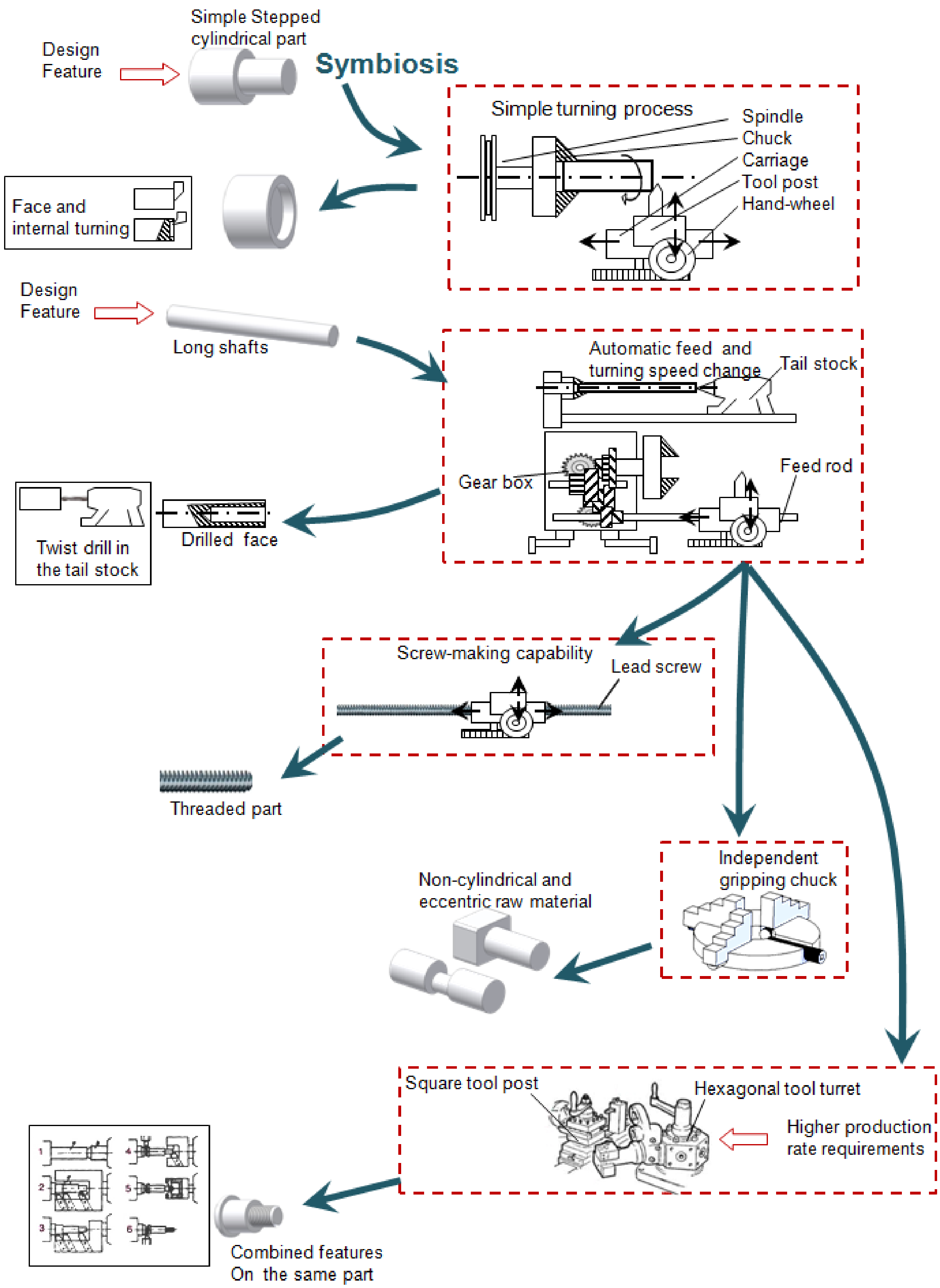


Figure 3.2 The Co-evolution Path of Rotational Parts Features and Industrial Lathes

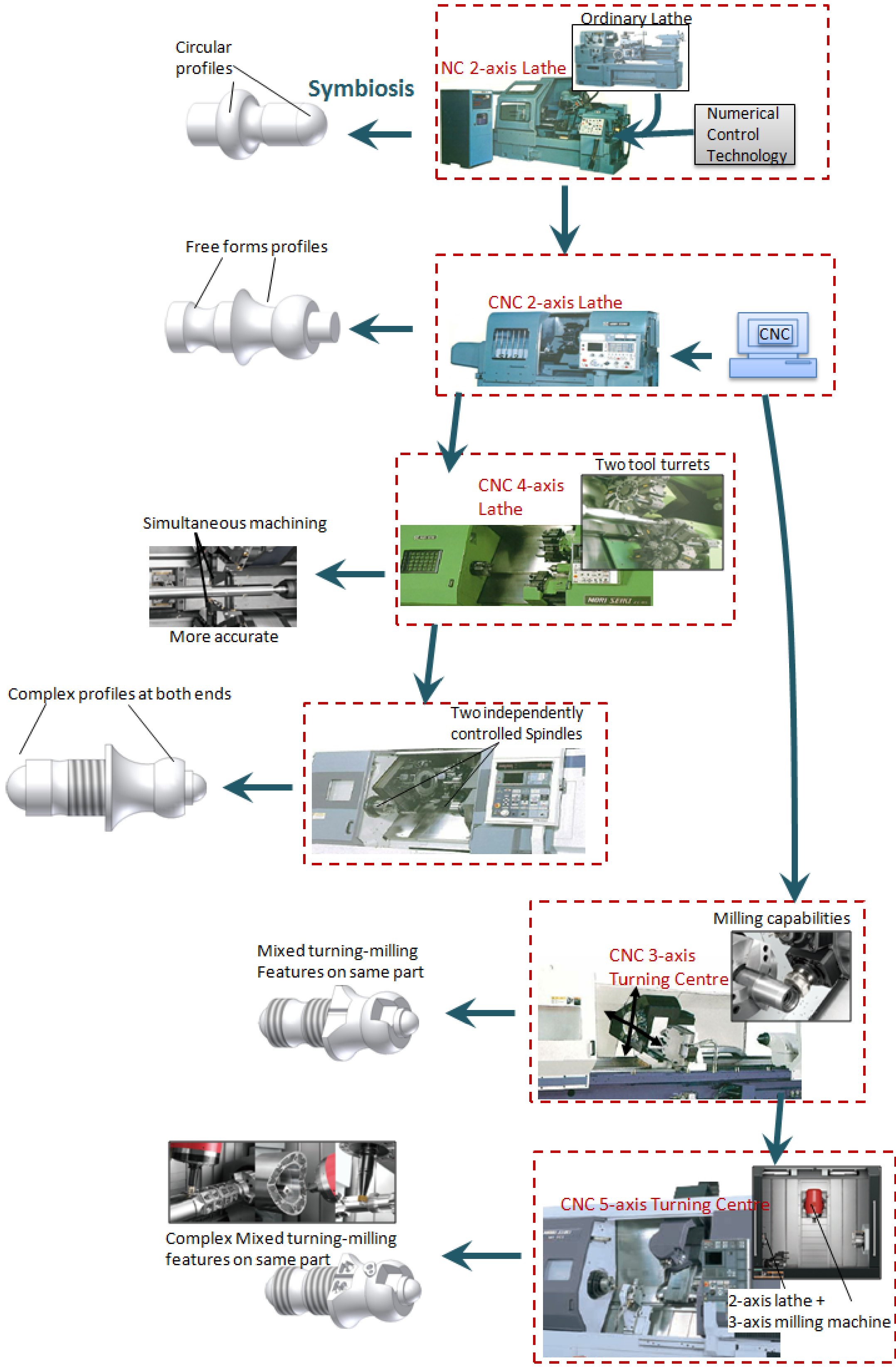


Figure 3.3 The co-evolution of part features and lathe rivals

The idea of having a lathe that is capable of turning and some milling operations led to introducing a 3-axis turning center capable of manoeuvring in Y-axis either by the main-spindle or by the tool turret. That affected parts design as more complex milled yet straight surfaces could be incorporated. Later on, 5-axis turning centers were introduced with a 2-axis lathe and full-capability 3-axis milling machines. The complexity of generated parts was significantly extended since localized milled features could be added along the turned work-piece. Now with CNC technology it seems that good possibilities exist to allow more controlled axes, and hence, more capabilities and flexibilities to a single machine representing a whole new breed of processing capabilities and opening the door for a wider variety of products with more complex features to be produced.

3.3.2 Types of Symbiosis in manufacturing

It can be seen from the previous example that changes in manufacturing capabilities (machine, tools, control, material handling, equipment, etc.) are usually triggered by diverse drivers that are sufficiently strong to infuse a series of milestone effects in both the product design and manufacturing capabilities domains. These drivers do not always result in minor tweaks; rather, they might suggest total re-evaluation, redesign or re-configuration. Some examples of these powerful drivers and their effects may include:

a) On the product side: the need for higher production volumes, moving to a new product family or using new materials, as well as the introduction of new production technologies and processes.
b) On the manufacturing capabilities side: the transition from dedicated or transfer lines to flexible or reconfigurable manufacturing.

These drivers can be massive in their effects and often lead to major production paradigm shifts in light of decreasing product life span and increasing varieties. They would need extreme manufacturing systems makeovers, for example, to replace dedicated specialized equipment with flexible ones and a complete re-assessment of the product design. This type of symbiosis is impulsive and disruptive in nature where innovation, inventiveness and creativity in producing new solutions play an important role in triggering the changes.

The other type of symbiosis between products and manufacturing capabilities can be seen as gradual and steady; it does not involve big leaps or major changes on either side. This is similar to what is found in nature (ElMaraghy *et al.* 2008). Biological co-evolution happens when two or more species influence each other's evolution, which is a slow and gradual process. Biological co-evolution is often invoked to explain co-adaptation between species, as a result of the reciprocal manner of these influences (Ridley 2007). This type of manufacturing symbiosis needs to be carefully directed and managed to gain the most benefits from the change with the least possible effort. 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 commonly encountered change-drivers that do not require massive change in either domains. New vision to direct these changes and their consequential effects in a clear and streamlined process is needed. There are no analytical models developed in the literature to capture this notion of reciprocal interactions between products and manufacturing systems and their capabilities.

3.3.3 Symbiosis Loop in Manufacturing

A design closed loop schematic model was proposed by AlGeddawy and ElMaraghy (2008b), based on their survey of many manufacturing system design methodologies, which were found to be reliant mathematically on a unidirectional flow of design activities, starting from abstraction and ending with the detailed design. The manufacturing co-evolution model presented in this research offers a new design framework, where design process flow becomes a loop with bi-directional interaction that relates both product and system components designs (Figure 3.4). This loop was meant to capture the natural progression of products design and technology breakthroughs of manufacturing capabilities by expressing their close interdependencies and symbiotic relationships. The terms of Axiomatic Design (Suh 2001) were used for modeling. A change in product design can be translated through the process matrix to the manufacturing capabilities system component, which would cause changes in the system design unless the current manufacturing capabilities are sufficient to accommodate the changes in product features. The modified capabilities in turn would present new opportunities to introduce additional features in the products through their evolution. These new capabilities are mapped from their side to the product side through a capability matrix, which is the inverse of the process matrix.

In this research, that simple cycle is taken a step forward by providing the tools that can connect both sides – products and manufacturing capabilities – not just at the current state or for the next step, but more importantly over all of their past history of changes. In biological science, the evidence for co-evolution of different species is driven from the similarity of their evolution courses (Ridley 2007). This research mimics this co-evolution behaviour of biological species and applies it in manufacturing.

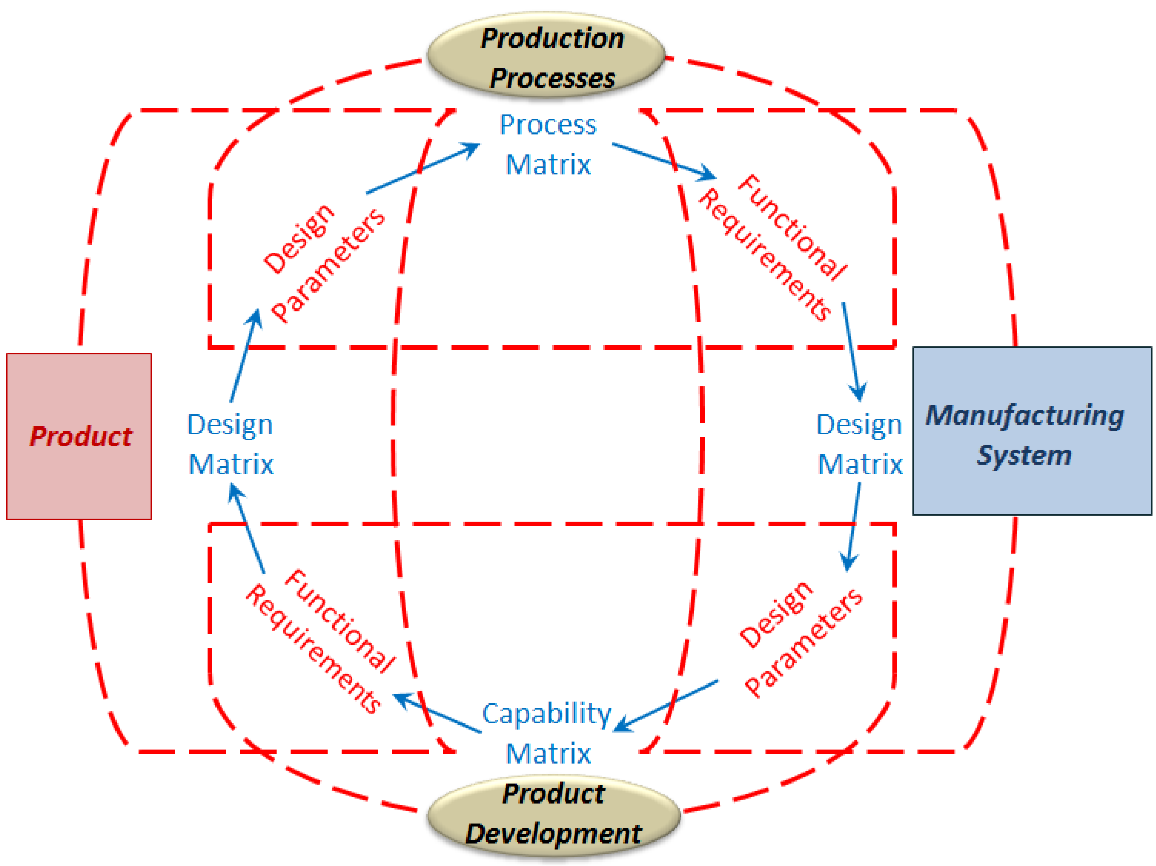


Figure 3.4 The proposed 'product - processing capabilities' design loop
(Adapted from AlGeddawy and ElMaraghy 2008b)

3.4 Co-Evolution Hypotheses

A set of hypotheses are derived both from evolution in biology and by observing evolution behaviour in manufacturing. These hypotheses are discussed in this section since they form the foundation framework of the manufacturing co-evolution model.

Hypothesis 1 - Manufacturing Symbiosis

'*Changes in products and manufacturing capabilities affect each other, where the type and/or nature of the effect correspond to those of the stimulating change*'

This symbiosis has an impact on both the products and manufacturing capabilities evolution path, which can be categorized as either disruptive or gradual. Some changes are sufficiently significant and require major overhaul as a reaction; causing the disruption of the natural progression of products design and characteristics of manufacturing capabilities; this is referred to as disruptive symbiosis. Other changes, the impact of which can be managed within the boundaries of the current product configuration and manufacturing capabilities, represents gradual symbiosis (AlGeddawy and ElMaraghy 2009b). Both symbiosis categories shape the progression of products and manufacturing capabilities, which can be tracked and captured in the same manner as establishing biological species taxonomies. The evolution hypothesis of a set of products can be presented by cladogram T_P. Similarly, the evolution hypothesis of a set of manufacturing capabilities can be presented by cladogram T_M, yet. If $T_P \approx T_M$ then both T_P and T_M have similar topologies and branching events, i.e. they are associated through co-evolution. The pair of cladograms (T_P, T_M) is called a "Tanglegram" when charted facing each other.

Lemma - Perfect Co-evolution

'A one-to-one change and effect association labels the status of perfectly co-evolving products and manufacturing capabilities'

This perfect co-evolution can be shown by untangled mirror reflection cladograms of both products and manufacturing capabilities optimum cladograms. The tendency for having such association is derived from the desire for exploiting all available manufacturing capabilities before initiating a change, and similarly for products features which aim to fully utilize the available manufacturing capabilities.

Proof: Let $d(T_P, T_M)$ *be the cladistic difference between the pair* (T_P, T_M)

Find the sets of { $T_{P_{min}}$ *} and {* $T_{M_{min}}$*} of minimum cladogram length*

Select $T_{P_{min}}$ *and* $T_{M_{min}}$ *that minimize* $d(T_P, T_M)$

If there exists a pair of best cladograms $\left(T_{P_{min}}, T_{M_{min}}\right)$ *at which* $d\left(T_{P_{min}}, T_{M_{min}}\right)=0$

> *Then* $T_{P_{min}} \equiv T_{M_{min}}$, $d(T_P, T_M) = 0$, *Topologies of* $T_{P_{min}}$, $T_{M_{min}}$ *are equivalent, and one-to-one branching events exist (a perfect co-evolution has been reached).*

Hypothesis 2 - Equilibrium Preservation

'The Perfect Co-evolution can rule manufacturing association to replace unplanned manufacturing association'

Many changes take place on both the product and manufacturing capabilities sides. The symbiosis of design features and manufacturing capabilities that emerged overtime due to those changes might not be obvious particularly if they came about due to a disruptive change. One-to-one symbiosis can be used as an objective and a guiding rule to rectify the unorganized evolution paths of products and manufacturing capabilities, and promote better and more sustainable manufacturing environment, where all processing capabilities are better utilized and all achievable product features are explored, which indicates a perfect co-evolution state. That futuristic objective of co-evolution can be set through equations 3.1 and 3.2.

$$\text{Min } d(T_{t+1}, T_t)|_{\text{P or M}} = (\|T\|_{t+1} - \|T\|_t)|_{\text{P or M}} \quad (3.1)$$

S.t.

$$\Delta_t d\left(T_{P_{min}}, T_{M_{min}}\right) = 0 \quad (3.2)$$

Where $\|T\|_{\mathrm{t}}$ is the length of cladogram T at current time (t), and $\Delta_t d\left(T_{P_{min}}, T_{M_{min}}\right)$ is the cladistic difference between products and manufacturing capabilities evolution paths between generations at time (t+1) and time (t). That difference is only allowed a zero value, hence cladogram topologies are always identical and a one-to-one symbiosis exists, consequently co-evolution is always kept in equilibrium state (perfect) over the generations.

It is important to stress that the proposed hypotheses and model apply to classes of products and classes of manufacturing capabilities and technologies used to produce them over time. A single product and its manufacturing system represent specific instants of these classes.

Hypothesis 3 - Equilibrium Restoration

‘Co-evolution imperfection can be treated by introducing new species of products and manufacturing systems’

When least different cladograms of products and manufacturing systems are obtained; they would be similar only if their co-evolution is perfect; then their difference is zero. However; if there exist difference between the two sides; then their co-evolution is imperfect and future planning efforts will be devoted to reaching their co-evolution equilibrium state. Adding new cladogram terminals at the specific locations at both sides would result in identical cladograms; hence reaching the equilibrium state. This process of terminals’ addition is similar to the emergence of new species in nature; where each terminal represents a single species.

In summary; chapter 3 has introduced the theoretical fundamentals of the proposed manufacturing co-evolution model. Based on the observations from real manufacturing world examples and theories of biological co-evolution of different species in nature; a series of manufacturing co-evolution hypotheses has been introduced. Hypothesis (1) advocates the existence of products/systems change symbiosis and its bi-directionality. A lemma that connects identical historical evolution paths of products/systems to their perfect co-evolution has been proven. Hypothesis (2) indicates keeping the existing perfect co-evolution state as guidance for future planning for product design and manufacturing system synthesis. Hypothesis (3) suggests the introduction of new species of products and manufacturing systems to reach equilibrium and perfect manufacturing co-evolution state.

In the next chapter (4); a mathematical model of 4 activities - based on co-evolution hypotheses - is introduced. The activities include; 1) applying cladistics analysis to realize the history of products and manufacturing systems separately; 2) applying tree reconciliation to associate products/systems evolution history and recognize their co-evolution state; 3) keeping perfect co-evolution state for further future product design and system synthesis activities; and 4) restoring the out-of-equilibrium co-evolution state by introducing new species of products and manufacturing systems; and introducing their predicted design and structure based on the synthesis knowledge that has been collected from their history by the model. Detailed mathematical formulation of the model is introduced and translated into several solution algorithms to perform the different activities of the model.

CHAPTER 4
THE CO-EVOLUTION MODEL

The proposed co-evolution model in this dissertation is adhering to the aforementioned way of thinking. It implicitly embeds economic sustainability of manufacturing systems and products while facing their changes; by prolonging the life of the system to handle multiple product generations, and managing future product generations to exploit available manufacturing capabilities. The co-evolution model suggests a biological analogy to the targeted co-evolution; and develops some mathematical tools to manage it.

The co-evolution model in the artificial world applies the analogy of biological co-evolution. In nature; biological co-evolution occurs when two or more species influence each other's evolution by reciprocal effects. This process often explains co-adaptation between species in nature (Page 2003). The presented model perceives the co-development of the entities of the artificial world of design and technology in a similar way to co-evolution of species in nature. A four activities IDEF0 representation (Figure 4.1) illustrates the proposed co-evolution model in the artificial world.

Model activities

Activity A1: Is responsible for the data input of the model. Both historical data of manufacturing systems and the corresponding products are fed to the model independently, i.e. data don't assume symbiosis and dependence. This activity result in two sets of evolution trends (cladograms) that hypothesize how systems and products could have been evolving through history, using parsimony analysis.

Activity A2: Dependence of data is established in this activity. The most similar pair of evolution trends (tanglegram) of both systems and products is searched for. This activity constructs the present association of systems and products, and realizes their common history.

Activity A3: If evolution trends of systems and products are topologically symmetrical (equilibrium); they are kept symmetrical in the future by applying this activity. Best associated systems and products result as model output after this activity.

Activity A4: In case of asymmetrical evolution trends of systems and products (out-of-equilibrium state); this activity applies a perfecting method to restore symmetry. The result is a series of predictions of new systems and products as model output that are suggested to restore equilibrium state in the co-evolution model.

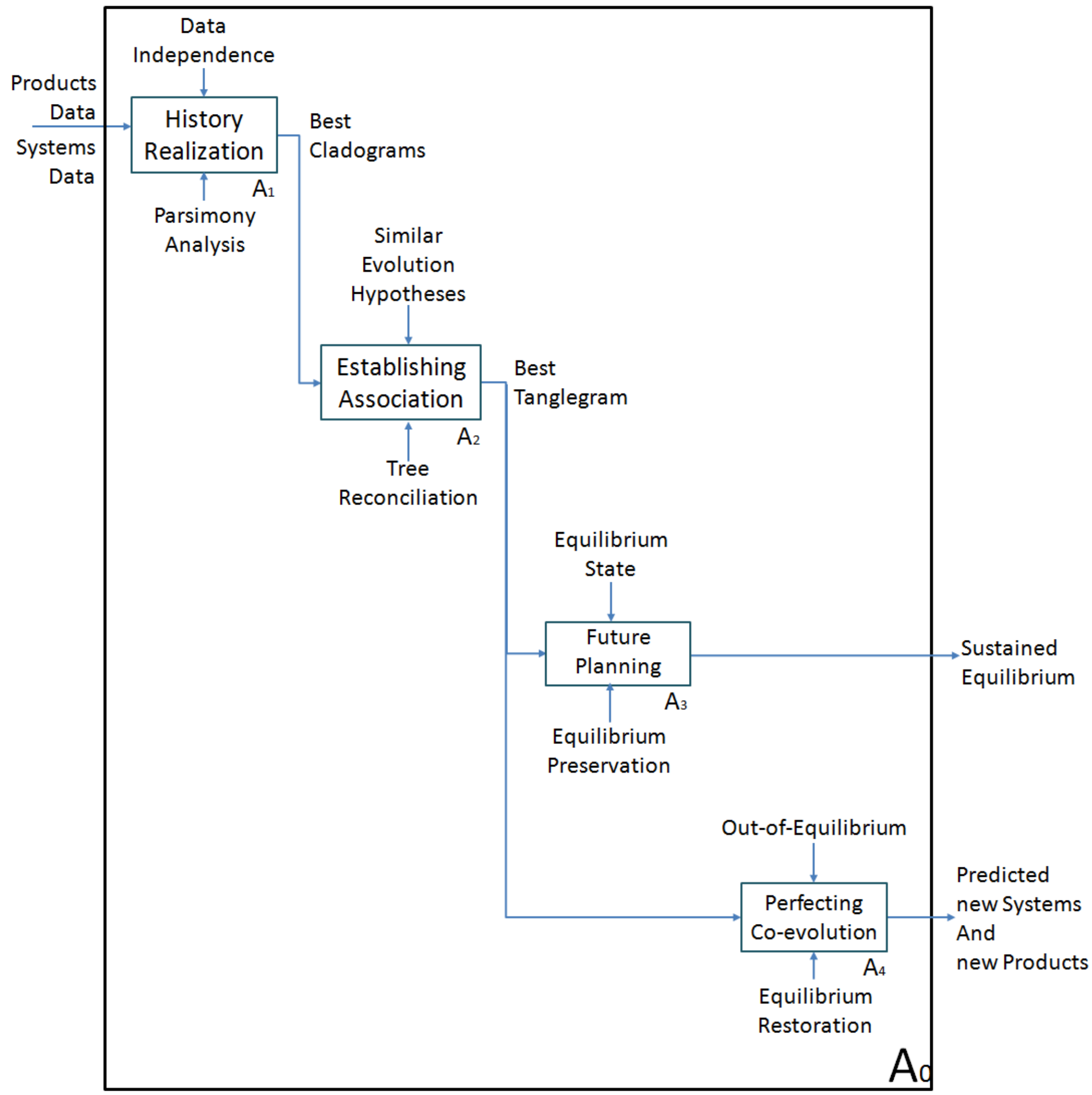


Figure 4.1 IDEF0 of Systems/Products Co-evolution Model

4.1 History Realization

In this model activity; independent histories of manufacturing systems and products are studied and analyzed. This is performed by using cladistics to realize the independent evolution trends of systems and products. The problem of searching for the most parsimonious cladogram is uniquely formulated in this research to allow the division into topology construction and taxa arrangement sub-problems, and for future flexibility of constraints addition and cost function modification to suite the criteria and objectives commonly used in manufacturing. Equations 4.1 to 4.7 represent cladogram formulation of *n* end-taxa and N characters.

$$\text{Min } L(T) = \sum_{K=1}^{N}\sum_{I=1}^{n}\sum_{J=1}^{n-1}\beta_{KIJ} \qquad (4.1)$$

S.t.

$$\sum_{j=1}^{I} X_{Ij} \cdot \sum_{j=1}^{I} X_{I-j\,j} = 0 \quad \forall\, I = 1 \ldots n-1 \qquad (4.2)$$

$$\sum_{j=1}^{I} X_{Ij} + \sum_{j=1}^{I} X_{I-j\,j} = 1 \quad \forall\, I = 1 \ldots n-1 \qquad (4.3)$$

$$\sum_{i=1}^{1} Y_{iJ} = 0 \quad \forall\, J = 1 \ldots n-1 \qquad (4.4)$$

$$\sum_{j=1}^{1} Y_{Ij} = 0 \quad \forall\, I = 1 \ldots n-1 \qquad (4.5)$$

$$\alpha_{K\,i-l\,\,j-m} - C_{KI}X_{ij}.\sum_{J=1}^{n} Y_{IJ} = 0 \quad \forall\, I = 1 \ldots n-1\,, \quad \forall\, l = 1 \ldots n-i \;\&, \forall m = 1 \ldots n-j \qquad (4.6)$$

$$\alpha_{KIJ} + \sum_{j=J+1}^{n-1}\beta_{kIj} + \sum_{\substack{i=I \\ j=J+i-I+1}}^{n-1}\beta_{kij} \le 1 \quad \forall\, K = 1 \ldots N\,, \forall\, I, J = 1 \ldots n-1 \qquad (4.7)$$

The objective function $L(T)$ in equation 4.1 represents the length of the cladogram, while equations 4.2 and 4.3 ensure the feasibility of the topology by limiting each cladogram terminal to connect to only, and at least, one node (connected node X_{ij}=1, else X_{ij}=0). Equations 4.4 and 4.5 indicate the assignment of end-taxa to each terminal (taxon *i* assigned to terminal *j* then Y_{IJ}=1, else Y_{IJ}=0). Finally, equation 4.6 eliminates the nodes that do not share a specific character (K) for a specific end-taxon (I) and equation 4.7 keeps only the upper node of all the nodes that share that specific character (K) for that specific end-taxon (I) (character exists C_{KI}=1, else C_{KI}=0, while $\alpha_{K\,i\,j}$ stores eliminated nodes and β_{Kij} stores upper nodes occurrences which represents the cost).

The problem of obtaining the group of most parsimonious cladograms has been divided by AlGeddawy and ElMaraghy (2009a) into two separate sub-problems;

1. The construction of cladogram topologies, where number of topologies is *n*-1!
2. The arrangement of taxa at cladogram terminals, where number of assignments is *n*! and *n* is the number of studied taxa

This solution technique begins with choosing end-taxa (the entities to be investigated) placed at the end of cladogram terminals, such as taxa A, B, C, D and E shown in Figure 4.2 Parsimony Analysis, then determining the characters that will provide relationships evidence (1 to 6 in Figure 4.2). All inherited character states by each taxon are identified, and then a topology is generated and complemented with a specific taxa assignment. In Figure 4.2 the shown cladogram has a total length of 8 steps, while there are only 6 characters because some characters are repeated (character 1 and 3), which represents cladistic conflicts that increase its length. The objective is to always avoid these conflicts; and this is the essence of parsimony analysis.

The solution algorithm of parsimony analysis is presented as Algorithm 1. Also cladistic topologies are coded using binary variables (Figure 4.3) in that algorithm; for a connected node X_{ij}=1, else X_{ij}=0. For the assignment of end-taxa combination e_I specifies terminal I for an end-taxon e. The length of a cladogram is the sum of Y_{cij} , where Y_{cij}=1 when character c exists at node (i,j), else Y_{cij}=0.

Binary Characters' states of End-Taxa

	1	2	3	4	5	6
A	1	1	0	1	0	1
B	0	1	1	0	0	0
C	1	1	0	0	1	0
D	1	0	0	0	0	0
E	1	1	1	0	0	1

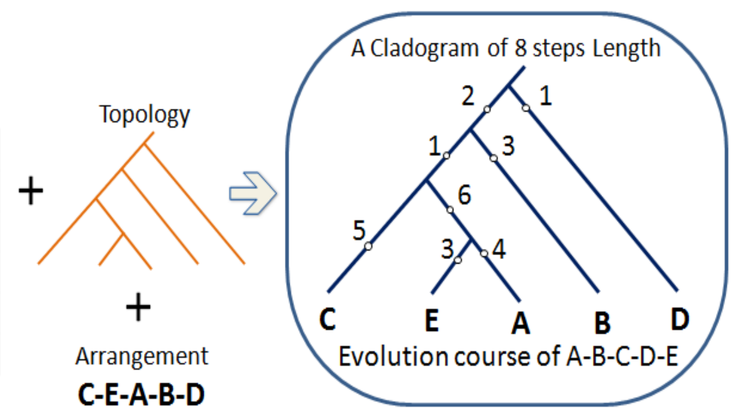


Figure 4.2 Parsimony Analysis

Algorithm 1: Parsimony Analysis

Set characters to end-taxa occurrence

{C: c=1 character exists, c=0 character does not exist}

Generate end-taxa combinations E

Generate a Topology matrix:

$X_{11} \leftarrow 1$

∀ J=1…n-1, do:

  $X_{iJ} \leftarrow 1$

  $X_{1\ldots i-1\,J} \leftarrow 0$

  $X_{i+1\ldots n\,J} \leftarrow 0$, where i∈R, R=1…J

  ∀ I=1…n, check:

    If $\sum_{j=1}^{J} X_{I+1\,j} = 1$

    then add empty column $\{X_{I+1\,j}=0: j=1\ldots J\}$

    If $\sum_{\substack{i=1\\ j=i}}^{I-1} X_{ij} = 1$

    then add empty diagonal

    $\{X_{ij}=0: i=1\ldots I-1, j=i\}$

Cladogram length calculation:

$Y_c \leftarrow X$

∀ C, do:

  ∀ I=1…n, do:

    If $C_{e_I} = 0$

    then$\{Y_{c\,e_I\,j}=0: j=1\ldots n-1\}$ and$\{Y_{c\,e_I\,j}=0: i=1: e_I, j=i\}$

  ∀ J=1…n-2, do:

    If $Y_{c\,iJ} = 1$

    Then $Y_{c\,i\,J+1} = 0$

    and $Y_{c\,i+1\,J+1} = 0$

  $L=\sum_{K=1}^{N}\sum_{I=1}^{n}\sum_{J=1}^{n-1} Y_{C\,I\,J}$ <Cladogram Length>

End

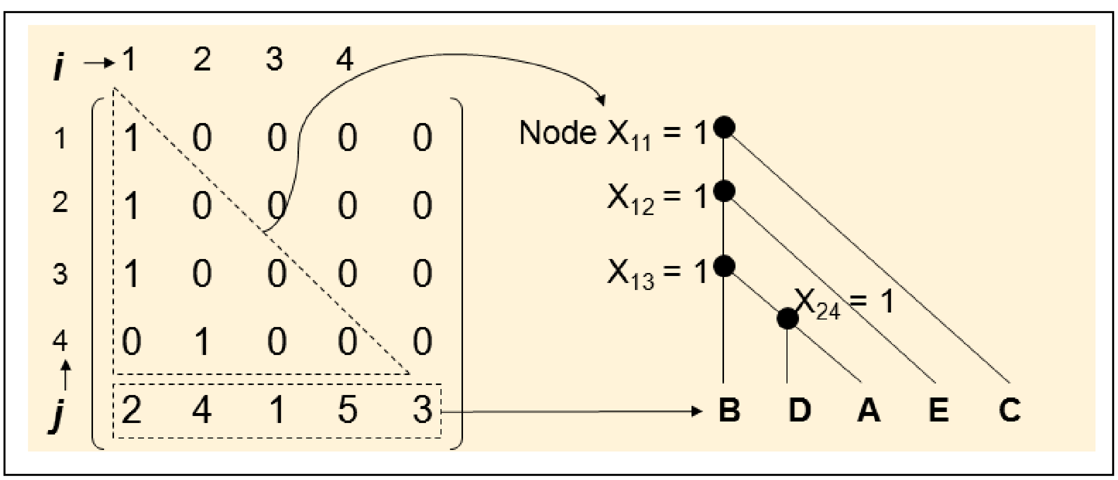


Figure 4.3 A Matrix Representation of a Topology and an Assignment of 5 End-Taxa (A,B,C,D,E)

4.2 Establishing Association

This model activity establishes the current state of manufacturing systems and products co-evolution; and identifies how similar their evolution trends (cladograms) are. Finding the parallels between the cladograms that depict history of co-existing species in nature is known as the study of historical association. Exact mirror images of their associated cladograms can be found if the co-existing species have co-speciation as well, which means they have the exact turn by turn evolution and speciation. The existence of biological co-speciation is tested by the degree of cladograms topological similarity of the studied species. Significant similarity between trees may suggest species evolution interdependence over joint adaptation (Page 1994). This type of study is stereotypically attributed to biology specially in the field of parasite and host relationships, though, other fields of study adopted the technique to realize different entities association, such as the historical study of social patterns that are related to material culture evolution (Shennan 2009) to associate developed shapes of forks and knives over time.

A special problem arises when evolutionary courses are compared. Trees reconciliation is the problem of graphically representing the conjugated cladograms in one representation (tanglegram) while minimizing the tangleness of those trees (Figure 4.4 and Figure 4.5). This model activity can be formulated through equations 4.8 to 4.16.

$$\text{Min} \quad d(T_P, T_M) = \sum_{\mathrm{J}=1}^{n} \gamma_{\mathrm{J}} \tag{4.8}$$

S.t.

$$\mathrm{I_J} = \sum_{i=1}^{n} i\mathrm{Y}_{i\mathrm{J}} \quad \forall\ \mathrm{J} = 1 \dots n \tag{4.9}$$

$$\psi_{\mathrm{QJ}} = \sum_{j=1}^{\mathrm{Q}} \mathrm{QX}_{\mathrm{I_J}\ j} \quad \forall\ \mathrm{Q} = 1 \dots n-1, \mathrm{J} = 1 \dots n \tag{4.10}$$

$$\omega_{\mathrm{QJ}} = \sum_{j=1}^{\mathrm{Q}} \mathrm{QX}_{\mathrm{I_J}-j\ \ j} \quad \forall\ \mathrm{Q} = 1 \dots n-1, \mathrm{J} = 1 \dots n \tag{4.11}$$

$$\lambda_{\mathrm{J}} = \mathrm{I_J} \sum_{j=1}^{n-1} \mathrm{X}_{\mathrm{I_J}\ j} + \left(\mathrm{I_J} - \min\{\omega_{\mathrm{QJ}}\}\right). \sum_{j=1}^{n-1} \mathrm{X}_{\mathrm{I_J}-j\ \ j}$$

$$\forall\ \mathrm{Q} = 1 \dots n-1, \mathrm{J} = 1 \dots n,\ \omega_{\mathrm{QJ}} > 0 \tag{4.12}$$

$$\mu_{\mathrm{J}} = \min\left\{\psi_{\mathrm{QJ}}\right\}. \sum_{j=1}^{n-1} \mathrm{X}_{\mathrm{I_J}\ j} + \min\{\omega_{\mathrm{QJ}}\}. \sum_{j=1}^{n-1} \mathrm{X}_{\mathrm{I_J}-j\ \ j}$$

$$\forall\ \mathrm{Q} = 1 \dots n-1, \mathrm{J} = 1 \dots n,\ \psi_{\mathrm{QJ}} > 0, \omega_{\mathrm{QJ}} > 0 \tag{4.13}$$

$$\eta_J = \left|\lambda_J|_P - \lambda_J|_M\right| + \left|\mu_J|_P - \mu_J|_M\right| \ \forall \ J = 1 \dots n \quad (4.14)$$

$$\gamma_J . \nu_J = \eta_J \ \forall \ J = 1 \dots n \quad (4.15)$$

$$\nu_J \geq 1 \ \forall \ J = 1 \dots n \quad (4.16)$$

The objective function $d(T_P, T_M)$ in equation 4.8 calculates the cladistic difference between the pair of cladograms T_P of the Products and T_M of the Manufacturing capabilities, which adds up the number of non-conforming nodes in both cladograms. Equation 4.9 converts the end-taxa combination at cladogram terminals to indices, while equations 4.10 to 4.13 estimate the location coordinates (λ_J, μ_J) of the nodes that connect each index to the cladogram tree. Equation 4.14 detects if the counterpart nodes in both cladograms (T_P, T_M) are conforming $(\eta_J = 0)$ or not$(\eta_J > 0)$. Finally, equations 4.15 and 4.16 assign a difference cost (γ_J) =1 for each non-conformity.

Most of tree reconciliation techniques in literature start with an already chosen pair of cladograms, then start the untangling process to produce planar graphs (Buchin *et al.* 2009). It depends on the user's choice of the pair of cladograms that are felt to best represent the alleged association. However in co-evolution model in this research; the whole set of the most parsimonious cladograms obtained from both manufacturing systems and products sides are compared to find the best matching pair of cladograms (Figure 4.5). If the two trees are topologically identical; then the resulted tanglegram is symmetrical (untangled).

All obtained equally parsimonious cladograms from parsimony analysis (Algorithm 1) are kept to be examined by Algorithm 2, which finds the best tanglegram with the least tangling. The cladistic difference is the sum of γ which assigns the non-conformity cost between products and manufacturing systems cladograms, where γ=1 for non-conforming nodes, else γ=0. λ and μ identify the *ij* coordinates of node *X* that connects an end-taxon to a cladogram.

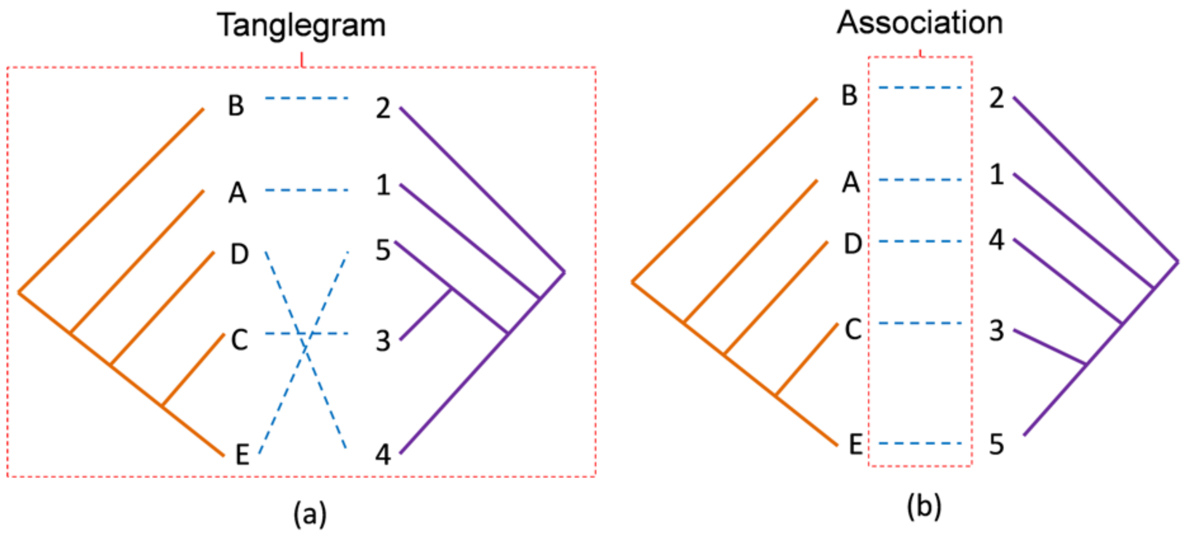


Figure 4.4 Comparative Study of Historical Association
(a) Tangled tanglegram (b) Untangled tanglegram

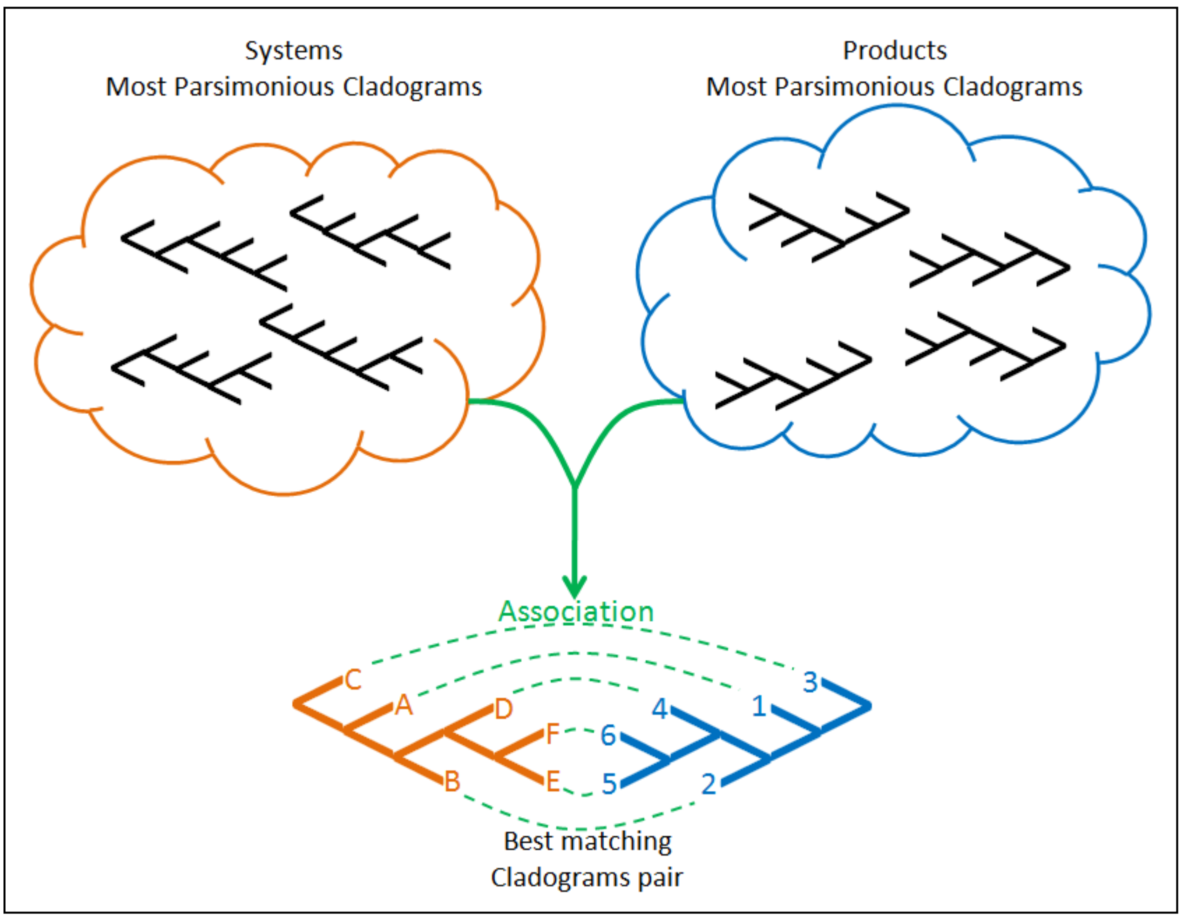


Figure 4.5 Establishing Associated Evolution trends

Algorithm 2: Best Untangled Tanglegram

Initiate end taxa combinations P, M
Initiate cladistic topologies X_P, X_M
∀ I=1…n, do:
<Product Side>
Increase j=1…n-1
    Until $X_{P_{I\ j}} = 1$ <search for the existing nodes>
Increase i=1… I -1
    Until $X_{P_{I-i\ j-i}} = 1$ <find the node connecting the whole branch>
        Then λ_{P_I}= I-i and μ_{P_I}=j   <store coordinates>
Similarly:
<Manufacturing System Side>
Increase j=1…n-1
    Until $X_{M_{I\ j}} = 1$
Increase i=1… I-1
    Until $X_{M_{I-i\ j-i}} = 1$
        Then λ_{M_I}= I-i and μ_{M_I}=j
$\eta_I = |\lambda_{P_I} - \lambda_{M_I}| + |\mu_{P_I} - \mu_{M_I}|$ <calculate coordinates difference>
If η_I>0 then γ_I=1, else γ_I=0 <assign cladistic unit cost if a coordinates difference exists>
d= $\sum_{i=1}^{n} \gamma_i$ <Total cladistic difference cost>
End

4.3 Future Planning

This model activity uses the previously established association if the resulted tanglegram is found to be symmetrical. In this case manufacturing systems and products are said to be co-evolving perfectly and their symbiosis is in an equilibrium state. That perfect co-evolution can be preserved by always keeping it as the objective of future evolution of systems and products (Figure 4.6).

The perfect co-evolution hypothesis can be implemented after the success of the co-evolution check to detect high likelihood of common history for products and manufacturing system. The mathematical model described in equations 4.1 to 4.7 remains the same except for the objective function which is modified to reflect the succession of cladograms development. The cladistic difference minimization objective is described in equation 4.17.

$$\text{Min } d(T_{t+1},T_t)|_{\text{P or M}} = \left(\sum_{\text{K}=1}^{\text{N}}\sum_{\text{I}=1}^{\text{n}}\sum_{\text{J}=1}^{\text{n}-1}\beta_{\text{K I J}}\,|_{t+1} - \sum_{\text{K}=1}^{\text{N}}\sum_{\text{I}=1}^{\text{n}}\sum_{\text{J}=1}^{\text{n}-1}\beta_{\text{K I J}}\,|_{t}\right)|_{\text{P or M}} \qquad (4.17)$$

Where decision variables of T_t are already known. Also The topology of T_{t+1} is built on the same topology of T_t to keep the same $d(T_P, T_M)$ of time (t) at time (t+1).

Parsimony analysis algorithm (Algorithm 1) can be modified to preserve perfect co-evolution in the future by only examining a limited number of topologies that share the best obtained topology at time (*t*) as their common core topology, then adding the expansion nodes at the different branches combinations. Hence, the topology generation step would read as follows:

Algorithm 3: Preserving Co-evolution	
For P and M do:	<Addressing Products and Systems Topologies>
Recall $\text{X}_{1\ldots\text{n}\ \text{n}-1}$ at time (*t*)	<topology matrix element>
At t+1do:	<build on same topology for next time period>
Set *i*	<new branch location>
$\text{X}_{i\text{n}} \leftarrow 1$	<adding the new branch>
$\text{X}_{1\ldots i-1\ \text{n}} \leftarrow 0$	<expand topology matrix above branch>
$\text{X}_{i+1\ldots\text{n}\ \text{n}} \leftarrow 0$, where $i \in R$, R=1…n	<expand topology matrix below branch>
End	

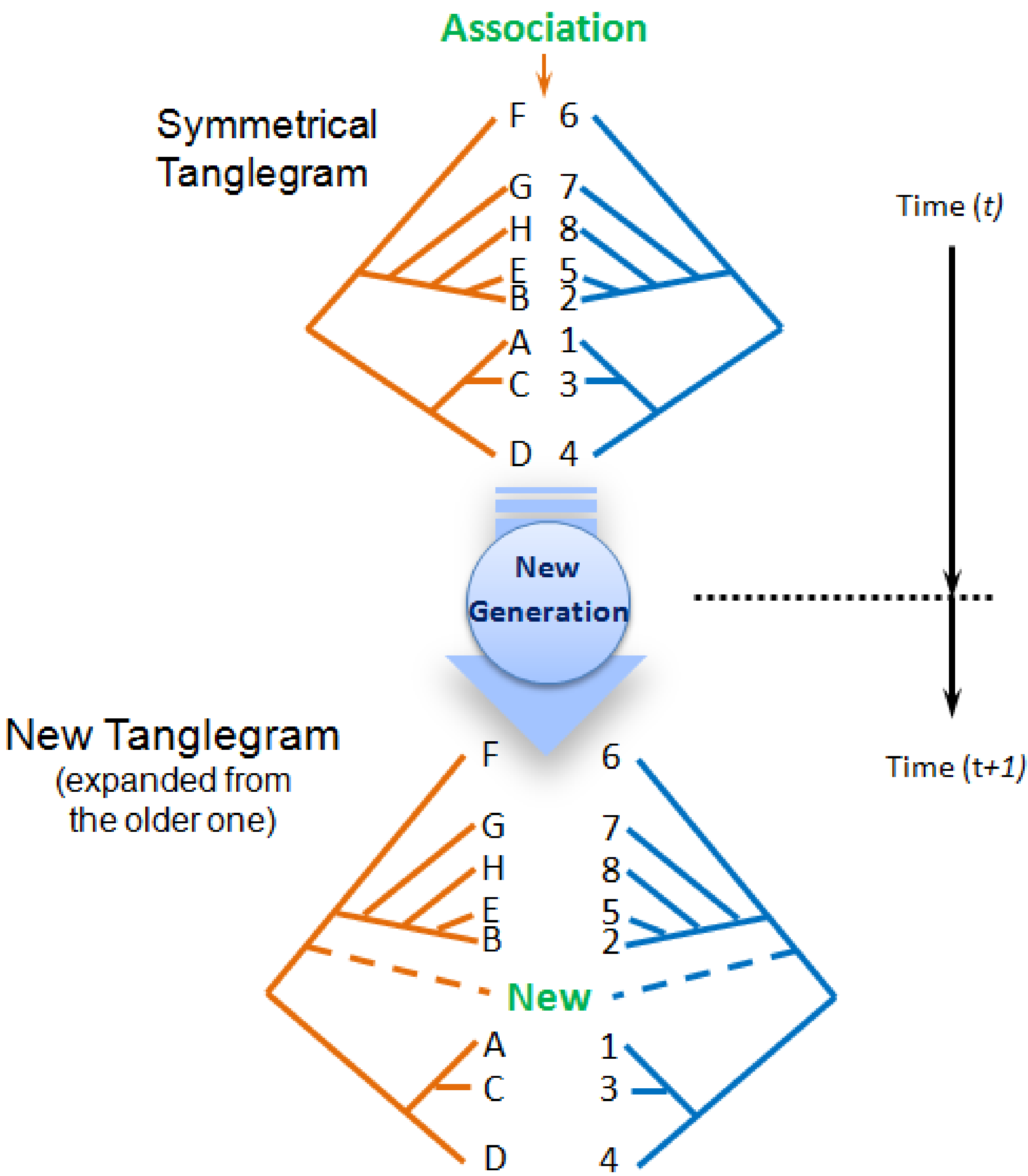


Figure 4.6 Planning Manufacturing Future

4.4 Perfecting Co-evolution

This model activity promotes co-evolution in the case of an out-of-equilibrium state. Sometimes after realizing the common history of manufacturing systems and the produced artifacts; some discrepancies might be found. Those discrepancies are spotted as non-conformities between systems and artifacts cladograms (Figure 4.7). Those non-conformities are illustrated by the counterpart branches that do not connect at the same locations on the tanglegram left and right cladograms; causing asymmetrical tanglegram.

4.4.1 Equilibrium Restoration by Species Introduction

The presented algorithm 4 identifies those branches and cures the present tanglegram to look symmetrical by expanding both cladograms. This process involves predicting the missing manufacturing systems and artifacts that assure tanglegram symmetry. If these predictions are to be considered; the current manufacturing systems would be totally exploited by the predicted artifacts and current artifacts would fully exploit the manufacturing boundaries of the predicted systems, thus achieving equilibrium state in manufacturing co-evolution.

Algorithm 4: Species Introduction	
Recall X_P, X_M	<chosen topologies>
Recall γ	<tanglegram non-conformities from algorithm 2>
Recall λ_P , μ_P , λ_M , μ_M	<nodes coordinates>
∀ I=1…n, do:	
If γ_I=1 then	<in case of non-conformity>
Append X_P by $x_{\lambda_{P_I}\mu_{P_I}}=1$	<adding counterpart nodes to topology structure>
Append X_M by $x_{\lambda_{M_I}\mu_{M_I}}=1$	<adding counterpart nodes to topology structure>
End	

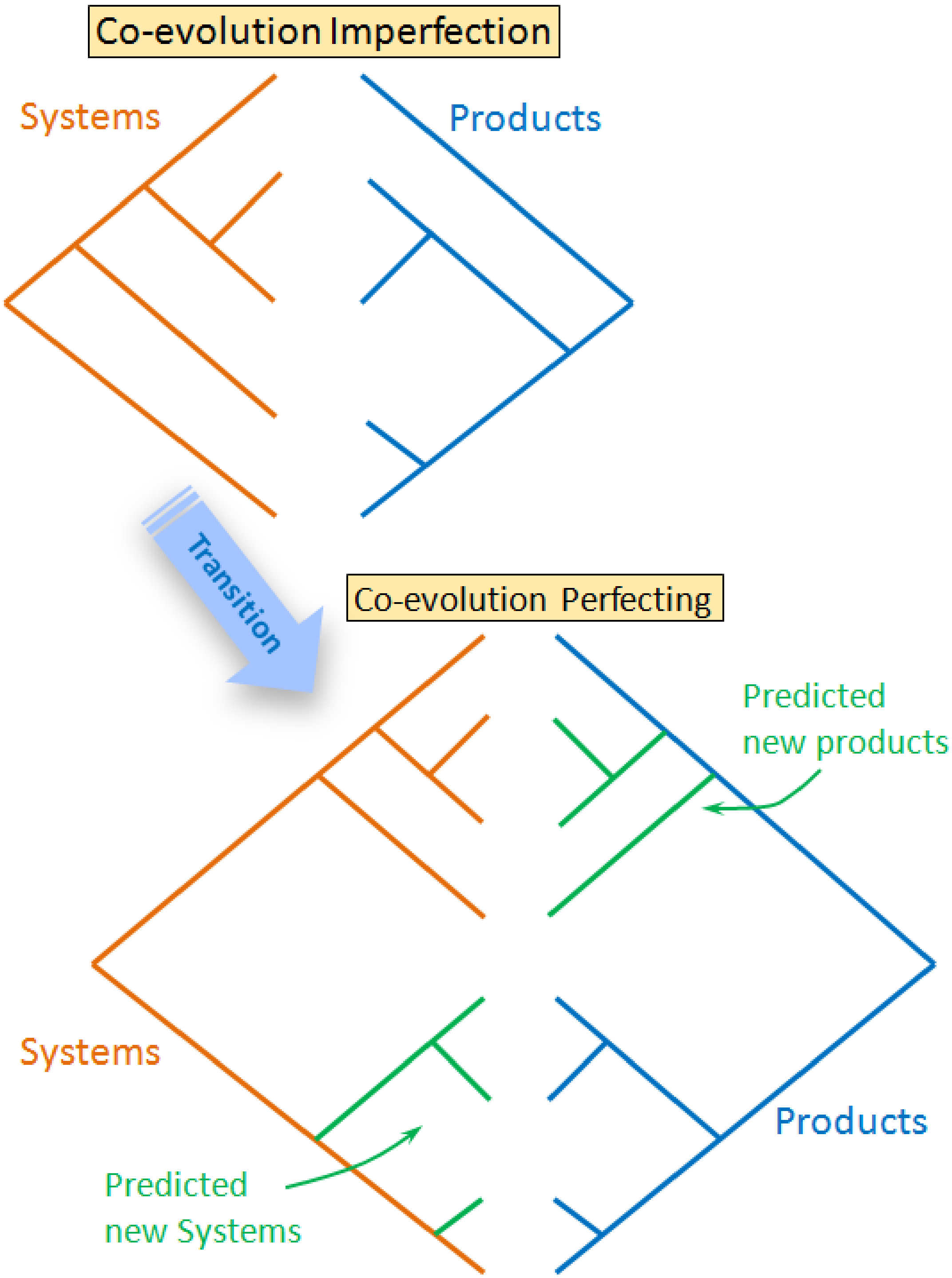


Figure 4.7 Predictions made Through Perfecting Manufacturing Co-evolution

4.4.2 Systems Synthesis and Products Design

The new predicted species of manufacturing systems and products that are used to restore equilibrium need to be synthesized to create real manufacturing systems and products variants made of industrial manufacturing capabilities and practical design features. The co-evolution model has to be able to determine what are the components and features of the new species of systems and products, not just the need for these instances. The co-evolution model is able to automatically perform the synthesis process by discovering the relationships between manufacturing capabilities and product features from their past co-evolution history. If the corresponding capabilities and features could be identified; they can be further used to synthesize the needed systems and products.

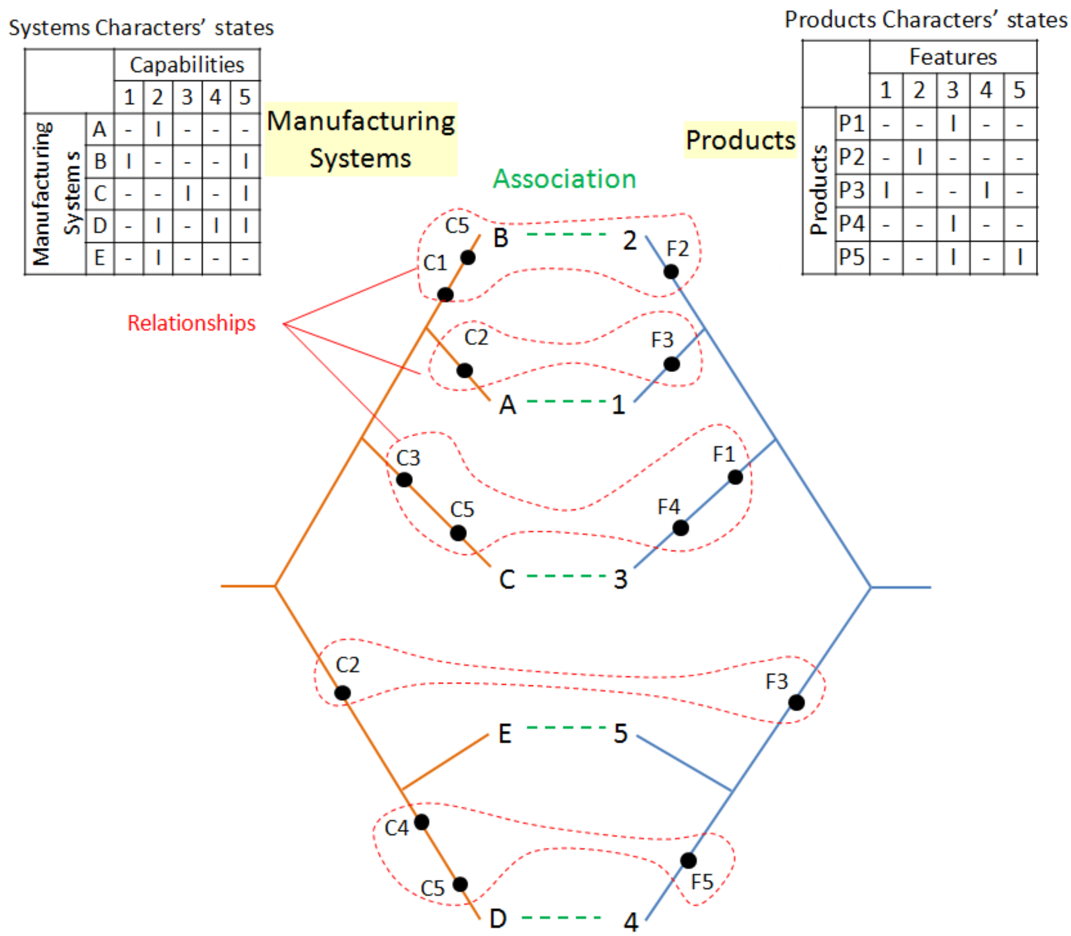
Discovering capabilities/features relationships begins with looking at the developed tanglegram of systems and products. Branches and leaves of cladograms carry the characters (capabilities / features) of both systems and products. Corresponding branches of the identical parts of these cladograms associate manufacturing capabilities of the studied systems with the corresponding product features. The resulting association would constitute the preliminary relationships between capabilities and features.

Figure 4.8 shows an example of a pair of classification trees of manufacturing systems and their corresponding products. In this example both trees are identical; consequently all corresponding tree branches are candidates to establish relationships between manufacturing capabilities and product features. Established relationships between manufacturing capabilities (noted by C) and product features (noted by F) are marked by dashed lines in Figure 4.8.

The preliminary established relationships between manufacturing systems capabilities and product features can be further analyzed and reduced to the simplest sets of relationships. In order to perform all production processes for a specific product; the corresponding manufacturing system should possess all the required manufacturing capabilities to produce all its features. Therefore, manufacturing capabilities of the system should be sufficient or exceed those required to develop the product features.

The relationships between individual manufacturing capabilities and products features are not necessarily one-to-one; relationships between sets of capabilities and features exist The largest sets of individual capabilities are the whole manufacturing system; while a whole product is the largest set of individual features. Therefore; systems and corresponding products are the sources of sets relationships; however the model objective is to reduce related sets to their simplest format (irreducible set) in order to synthesize the most efficient manufacturing systems in the future that only consist of the necessary manufacturing capabilities to produce newly introduced products.

Logically; an individual feature in an irreducible product features set can exist alone but will require the whole associated irreducible manufacturing capabilities set; while an individual capability in an irreducible manufacturing capabilities set cannot exist alone; it should be accompanied by its other set members. For example; a cutting tool, a rotary spindle and a chuck have to exist simultaneously in a machine-tool in order to be able to machine any single feature in a work-piece; while that work-piece might have external or internal features or both.



Manufacturing Systems	Capabilities 1	2	3	4	5
A	-	I	-	-	-
B	I	-	-	-	I
C	-	-	I	-	I
D	-	I	-	I	I
E	-	I	-	-	-

Products	Features 1	2	3	4	5
P1	-	-	I	-	-
P2	-	I	-	-	-
P3	I	-	-	I	-
P4	-	-	I	-	-
P5	-	-	I	-	I

Figure 4.8 Best matching pair of classification trees of systems/products

That logic of relationships between manufacturing capabilities and product features are further detailed in the next set of rules. These rules are necessary to convert the established relationships between capabilities and features to a linear system of equations and reduce it later in this stage of the model.

Rule 1 - Capabilities Sufficiency

'The capabilities of a manufacturing system should be sufficient to produce all features of the corresponding product/products' family'. This rule translates to having a manufacturing system represented by set S consisting of the capabilities $\{C_1 \ldots C_n\}$ that can fully produce product set P consisting of the features $\{F_1 \ldots F_N\}$, then set S corresponds to set P or $\{C_1 \ldots C_n\} \rightarrow \{F_1 \ldots F_N\}$

Rule 2 - Features Sets Divisibility

'Product features related to irreducible set(s) of manufacturing capabilities can exist individually in other products'. This means that product features can exist independently and gives full freedom to combine product features in any future design arrangement. This rule can be expressed by;

Let {Cx, Cy: irreducible set} → {Fx, Fy}

Since individual features require the whole associated capabilities set to be present

Then {Cx, Cy}→{Fx} and {Cx, Cy}→{Fy}

{Fx} and {Fy} are two independent sets

Rule 3 - Capabilities Sets Indivisibility

'Manufacturing capabilities of irreducible sets cannot exist individually in other systems'. This rule is due to the fact that if a group of manufacturing capabilities are indispensible to produce a group of product features; subgroups from capabilities group would lack functionability. This rule can be illustrated by;

Let {Cx,Cy: irreducible set}→{Fx,Fy}

Since {Cx,Cy: irreducible set }→{Fx} and {Cx,Cy: irreducible set }→{Fy}

Then {Cx}→Φ, {Cy}→Φ

Rule 4 - Sets Exclusion

'The remainder sets of capabilities and features, after excluding related sets, are related'. This is due to the fact that related groups of capabilities and features are coming from the coalition of a number of irreducible sets of capabilities and features. This rule can be illustrated by;

<For irreducible sets>

Let {Cx,Cy,Cz}→{Fx,Fy,Fz}

Since {Cx,Cy: irreducible set}→{Fx,Fy}

Consequently {Cz}→{Fz}

<For generality>

Let {Cx,Cy,Cz,Cw}→{Fx,Fy,Fz,Fw}

Since {Cx,Cy}→{Fx,Fy} and {Cz}→{Fz}

Then {Cw}→{Fw}

Rule 5 - Inclusion / Exclusion of Features

'Product features may not be fully included while applying rules of association'. Although excluding a product feature means less than full utilization of manufacturing capabilities, it does not conflict with the association logic; a specific set of capabilities can produce less features than designated but not more. This exclusion of features is permitted to allow row operations in manipulating the resulting linear system of equations. This rule can be expressed as;

Let {Cx,Cy,Cu}→{Fx,Fv}

If {Cx,Cy: irreducible set}→{Fx,Fy}

Then from rule 2, {Cx,Cy}→{Fx}

Consequently from rule 4, {Cu}→{Fv}, i.e. Feature Fy is lost in the previous operations

The sets of relationships between system capabilities and product features are represented by a system of linear inequalities (equation 4.18) to facilitate the solution. Since all algebraic operations must follow set membership rules, being only true or false. Consequently; the value of coefficients in these inequalities must be positive 1 or 0.

$$A\ C \geq B\ F \tag{4.18}$$

Where, C: System capabilities vector

F: Products Features vector

A: membership matrix of system capabilities

B: membership matrix of product features

This linear system of inequality can be transformed to the linear system of equations:

$$A\ C = (B+L)\ F \tag{4.19}$$

Where L: membership matrix of lost product features (during rows operations)

That linear system can be further reduced to the simpler linear system:

$$A\ C = B\ F \tag{4.20}$$

Under two conditions:

1) No manufacturing capabilities are allowed to have negative coefficients (Equivalent to capabilities indivisibility - *Rule 3*).
2) All negative product features coefficients are nullified (Equivalent to permitting features divisibility and exclusion - *Rule 2* and *5*).

The objective is to reduce the relationships between C variables and F variables; which represent manufacturing capabilities and product features, in order to obtain the most efficient future system synthesis. To reduce those relationships to the simplest format; the block matrix (A|B) should be reduced by a series of Gauss eliminations similar to reduced row echelon form (Weidner 1985). This can be done mathematically for any linear system; but the system of equations in this research has specific physical properties that must be observed. Conditions 1 and 2 can be mathematically converted to;

1) Allow only (0,1) elements after any A matrix transformation
2) Delete all (-1) elements after any B matrix transformation

The reduction algorithm of block matrix (A|B) is described as follows;

Algorithm 5: Block Matrix (A|B) Reduction

Sort rows of (A|B) in a descended order of number of (1) elements in each row

For i=N…2, where N is the number of equations

    For j=1…i-1

        If all A_{jq}-A_{iq} > -1, $\forall$ q then:

            $A_j \leftarrow A_j - A_i$

            $B_j \leftarrow B_j - B_i$

            For k=1…M, where M is the number of columns of B

                If B_{jk} = -1 Then:

                    $B_{jk} \leftarrow 0$

End

The system reduction step results in a block matrix (A|B) of fewer (1) elements. The reduced linear system is represented by equation 4.21. The reduced block matrix ($A_{reduced}$|$B_{reduced}$) represents the synthesis discovered knowledge from the history of manufacturing systems and product co-evolution.

$$A_{reduced}\, C = B_{reduced}\, F \qquad (4.21)$$

Future manufacturing synthesis using the obtained reduced block matrix is an application of simple matrices multiplications. This is perfectly consistent with the closed loop representation in chapter 3, where the block matrix corresponds to the process and capabilities matrices; depending on either products or systems are to be synthesized.

In the previous systems/products example represented in Figure 4.8; the pair of classification trees is identical; consequently all corresponding tree branches are candidates for establishing relationships between system capabilities and product features. However; only five relationships could be established from trees association; since not all branches are populated with characters. These relationships can be represented in the form of the block matrix (A|B); where matrix A constitutes character states of manufacturing systems that exist on these five branches and matrix B is the same for product features.

Block matrix (A|B) =

C1	C2	C3	C4	C5	F1	F2	F3	F4	F5
1	0	0	0	1	0	1	0	0	0
0	0	1	0	1	1	0	0	1	0
0	1	0	0	0	0	0	1	0	0
0	0	0	1	1	0	0	0	0	1
0	1	0	0	0	0	0	1	0	1

Performing the reduction algorithm on block matrix (A|B) produces the reduced matrices:

$A_{reduced}=\begin{pmatrix}1&0&0&0&1\\0&0&1&0&1\\0&1&0&0&0\\0&0&0&1&1\end{pmatrix}$, $B_{reduced}=\begin{pmatrix}0&1&0&0&0\\1&0&0&1&0\\0&0&1&0&0\\0&0&0&0&1\end{pmatrix}$

These two matrices represent the simplest form of relationships between systems capabilities and product features in this example.

If a new manufacturing system is introduced by vector C= $\begin{pmatrix}C1\\0\\C3\\0\\C5\end{pmatrix}$, it means that the new manufacturing system only has capabilities C1,C3 and C5. Consequently any relationships that involve C2 and C4 should be crossed out (rows that have '1' elements at C2 and C4 columns).

($A_{reduced}$|$B_{reduced}$) =

C1	~~C2~~	C3	~~C4~~	C5	F1	F2	F3	F4	F5
1	~~0~~	0	~~0~~	1	0	1	0	0	0
0	~~0~~	1	~~0~~	1	1	0	0	1	0
~~0~~	~~1~~	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~	~~1~~	~~0~~	~~0~~
~~0~~	~~0~~	~~0~~	~~1~~	~~1~~	~~0~~	~~0~~	~~0~~	~~0~~	~~1~~

Then, taking the remaining elements; $\begin{pmatrix}1&0&1\\0&1&1\end{pmatrix}$ x $\begin{pmatrix}C1\\C3\\C5\end{pmatrix}$ = $\begin{pmatrix}0&1&0&0&0\\1&0&0&1&0\end{pmatrix}$ x $\begin{pmatrix}F1\\F2\\F3\\F4\\F5\end{pmatrix}$

Thus; only two relationships exist; {C1,C5} →{F2}, and {C3,C5} →{F1,F4}

Then the new product will include features F1, F2 and F4.

Alternatively; if a new product is presented by vector of features F= $\begin{pmatrix}F1\\F2\\0\\F4\\0\end{pmatrix}$; this means only relationships that involve F1, F2 and F4 would be considered (rows that have ‘1’ elements at F1, F2 and F4 columns).

$(A_{reduced}|B_{reduced})$ =

C1	C2	C3	C4	C5	F1	F2	F3	F4	F5
1	0	0	0	1	0	1	0	0	0
0	0	1	0	1	1	0	0	1	0
0	1	0	0	0	0	0	1	0	0
0	0	0	1	1	0	0	0	0	1

Then, taking the remaining elements; $\begin{pmatrix} 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 \end{pmatrix} \text{ x } \begin{pmatrix} C1 \\ C2 \\ C3 \\ C4 \\ C5 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \end{pmatrix} \text{ x } \begin{pmatrix} F1 \\ F2 \\ F4 \end{pmatrix}$

Therefore; two relationships exist; {C1,C5} → {F2}, and {C3,C5} → {F1,F4}. Then the new associated manufacturing system would have capabilities {C1, C3, C5}.

In summary; chapter 4 has introduced a mathematical model of 4 activities - based on co-evolution hypotheses of chapter 3. The activities include; 1) applying cladistics analysis to realize the history of products and manufacturing systems separately; 2) applying tree reconciliation to associate products/systems evolution history and recognize their co-evolution state; 3) keeping perfect co-evolution state for further future product design and system synthesis activities; and 4) restoring the out-of-equilibrium co-evolution state by introducing new species of products and manufacturing systems; and introducing their predicted design and structure based on the synthesis knowledge that has been collected from their history by the model. Detailed mathematical formulation of the model has been introduced and translated into several solution algorithms to perform the different activities of the model.

In the next chapter (5); several case studies are introduced to validate the manufacturing co-evolution model. Examples are obtained from machine-tools catalogues and industrial facilities to validate the model in machining and assembly areas. Parts; products, machine-tools and manufacturing cells data are extracted from catalogues, shop floor, parts classification codes and systems classification codes.

CHAPTER 5

CO-EVOLUTION MODEL VALIDATION

5.1 Case Study 1: Rotational Parts Machining vs. Turning Machine-tools Manufacturing Symbiosis & Perfect Co-evolution (*Hypothesis 1 & Lemma*)

A case study of two sets of machined parts and turning machine-tools is considered (AlGeddawy and ElMaraghy 2009b, AlGeddawy and ElMaraghy 2010d, AlGeddawy and ElMaraghy 2010e). Data were extracted from machine tools developed over a period of 50 years at Seiki Co. (Seiki 1970-2008 Catalogues). Each machine-tool is assumed to be a complete manufacturing system of which only automated machining capabilities are considered. On the other hand; each part in the set of parts is a composite part that represents a family of products design configurations associated with each machine-tool. The features of the group of parts and configurations of the group of machine tools are extracted, distilled and given in Table 1 and Table 2. Each machine tool represents a whole sum of its kind/class and not a specific machine tool model.

Table 1. Characters definitions and states of the studied machine-tools

Machine Configuration / Machine tool Class	Part on Spindle	Milling	CNC	Turret / Magazine	More axes (>3)
Lathe	1	0	0	0	0
Capstan Lathe	1	0	0	1	0
2-axis CNC Lathe	1	0	1	0	0
CNC Machining Center	1	0	1	1	0
3-axis Turning Center	1	1	1	1	0
5-axis CNC Turning Center	1	1	1	1	1

Table 2. Characters definitions and states of the studied machined parts

Feature / Part	Cylindrical	Prismatic	Thread / Undercut / Chamfer	Free Forms	Complex Profiles
A	1	0	0	0	0
B	1	0	1	0	0
C	1	0	0	1	0
D	1	0	1	1	0
E	1	1	1	1	0
F	1	1	1	1	1

After applying parsimony analysis (Algorithms 1) and obtaining the best tanglegram (Algorithm 2) from the given set of data, two cladograms of both parts and machine tools were found to have the least cladistic difference (Figure 5.1), which is zero difference. The two topologies and taxa assignments are perfectly identical. In this relatively small problem, exhaustive search was possible, where all cladogram shapes (5!) and taxa (studied individuals) assignments (6!) were tested. Both obtained cladograms are equal in having a length of 6 steps (features) and are identical in graph topology. The results indicate a perfect equilibrium state of the co-evolution of lathes and rotational products. No further improvements are possible unless a stimulus is applied to either side to cause further evolutions and developments.

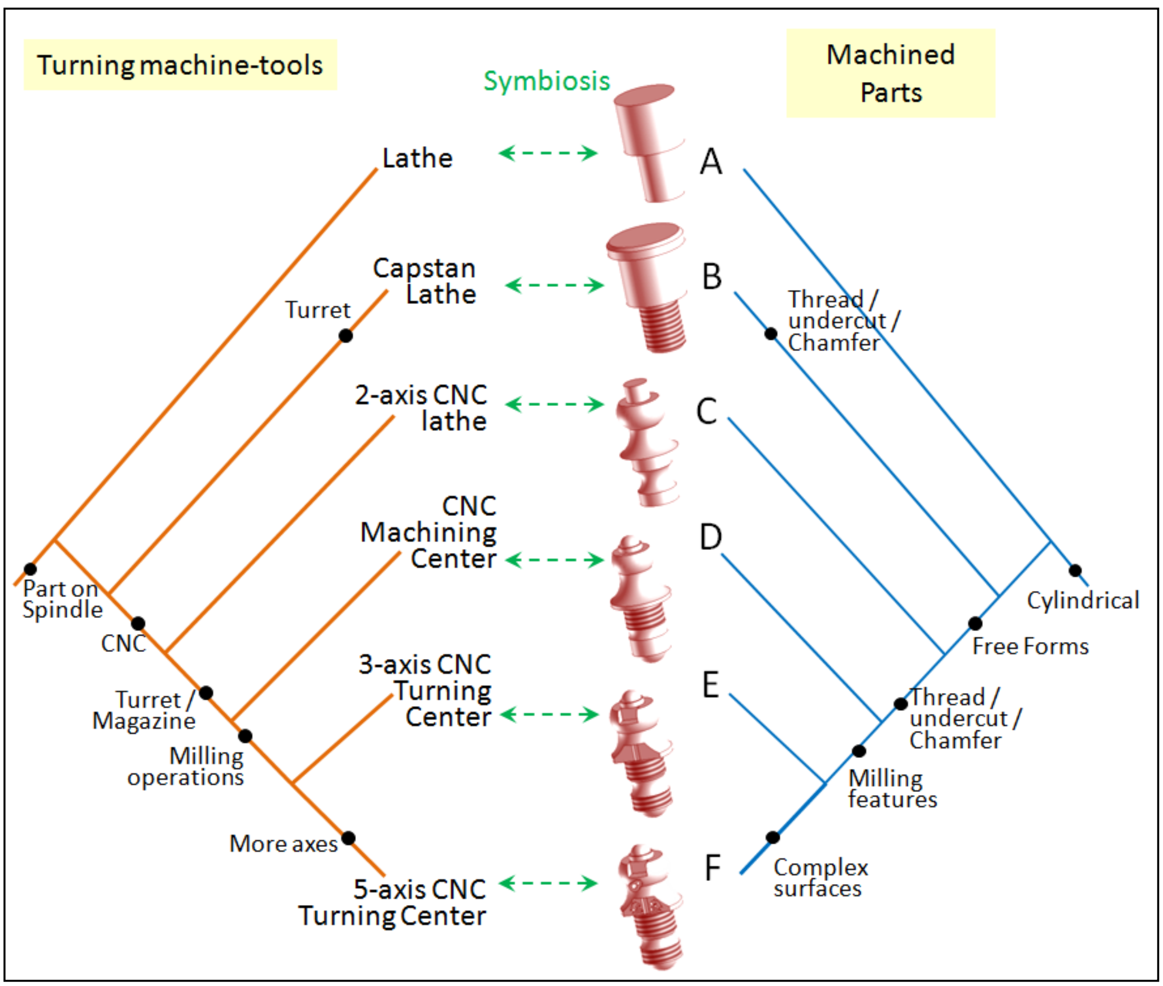


Figure 5.1 Equilibrium State of Turning Machines and Machined Parts Co-evolution (Adapted from AlGeddawy and ElMaraghy 2010e)

5.2 Case Study 2: Assembly of Engine Accessories Future Planning using Perfect Co-evolution (*Hypothesis 2*)

This case study demonstrates the use of the co-evolution model with a family of assembled products (AlGeddawy and ElMaraghy 2010b, ElMaraghy and AlGeddawy 2010). A company needs to explore the scope of its products line expansion. It produces OEM automotive engine accessories (Figure 5.2) for many car makes and models which requires an ability to adapt to the large products variety and frequent change. A group of automotive engine accessories produced by that company are used to demonstrate the implementation of the proposed co-evolution model. These accessories have many variants resulting from the different mechanical characteristics of torque load and damping requirement of different engines (refer to Cassidy *et al.*1979 and Ulsoy *et al.*1985) for more details on those mechanical characteristics and corresponding accessories features). All products are assembled in one facility using a number of assembly lines. In order to verify the co-evolution model; 8 products and their 7 corresponding assembly lines (Figure 5.3) are considered.

There are 4 idlers and 4 belt tensioners in that set of products; the first 2 idlers (A and B) and the first tensioner (E) have been discontinued from production, which is similar to species extinction in nature, however their assembly lines are still available and with good planning they could be re-utilized for other similar products to prolong their lives and benefit from the capital investment. Idlers B and D are produced on the same Assembly line (Man2) since they have the same assembly process requirements. Six main features are identified and differentiated in the 8 products; spring, damping element (could be symmetric or asymmetric), arm and housing combination (could be U- or N-shaped), fastening element (a pulley assembly can be attached by driving a bolt or pressing a pivot), alignment element (a taper insert liner for self alignment, or the pulley housing surface is accurately aligned with a datum when very tight alignment fit is needed), and finally the rolling assembly bushing (some pulley assemblies need to be raised to reach the serpentine belt). The 8 product variants and their components specification (character states) are shown in Table 3. The auto-parts used in the case study have a single level BOM resulting from the cellular layout of the facility; however the co-evolution model is equally applicable to multi-level BOM products since neither system layout nor BOM structure affect the cladogram construction.

The corresponding assembly lines for these products vary regarding the degree of automation; where 3 lines are manual, 2 are fully automated (only manual feeding might be used), and the last two are hybrid (automated and manual assembly). Eight main features are identified and differentiated in the 7 assembly lines; line type, axial press (if arm and housing or a pivot need pressing), twist press (if arm and housing need locking), CNC 3-axis milling machine (if a surface finish is needed), screw driver (if a bolt is to be driven), components feeders type (rolling bins and/or vibratory feeders for automatic feeding), and finally placing arms (could be simple flippers to reverse parts orientation or programmable robotic arms with grippers). The assembly lines specifications (characters and states) are detailed in Table 4.

The products and the corresponding assembly lines are considered the end-taxa of the products and manufacturing capabilities cladograms, while their features are their characters. Assembly line (Man2) is shown twice as lines B and D since it corresponds to products B and D. This repetition will balance the number of terminals of both cladograms and modify the input data to suit the format of the model algorithms.

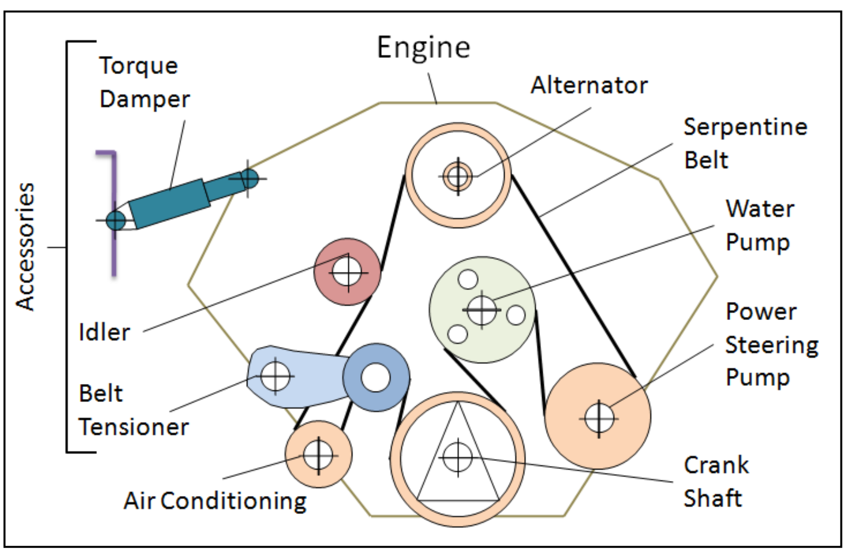


Figure 5.2 Schematic diagram of an assembled Automobile Engine and Accessories (AlGeddawy and ElMaraghy 2010b)

Some of the characters are multi-state characters, where there exists a character variation (not just primitive and derived states), while the model inputs are restricted to binary-state characters. A simple conversion process is performed based on the type of the character. Additive characters imply related states, where each state is a predecessor to the next, and the last one is the most advanced, hence 'one' step difference is assigned between each two consecutive states. Non additive characters entail independent states, where 'zero' steps difference is assigned between all derived (non-zero) states.

If a multistate character 'C' has three states '1, 2 and 3' and it is a non-additive character, then it can be converted to three separate binary characters, 'C.1, C.2 and C.3'. If it is an additive character then state '1' is converted to character 'C.1', while state '2' is converted into two characters 'C.1 and C.2' simultaneously and finally state '3' is converted to three characters 'C.1, C.2 and C.3' which are binary characters that can simultaneously exist. The corresponding conversions and types of characters are shown in Table 5.

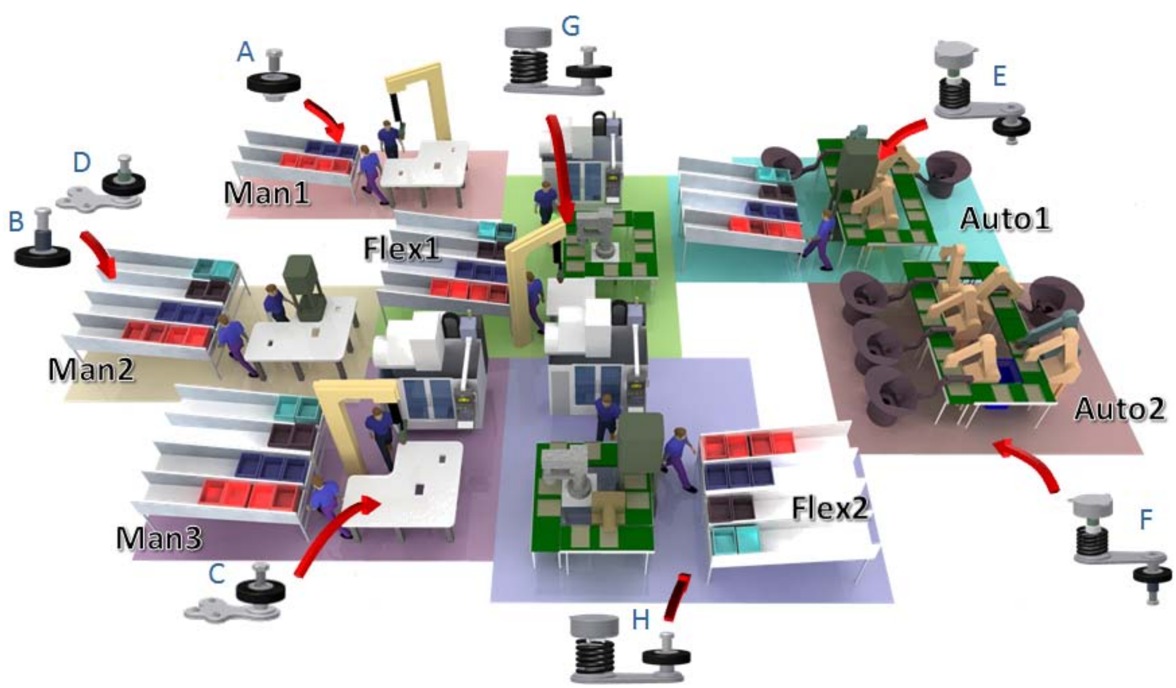


Figure 5.3 Engine Accessories and the Corresponding Assembly Cells
(Adapted from AlGeddawy and ElMaraghy 2010b)

Table 3. Engine accessories and their characters and states

Characters	Spring	Damper	Arm/ Housing	Fastening Element	Alignment Element	Bushing
States / Products	0-no 1-yes	0-non 1-Symmetric 2-Asymmetric	0-non 1-U 2-N	0-Bolt 1-Pivot	0-non 1-Self 2-Fixed	0-no 1-yes
	1	2	3	4	5	6
A-Simple Idler	0	0	0	0	0	0
B-Extended Idler	0	0	0	1	0	1
C-Armed idler	0	0	1	0	2	0
D-Self-align idler	0	0	1	1	1	0
E-Tensioner	1	1	2	0	1	0
F-Tensioner	1	1	2	0	1	1
G-Tensioner	1	2	1	0	2	0
H-Tensioner	1	2	1	1	2	0

Table 4. Assembly lines and their characters

Characters	Type	Axial Press	Twist Press	CNC M/C	Conveyor	Screw driver	Feeders	Placers
States / Lines	0-Manual 1-Hybrid 2-Auto	0-no 1-yes	0-no 1-yes	0-no 1-yes	0-no 1-Yes	0-no 1-yes	0-Bins 1-Advanced	0-non 1-Simple 2-Programmable
	1	2	3	4	5	6	7	8
A-Man1	0	0	0	0	0	1	0	0
B-Man2	0	1	0	0	0	0	0	0
C-Man3	0	0	0	1	0	1	0	0
D-Man2	0	1	0	0	0	0	0	0
E-Auto1	2	1	0	0	1	1	1	2
F-Auto2	2	0	0	0	1	1	1	2
G-Flex1	1	0	1	1	1	1	0	0
H-Flex2	1	1	1	1	1	0	0	1

Table 5. Multi-state Characters Conversion

<table>
<tr><td colspan="2"></td><td colspan="4">Non Additive</td><td></td><td colspan="3">Additive</td></tr>
<tr><td colspan="2">Converted Characters</td><td></td><td>C.1</td><td>C.2</td><td>C.3</td><td></td><td>C.1</td><td>C.2</td><td>C.3</td></tr>
<tr><td rowspan="4">Character States</td><td>State 0</td><td></td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>State 1</td><td></td><td>1</td><td>0</td><td>0</td><td></td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>State 2</td><td></td><td>0</td><td>1</td><td>0</td><td></td><td>1</td><td>1</td><td>0</td></tr>
<tr><td>State 3</td><td></td><td>0</td><td>0</td><td>1</td><td></td><td>1</td><td>1</td><td>1</td></tr>
<tr><td colspan="2" rowspan="5">Products</td><td colspan="4">Spring</td><td rowspan="6"></td><td colspan="3" rowspan="5"></td></tr>
<tr><td colspan="4">Damper</td></tr>
<tr><td colspan="4">Arm / Housing</td></tr>
<tr><td colspan="4">Fastening Element</td></tr>
<tr><td colspan="4">Alignment Element</td></tr>
<tr><td colspan="2">Manufacturing Capabilities</td><td colspan="4">Line Type</td><td colspan="3">Placers</td></tr>
</table>

Table 6. Updated Engine Accessories characters with the Introduction of a New Product

Characters	Spring	Damper	Arm / housing	Fastening Element	Alignment Element	Bushing	Rolling Assembly
States / Products	0-non 1-Torsion 2-Compression	0-non 1-Symmetric 2-Asymmetric	0-non 1-housing 2-U 3-N	0-Bolt 1-Pivot 2-Piston	0-non 1-Self 2-Fixed	0-no 1-yes	0-Eye 1-Pulley Assembly
	1	2	3	4	5	6	7
A-Simple Idler	0	0	0	0	0	0	1
B-Extended Idler	0	0	0	1	0	1	1
C-Armed idler	0	0	2	0	2	0	1
D-Self-align idler	0	0	2	1	1	0	1
E-Tensioner	1	1	3	0	1	0	1
F-Tensioner	1	1	3	0	1	1	1
G-Tensioner	1	2	2	0	2	0	1
H-Tensioner	1	2	2	1	2	0	1
I –Damper	2	1	1	2	1	1	0

For demonstrating future planning of the manufacturing system to suit product changes; an extra engine accessory is considered for production by the same manufacturing system. The company wishes to bid on the production of a torque damper (product 'I' in Figure 5.4), which has some common features and components with the currently produced products. It differs from the rest of the products mainly by not having a pulley which is added as a new differentiating character (the rolling assembly); besides some of its character states are different from the other products such as having a compression spring, having a housing with no arm, and being assembled by pressing the piston in the housing. Table 6 details the new characters and character states of the new product 'I' vs. old ones.

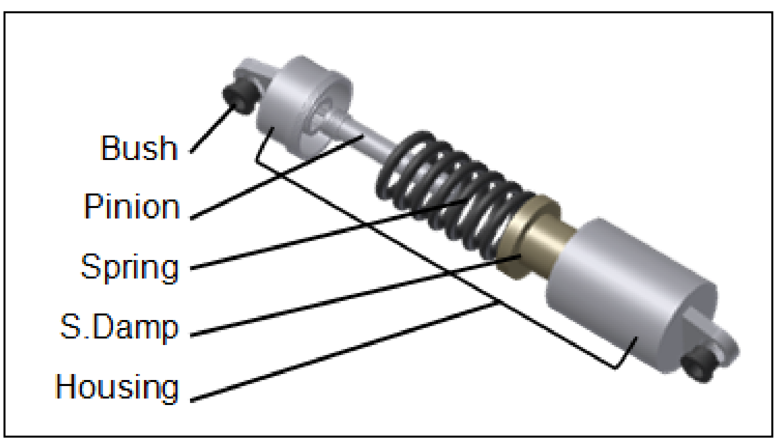


Figure 5.4 The New Engine Accessory – Torque Damper

Parsimony analysis (algorithm 1) is applied to find the most parsimonious cladograms for both products and systems. Searching exhaustively both entire solution spaces for products and systems is only practical for small number of end-taxa (<7 taxa). For larger numbers of end-taxa; other search techniques have been explored and implemented. The random destinations method (refer to Leon 1964) was applied to products and systems data, which only examined a portion of the solution space (set to 10% of the total solution space) with random generations, resulting in 2 equally most parsimonious cladograms for systems and 8 for products.

To find best co-evolution tanglegram representing the products and manufacturing capabilities; trees reconciliation (algorithm 2) is applied to all pair wise combinations of the most parsimonious cladograms of products and manufacturing capabilities to get the best tanglegram. For this problem; the solution space is very small (2×8=16 cladogram pairs comparisons); which makes exhaustive solution space search convenient.

Performing parsimony analysis on both products and assembly lines, followed by the tree reconciliation analysis resulted in the tanglegram shown in Figure 5.5. The tanglegram does not only show cladistic similarity between the products and the assembly lines, but also reveals exactness in topology and end-taxa assignment. Having a zero cladistic difference implies perfect evolution, with identical evolution courses of both products and manufacturing capabilities. For this case study, the engine accessories design and assembly capabilities are well developed, for each change on one side; there is a corresponding change in the other. This also means that an external stimulus has to occur for any further co-evolution of both sides to materialize. Such stimulus may be in the form of introducing new manufacturing capability such as a new machine with different characteristics or new assembly technology or introducing new and different product.

Planning the future development of manufacturing capabilities is carried out by following the evolution courses of both products and manufacturing capabilities that proved to be similar. Engine accessories and their assembly lines were shown to have been perfectly co-evolving. A torque damper is being considered as an additional product to be assembled using the same capabilities (existing assembly system).

Starting with the previously obtained products cladogram and following Algorithm 3 (preserving co-evolution) results in a very limited number of new cladograms to be considered. The new product 'I' can be added to a products cladogram at 8 different terminals, at two possible locations. One of these two locations will be selected by the algorithm depending on whether it is more (inner group) or less (outer group) sophisticated than the product at a given terminal. This results in 16 additional cladograms to be tested. The most parsimonious cladogram is 22 steps in length as displayed in the right hand side in Figure 5.6; where Product 'I' is shown as an outer group in the optimum cladogram. This location indicates that a new evolution branch is to be established for this particular product, which does not conform to any of the already established branches.

A corresponding assembly line 'I' also needs to be established in the assembly lines cladogram for this new product, but it would be totally new to the production facility and would not benefit from the existing manufacturing capabilities.

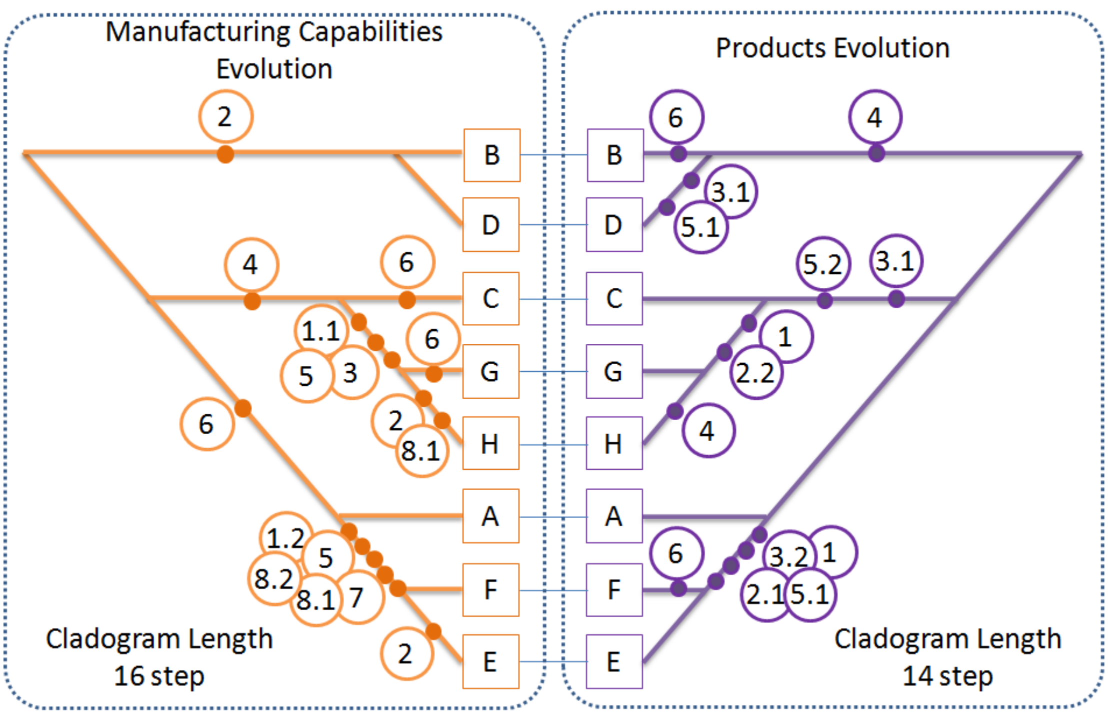


Figure 5.5 The Tanglegram representing the Minimum Cladistic Difference Co-evolution Hypothesis (AlGeddawy and ElMaraghy 2010b)

The existence of character '7' driven state (the pulley assembly) is what is preventing the torque damper and consequently its postulated assembly line from benefiting from commonality in characters with the earlier products. If character '7' (the pulley assembly) has been turned to a driven state (= 1) in the new product 'I', it can be removed from input data. This can possibly be achieved by redesigning this assembly step/process to simply allow inserting the rolling element (the eyes) of the damper in a manner similar to inserting the pulleys in idlers and tensioners.

If this process re-design is feasible then closer association between the new product and existing assembly system would be achieved, and with little modification; assembly line 'F: Auto-2' can be reused, which is the closest in configuration to the perceived new line for product 'I' (Figure 5.7). This discussion and analysis reveal the power of the co-evolution model; it does not only graphically represent the association history of products and manufacturing capabilities; but it also highlights their common and different features and shows their different possible future design plans based on the established association, and how to evaluate each plan and make decisions to achieve them.

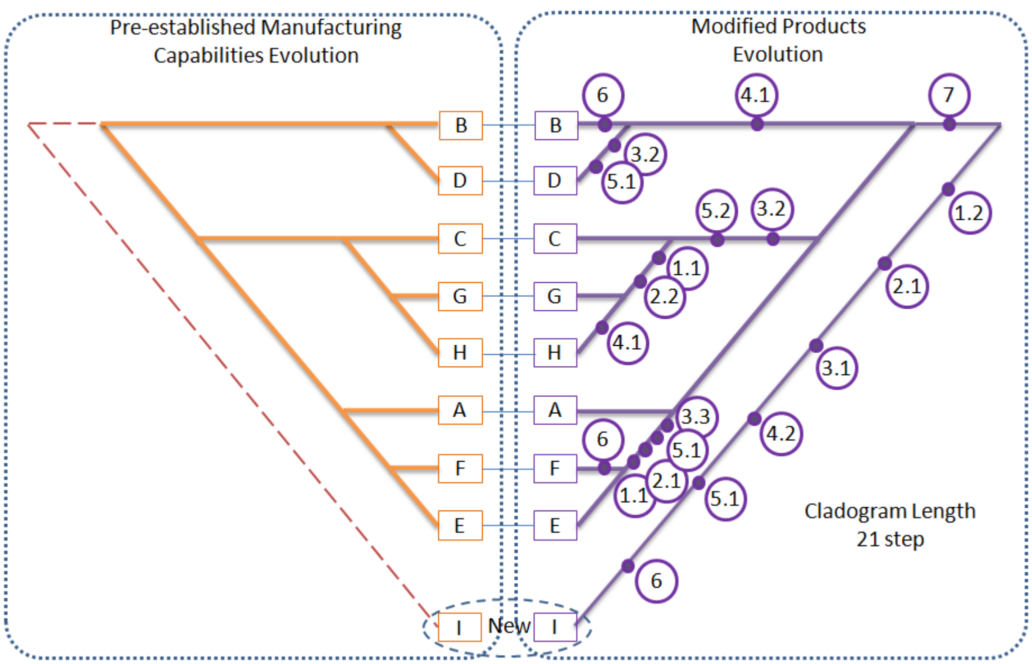


Figure 5.6 The Co-evolution State after a New Product Introduction (AlGeddawy and ElMaraghy 2010b)

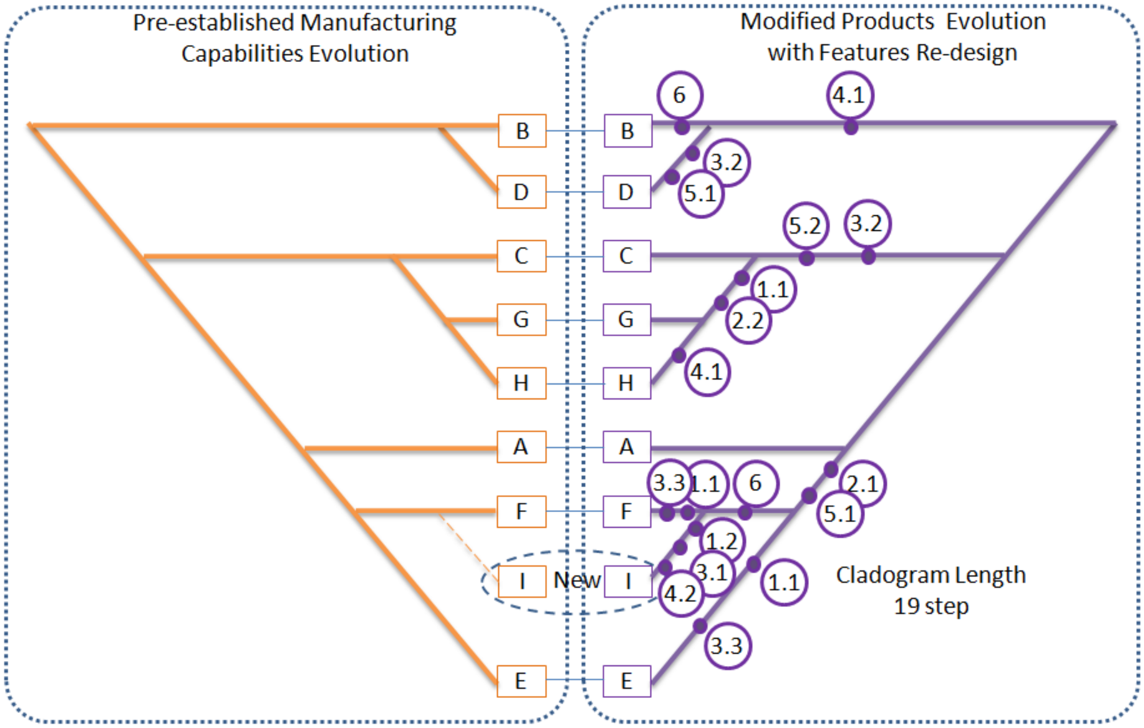


Figure 5.7 A Better Future Planning by Manufacturing Processes Redesign (AlGeddawy and ElMaraghy 2010b)

5.3 Case Study 3: Prismatic Parts Machining vs. Milling Machines Species Introduction for Future Prediction (*Hypothesis 3*)

The data for this case study is extracted from Mori Seiki Co. Catalogues of machine tools (Seiki 1970-2008). Two sets of associated Milling machine centers and machined parts are considered (AlGeddawy and ElMaraghy 2011). Seven different milling machines are considered in the two machine sets. Each milling machine-center represents a whole manufacturing system capable of completing all the corresponding machined composite part. Part flipping, work piece handling or tool change are not considered if they involve humans or robots involvement because these are not part of the inherent machine capabilities; consequently, switching between two machining processes is not considered unless the machine itself is capable of performing this task, e.g. considering only fully automatic operations. For example; switching between slab and keyway milling requires a tool change to end-mill. Performing these two processes on the same machine is not allowed in this example; unless this machine has a turret or a tool magazine to allow this capability. In reality, all of these restrictions can be relaxed; but the model seeks to determine the essential / minimum required manufacturing capabilities of each milling machine for the considered synthesis problem.

Seven milling machines are considered, each is a manufacturing system capable of machining a different composite part without human intervention. Manufacturing Systems Classification Code (ElMaraghy 2006) is used to encode their structure. An example of a 3-axis CNC machining center code is shown in Figure 5.8. However; not all code digits are used in this case study.

The detailed specifications of tools given by digits 5 to 10 are simplified in to only point out the ability of the machine-tool to automatically exchange cutting tools. Only one machine-tool (NT-CNC4XV) possessed this capability which means no further detailed specifications regarding tooling is needed in this case study to differentiate between machine-tools. Control and programming digits 11 to 16 are combined in one code digit indicating control type of each machine (manual or CNC) since no machine-tool in this case study had modular or reconfigurable controller and they all have the same programming difficulty (from same manufacturer). Code digit 17 is neglected since it is assumed that operation of all the studied machines is automatic. Definitions of all existing characters, their states and type are stated in Table 7. The existing character states in each of the seven case study milling machines are presented in Table 8.

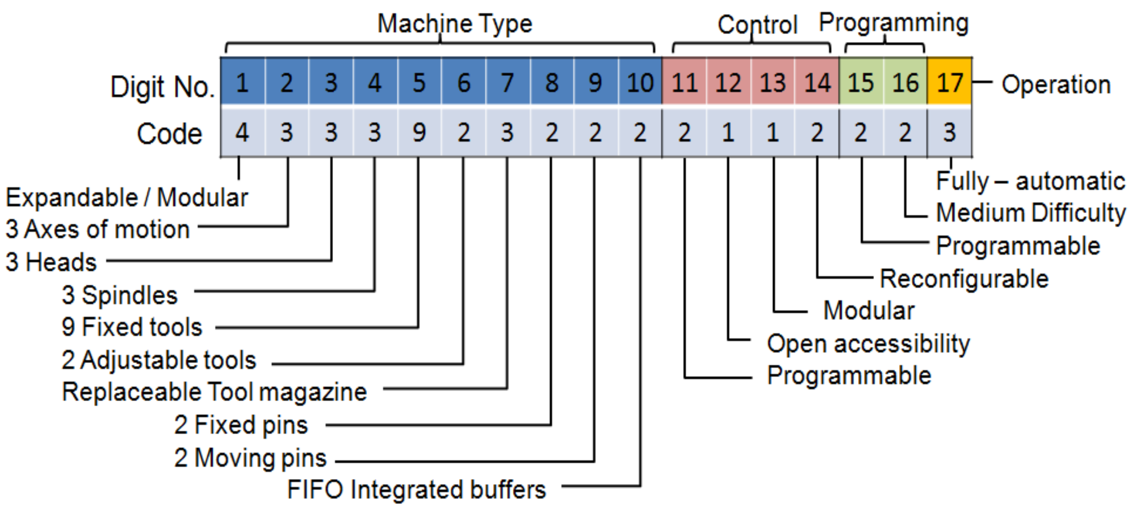


Figure 5.8 An example for a 3-axis CNC machining center code
(regenerated from ElMaraghy 2006)

Table 7. Definitions and values of machine-tools' characters code

Machine Characters	Character states		
1 Structure	0	Vertical	
	1	Horizontal	
2 Axes of motion	0	3-axis	Additive
	1	4-axis	
	2	5-axis	
3 No. of Heads	0	1 Machining Head	
	1	2 Machining Heads	
4 No. of Spindles	0	No spindles	
	1	Turning spindle	
5 Turret / Tool magazine	0	None	
	1	Exists	
6 Control	0	Manual	
	1	CNC	

Table 8. Encoded studied machine-tools data using previous definitions

Characters / Machines	1	2		3	4	5	6
		1	2				
HRZM-Conv3XH	1	0	0	0	0	0	0
VERM-Conv3XV	0	0	0	0	0	0	0
HG-CNC3XH	1	0	0	0	0	0	1
NH-CNC4XH	1	1	0	0	0	0	1
NT-CNC4XV	0	1	0	1	1	1	1
NMH-CNC5XH	1	1	1	0	0	0	1
NMV-CNC5XV	0	1	1	0	1	0	1

Table 9. Definitions and values of machined parts' characters code

Part Characters	Character states	
1 Dimensionality	0 Rail 1 Cube	
2 Shape	0 Rectangular cross section 1 Non rectangular cross section 2 Compound block	Non-additive
3 Rotational Features	0 Does not exist 1 Exists	
4 Machined surfaces	0 One direction 1 Stepped surfaces from one direction 2 More direction	Additive
5 Special surfaces	0 No features 1 Key ways / Grooves 2 Complex surfaces	Additive
6 Auxiliary holes	0 Do not exist 1 Exist	

Seven machined parts were studied. Machined parts are families of composite parts. They are mainly prismatic requiring milling machines. An example of prismatic part that is encoded by OPITZ part code is shown in Figure 5.9. However; a reduced OPITZ-like code from the original OPITZ part code was used to describe the characters of the studied prismatic parts, excluding rotational parts and other non-geometric features. The existing features in this case study are represented by the code digits (character states) from 0 to 2 and shown in Table 9. Similar to milling machines characters, some part's characters are multi-state non-additive or additive (such as machined surfaces and special surfaces). Character states of each of the seven studied parts are presented in Table 10.

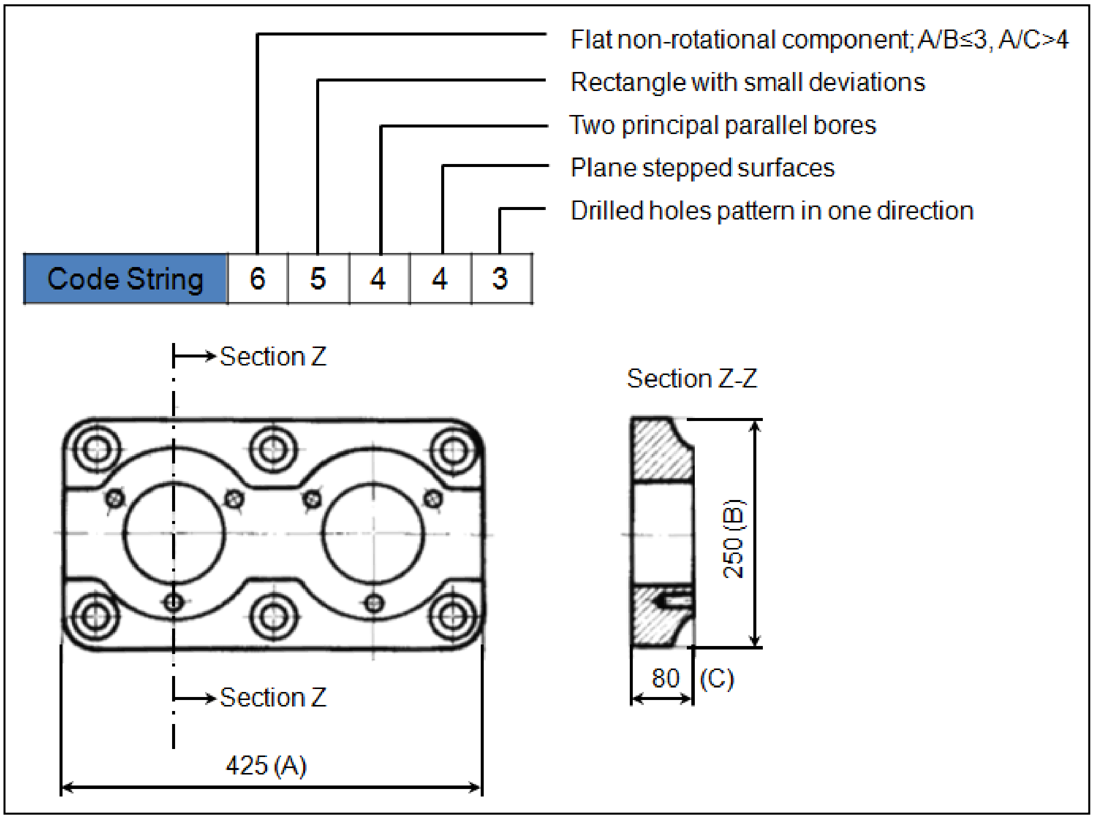


Figure 5.9 An prismatic part OPITZ-code example (regenerated from Opitz 1970)

Table 10. Encoded studied machined parts data using previous definitions

Characters / Part	1	2		3	4		5		6
		1	2		1	2	1	2	
BLOC - Block	1	0	0	0	0	0	0	0	0
BLOK - Keyed Block	1	0	0	0	0	0	1	0	0
BLOS - Stairs Block	1	0	1	0	1	0	0	0	0
ANG - Widge	0	1	0	0	1	1	0	0	0
MNT - Mount Block	1	0	1	1	1	0	1	1	1
BLD - Blade	0	1	0	0	1	1	1	1	0
ROT – Rotor Blade Hub	1	0	1	1	1	1	1	1	0

After establishing association between parts and machine tools using the given sets of data; the two classification trees of parts and machine tools that have the least cladistic length and differences were found (Figure 5.11). The existing cladistic difference, which is equal to 2 and not zero, corresponds to two pairs of nodes that are not in topologically similar. These are the ones connecting machines tree subset [machines NMV and NT] and parts tree subset [parts ROT and MNT] to the higher tree branches. Consequently their arcs are not associated and do not indicate relationships between manufacturing capabilities and product features. However their direct association of machines with machined parts (Rule 1) can still be used to present two relationships; since machine NMV capabilities can produce all part ROT features, and machine NT capabilities can produce all part MNT features, and represented by relationships (h) and (i). Since other branches are perfectly identical; their corresponding arcs are used to construct relationships between manufacturing capabilities and products features.

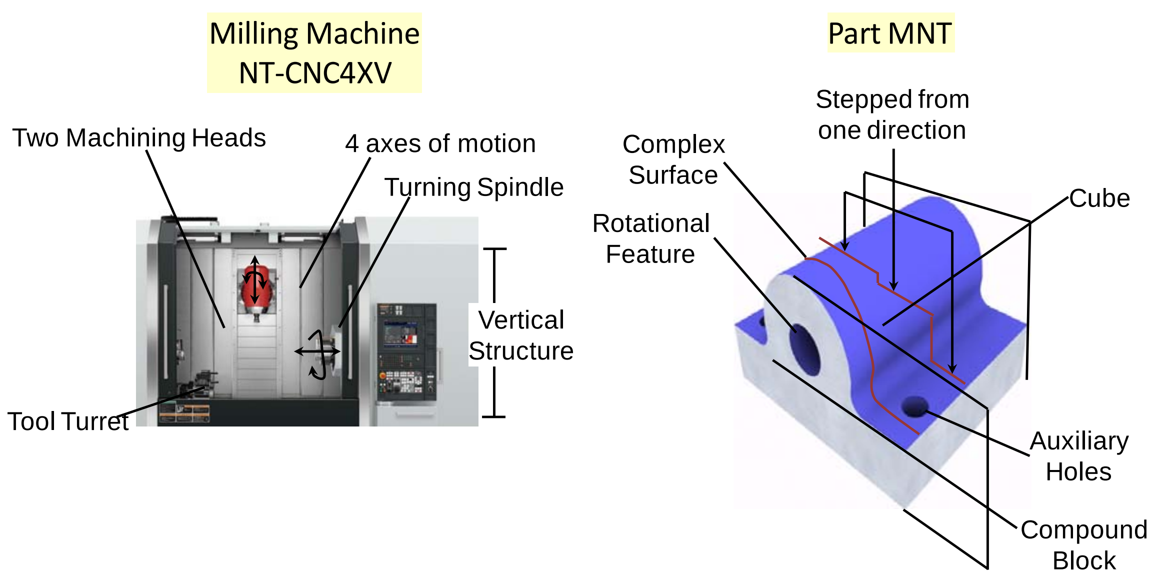


Figure 5.10 A 4-axis vertical milling machine (Seiki 1970-2008) and the corresponding composite part

A set of 7 arc correspondence relationships (‘a’ to ‘g’) and 2 direct association relationships (‘h’ and ‘I’) makes a total of 9 relationships between manufacturing capabilities and product features (Table 11).

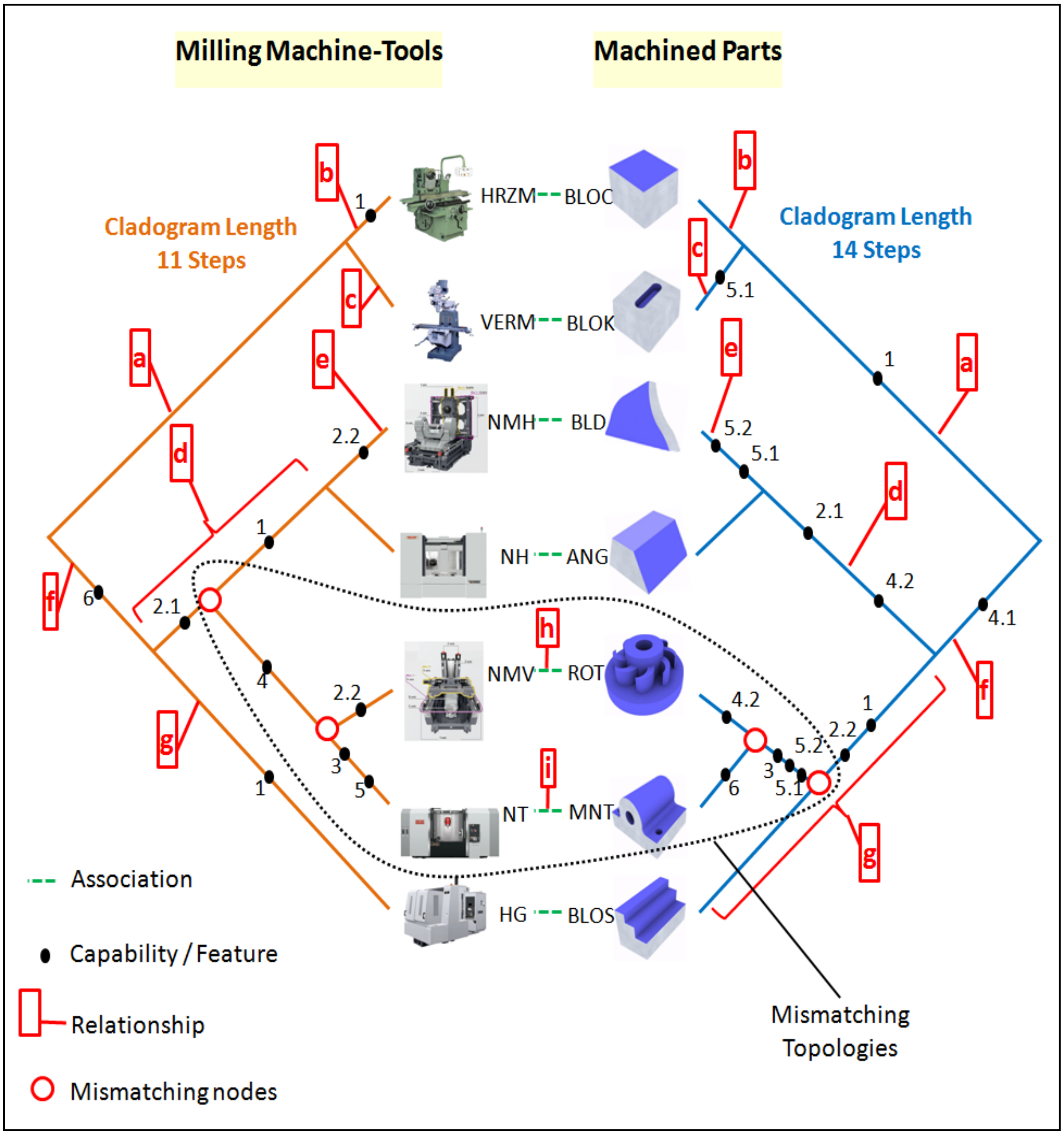


Figure 5.11 Best matching pair of classification trees of Milling Machines and Machined Parts

Table 11. Relationships between Manufacturing capabilities and product features

Relationships	Capabilities							Features								
	1	2.1	2.2	3	4	5	6	1	2.1	2.2	3	4.1	4.2	5.1	5.2	6
a	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
b	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
c	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
d	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0
e	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0
f	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
g	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
h	0	1	1	0	1	0	1	1	0	1	1	1	1	1	1	0
i	0	1	0	1	1	1	1	1	0	1	1	1	0	1	1	1

Algorithm 5 (Block Matrix Reduction) has been applied to the block matrix (A|B) of manufacturing capabilities and product features. The original number of relationships / linear equations is 9; however that number decreased to 8 during algorithm application which is equal to the rank of the block matrix. The calculated reduced block matrix is shown below.

$(A_{reduced}|B_{reduced})$ =

1	2.1	2.2	3	4	5	6	1	2.1	2.2	3	4.1	4.2	5.1	5.2	6
0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1
0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

The obtained reduced block matrix can be translated to the following associated irreducible capabilities and features relationships sets:

1. {C3,C5}→{F5.2,F6}: 2 machining heads and a tool magazine can produce complex surfaces and auxiliary holes
2. {C4}→{F2.2,F3}: A turning spindle can produce compound block and rotational features

3. {C2.1}→{F2.1,F4.2}: 4 axes of motion can produce non-rectangular cross sections and do machining in more than one direction
4. {C2.2}→{F5.2}: 5 axes of motion can produce complex surfaces
5. {C6}→{F4.1}: CNC controller can produce stepped surfaces
6. {C1}→{F2.2}: A horizontal structure can produce compound blocks
7. Φ→{F1}: Cube parts do not need specific milling capabilities
8. Φ→{F5.1}: key ways do not need specific milling capabilities

Algorithm 4 (Species Introduction) is applied to restore equilibrium in this imperfect co-evolution. Machines cladogram is expanded at the counterpart location of parts subset [ROT, MNT] stemming from machine HG branch. On the other hand; parts cladogram is expanded at counterpart location of machines subset [NMV, NT] stemming from subset [BLD, ANG] branch. Both additions and the modified cladograms are shown in Figure 5.12. The resulted tanglegram is completely untangled reaching a point of co-evolution equilibrium. The emergence of two taxa in each cladogram is the prediction made by the co-evolution model. This prediction proposes the need for two new milling machines [M1, M2] with more suitable capabilities to machine parts [ROT, MNT]. Also algorithm 4 proposes two new parts [P1, P2] that exploit the capabilities of machines [NMV, NT] to their maximum.

The predicted machines and parts can be synthesized using the reduced block matrix ($A_{reduced}|B_{reduced}$). Machine NMV of capabilities {C2.1, C2.2, C4, C6}, vertical 5-axis CNC machine with turning spindle, can produce part P1of features {F2.1, F2.2, F3, F4.1, F4.2, F5.2}. This a compound block machined in more than one direction with complex surfaces and rotational features.

Machine NT of capabilities {C1, C3, C4, C5, C6}, horizontal 3-axis CNC machine with two machining heads, turning spindle and a tool magazine relates to part P2 of features {F2.2, F3, F4.1, F5.2, F6} that is a compound block machined in more than one direction with complex surfaces, rotational features and auxiliary holes.

Also on the parts side; part ROT of features {F1, F2.2, F3, F4.1, F4.2, F5.1, F5.2} which is a cubic compound block with rotational features, complex surfaces and machined in more than one direction relates to machine M1 of capabilities {C2.1, C2.2,C4, C6} that is a vertical 5-axes CNC machine with turning spindle. While part MNT of features {F1, F2.2, F3, F4.1, F5.1, F5.2, F6} which is a cubic compound block with rotational features, complex surface and auxiliary holes; can be produced on machine M2 of capabilities {C3, C4, C5, C6} are related; which translates to a vertical 3-axis CNC machine with turning spindle and a tool magazine/turret. Figure 5.13 shows the newly synthesized machines and parts that were predicted from the imperfect co-evolution of systems and products.

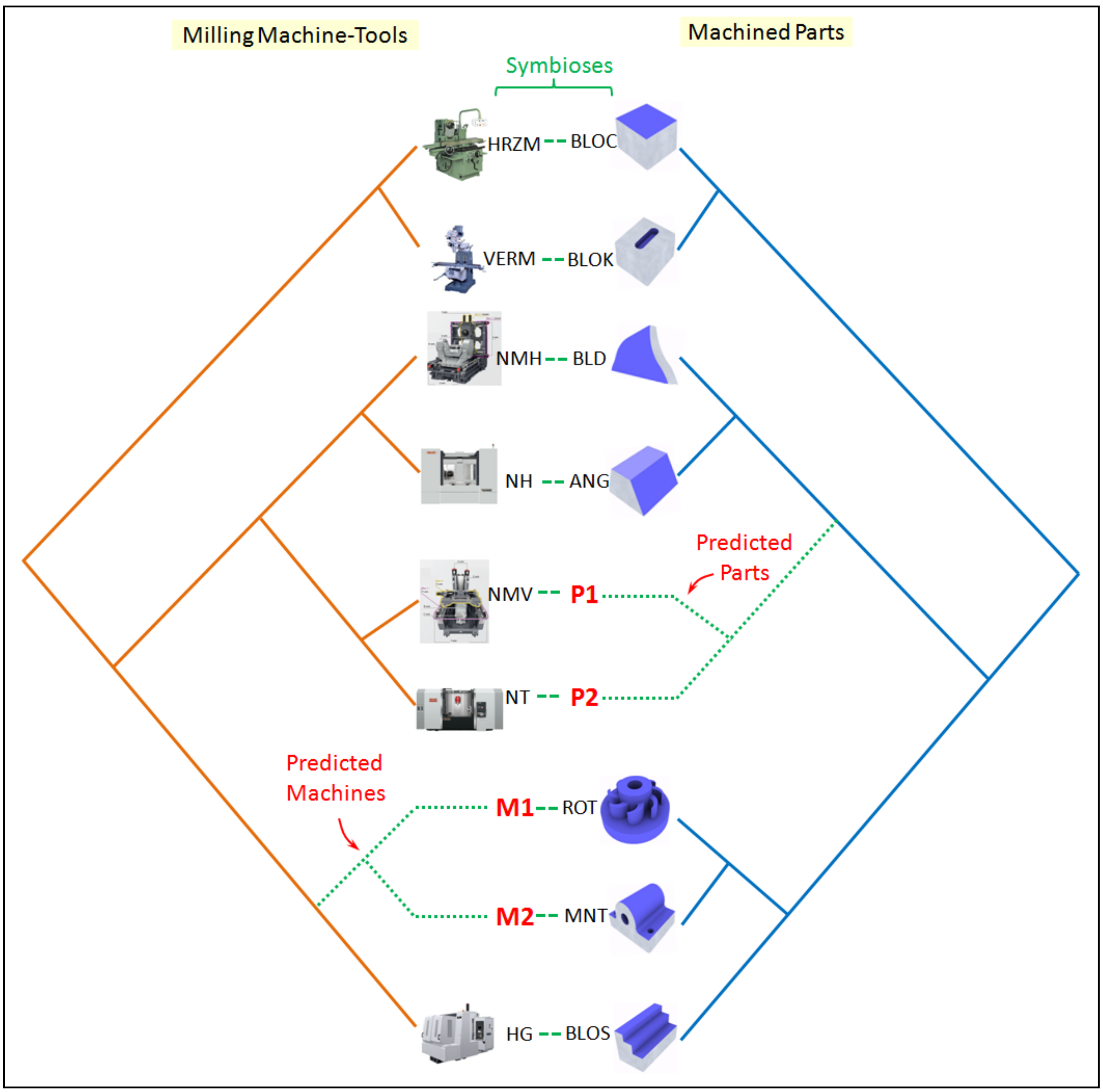


Figure 5.12 Restoring equilibrium state by co-evolution predictions

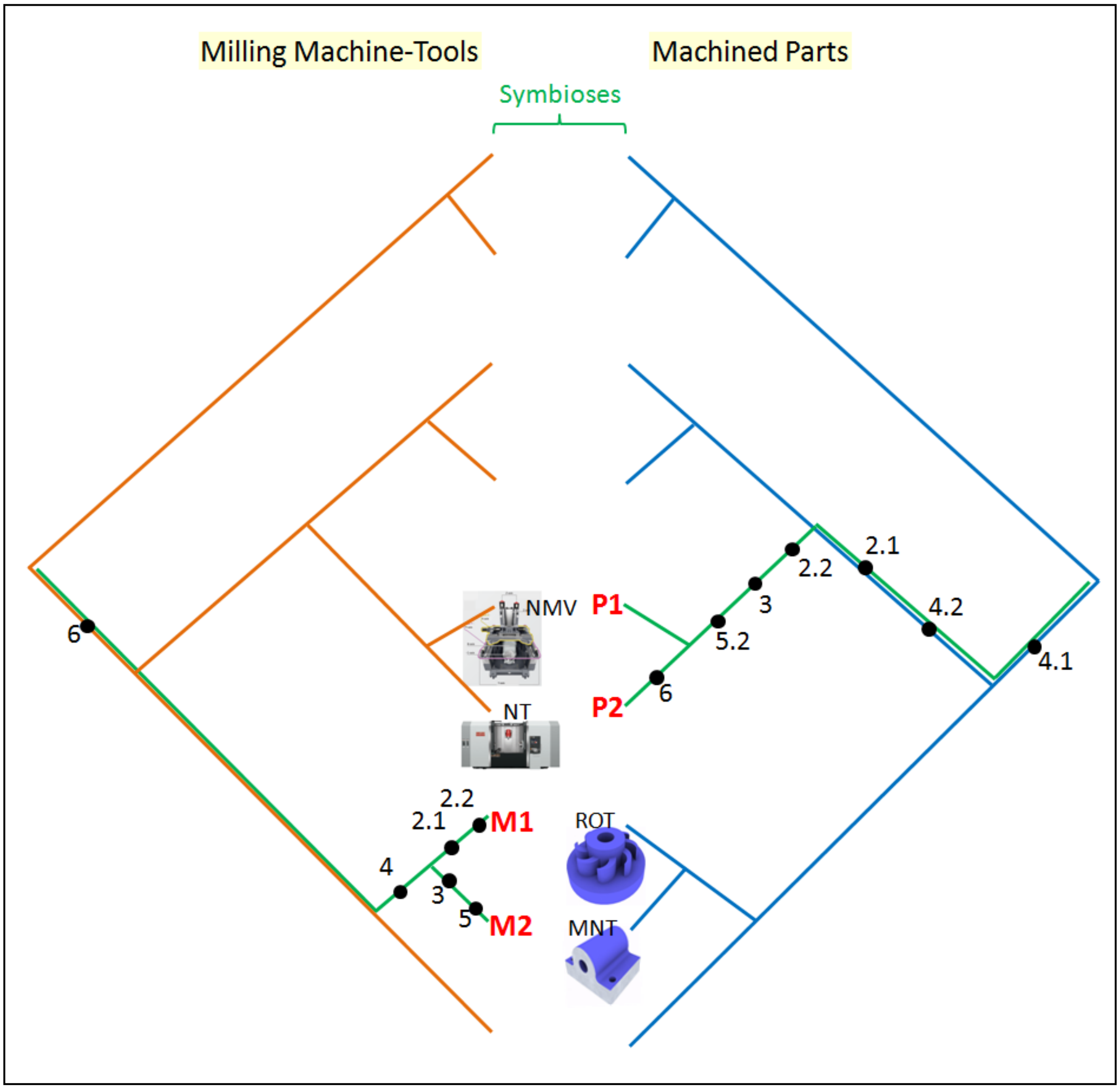


Figure 5.13 The predicted machines and parts in relation to current co-evolution state

5.4 Special Issues

5.4.1 Data handling

It should be noted that each cladogram terminal represents a manufacturing capability and the corresponding cladogram terminal represents a composite product including all possible product variants within a product family that can be produced using the manufacturing capability. The proposed model does not assign products/parts to systems/machines, or assign specific machines for a planned production. This would already be known since the historic data of different products/systems capabilities is used. Data for each pair of manufacturing capability and products are extracted independently and modeled for analysis; hence any existing cross relationships between the studied set products and systems are not assumed and do not constitute part of the input data.

The levels and complexity of products' Bill of Materials (BOM) only affect the preparation of data for modeling purposes. Figure 5.14 shows an example of 3 products (A, B and C) with 4 levels BOM and some cross relationships between them.

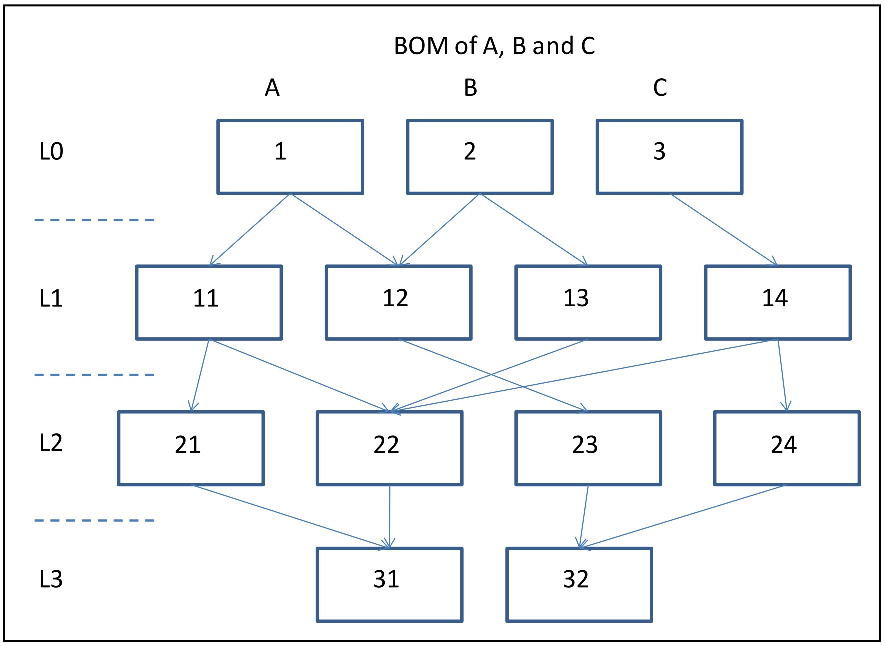


Figure 5.14 Products with cross relationships BOM

Data for these products is separated to generate 3 independent BOMs, one for each product, as shown in Figure 5.15. Existing components in each product are captured in the products' characters table (Figure 5.15) used by the co-evolution model. The final cladogram of the 3 products is generated and characters are populated according to their presence in each product and existing commonality between them.

Products with complicated relationships may be handled for modeling purposes by breaking them down into sub-products or modules. Figure 5.16 shows an example of dividing product A into two sub-products A1 and A2, the data for which would then be considered and modeled separately.

The modeled data is then represented by binary (acyclic) tree graphs (cladograms). Arcs of acyclic graphs do not form cycles. For a modelled set of products or systems; acyclic graphs give a sense of progress directionality and entities ancestry; pointing out the historical development of products or systems, and reducing the assumptions made about their evolution path. In biology, more complex ancestry relationships may exist allowing some cycles to be formed. Model constraints were developed to prevent the resulting trees from being cyclic. This does not only ensure the integrity of the generated cladograms but also reduces the problem solution space from including all types of graphs to only generating graphs of binary trees. This greatly reduces the computation burden and optimization time regardless of the used solution method.

Since the model does not synthesize systems from scratch, but uses the already gained synthesis experience, the extracted knowledge is function of the quality of that experience. In addition, the quality of model results depends on the size of the studied set of systems and products, and on the size of the encoded characters data. More studied entities and characters allow more embedded relationship knowledge to be discovered. More data and larger problems require longer computing time, which is not a real limitation since synthesis of manufacturing systems is not performed frequently – only at the initial design stage or subsequent modification. The modeling and computation effort is negligible compared to the benefits of the automatic discovery of the embedded manufacturing knowledge gained over many years by several experts. The co-evolution model supports greatly manufacturing systems' configuration and design efforts.

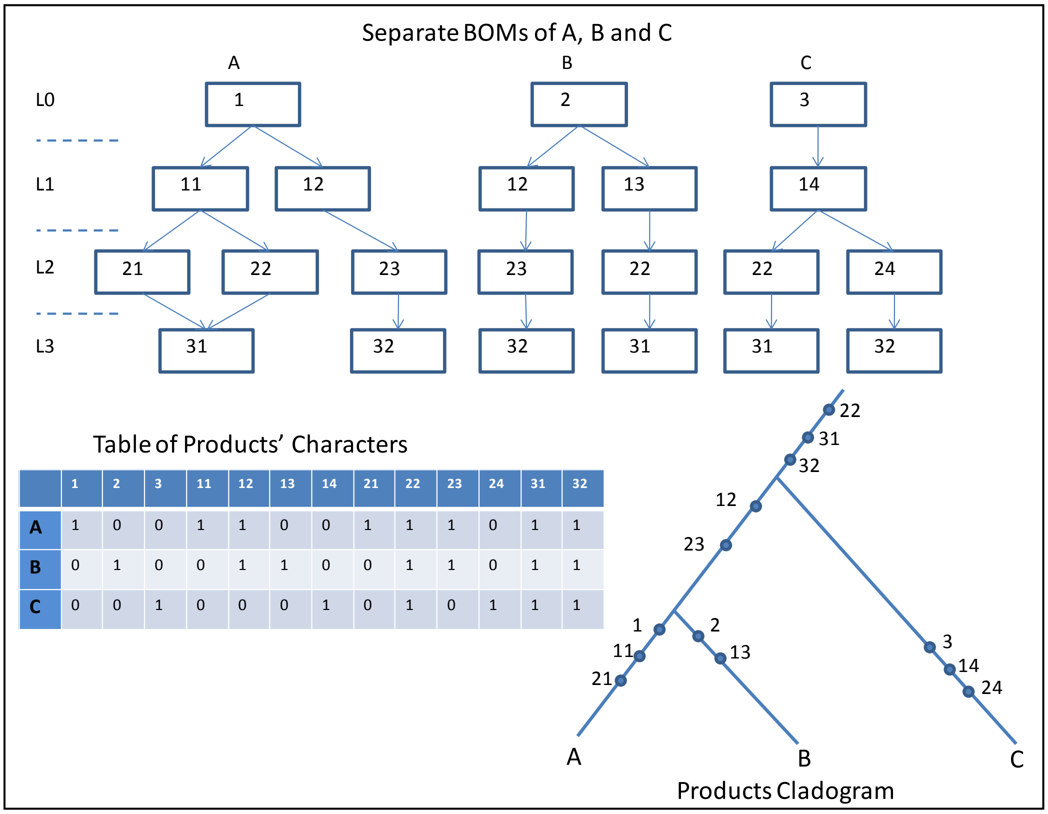


Table of Products' Characters

	1	2	3	11	12	13	14	21	22	23	24	31	32
A	1	0	0	1	1	0	0	1	1	1	0	1	1
B	0	1	0	0	1	1	0	0	1	1	0	1	1
C	0	0	1	0	0	0	1	0	1	0	1	1	1

Figure 5.15 Separation of products Bills of Material (BOM) for modeling

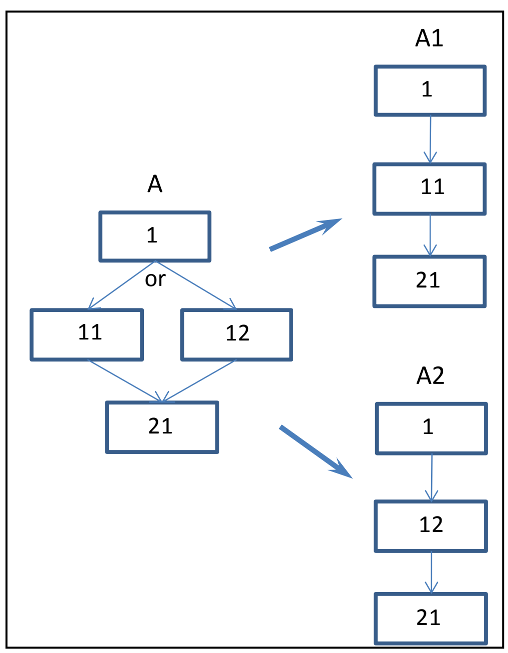


Figure 5.16 Product sub-division and corresponding simpler BOMs relationships

5.4.2 Computational Complexity

The presented algorithms in the manufacturing co-evolution model divides the nonlinear optimization problems of finding and reconciling trees into several solution stages to reduce the computational complexity. Algorithm 1 (parsimony analysis) constructs the cladograms of each manufacturing systems and products sides. The construction is made separately for each side (products and manufacturing capabilities). This algorithm is divided into two sub-problems to further reduce the computational complexity:

1) Constructing the tree topology; where there are (N-1)! topologies for a problem of size of N taxa, and

2) Arranging taxa at cladogram terminals; where there are N! combinations to select from.

The first parsimony analysis stage of the model is the most time consuming among all model stages, since the process of locating characters on the right tree branch is subjected to commonality constraints and is done level by level in the cladogram. Number of cladogram branch levels is equal to N-1. Consequently a total number of levels of ((N-1)!N!)×(N-1) represents the total problem space in this model stage.

Algorithm 1 (parsimony analysis) can be run exhaustively to cover the solution space of all end-taxa arrangements permutations and cladogram topologies, or can be integrated with any meta-heuristic search technique (e.g. Genetic Algorithms) by considering only a small number of end-taxa assignments and cladistic topologies. For a problem size of 10 taxa (10 products or 10 systems); the computation time to search all cladograms is typically 10 minutes using a 3GHz, 4G RAM PC. Since in the cladograms' space there are always many equally parsimonious cladograms; Algorithm 1 preserves some of these cladograms to be analyzed in the next stage.

All algorithms of the co-evolution model were encoded using MATLAB and its Genetic Optimization (GA) Toolbox. Searching exhaustively both entire solution spaces for products and systems is only practical for small number of end-taxa (<7 taxa). For larger numbers of end-taxa; other search techniques have been explored and implemented. The random destinations method (refer to Leon 1964), which examines a portion of the solution space with random generations outperformed Genetic Algorithms

(GAs) in mid-size problems (< 10 taxa), while GAs yielded better and faster results for larger size problems (>10 taxa).

In algorithm 2; the actual trees reconciliation is performed. This stage is much less computationally complex compared to the previous parsimony analysis stage, and depends on the number of obtained equally parsimonious cladograms. If the number of systems' cladograms is T_s, and Products T_p; then the total number of combinations is $T_s \times T_p$. In most of the tested cases (max number of products/systems pairs was 8) those numbers are often less than 10 cladograms, even when an exhaustive search is used for small taxa number problems. Since counterpart nodes of each branch level are compared for being identical; the total number of $T_s \times T_p \times$ (N-1) branch levels represents the search space in stage 2 of the model. Typical computation time for a problem of 10 pairs of cladograms is 2 seconds. For larger size problems trees-reconciliation software ('*Genetree*' by Page (1998)) can be used to untangle cladogram pairs, however it was not used in this research since the case studies did not require exceptional computational efforts.

In Algorithm 3; the problem of preserving the co-evolution state to be used for future planning of systems capabilities or products is the simplest optimization problem in this model. Since only the locations at the terminals of one cladogram are tested for introducing the new species of products or systems; there are a total of (N+1) locations per each introduced species, which is a linear size expansion. Typical computation time is less than one second.

In Algorithm 4; identifying non-identical branches in a tanglegram has also a linear size expansion regarding solution complexity, that for N species (products or systems) there are N pairs of branches to be checked. However, modifying each cladogram accordingly depends on the number of non-conforming pairs of branches and problem size. For M non-conforming pairs of branches and N species; there M×(N-1) levels of cladograms have to be reconfigured to allow new predicted species of products and systems to be introduced. Only case study 3 (Milling-machines vs. Prismatic parts) had such non-conformity at pairs of branches. Computation time for algorithm 4 in that case study was less than one second.

In the last stage; reducing the linear system of relationships between products and systems to a reduced block matrix (Algorithm 5) was only used for case study 3, when non-conformity of branches is found. Since this is a form of Gaussian elimination; it has an exponential expansion of computational complexity (n^3 for n relationships). Case study 3 had only 9 relationships to be considered for reduction; which is extremely simple for calculation. Computation time of algorithm 5 in case study #3 took less than one second.

CHAPTER 6
OTHER APPLICATIONS

The main research idea of manufacturing system synthesis being associated with product design has been expanded to cover other applications such as; the construction of manufacturing system layout, the recognition of product features sustainability and exploring the potential areas of modularization in products design.

6.1 Delayed Product Differentiation

Manufacturing System Layout is one element of its capabilities that is designed to reduce production complexities associated with product variety and change. Applying postponement strategies to production can increase flexibility, reduce uncertainties and decrease the cost of manufacturing complexity. Delayed Product Differentiation (DPD) targets Form Postponement in assembly lines, which requires deferring product differentiation activities as much as possible along production stages by delaying the insertion of specialized components or performing variant-specific processes. These specialization and customization production stages are called points of products differentiation. The layout of an assembly system that is delaying product differentiation is similar to the topology of a Cladogram. Such similarity was the motivation to expand the co-evolution model to design assembly systems with form postponement.

A new model has been developed to construct assembly line layout that is integrated with assembly line balancing and delayed product differentiation (AlGeddawy and ElMaraghy 2008a, 2009a, AlGeddawy and ElMaraghy 2010a, 2010c). The balanced delayed differentiation model adapts Cladistics to conduct commonality analysis of the studied products. This cladistics analysis was modified to incorporate assembly processes precedence constraints and the required production rates for each variant. Production capacities of the different assembly stations are considered in order to determine the number of identical parallel stations required at each assembly stage to fulfill the required production rates of various variants. The developed balanced delayed differentiation model was applied to groups of product variants that have some common features and/or assembly processes to be produced on a single assembly line/system. The balanced layout model produced an optimum balanced assembly line layout for their delayed products differentiation. Examining the assembled product variants cladogram identifies the candidate products features that could be made common in order to combine and unify as many of the assembly stages as possible and postpone and reduce the product-specific portions of the assembly system.

A set of five different engine accessories are studied (Figure 6.1). These are normally produced using different assembly lines, and they are reconsidered for production by a single system utilizing the concept of delayed differentiation. SAT01, ABT03 and NAT04 are three belt-tensioners with damping mechanisms; while EXI02 and SAI04 are two idlers without such damping. These products have some common components and assembly processes that can be explored for possible unification. Table 12 shows the processes needed to assemble each product. A '1' value means the process is needed for that specific product; while a '0' value indicates that it is not required and may be a candidate for amalgamation.

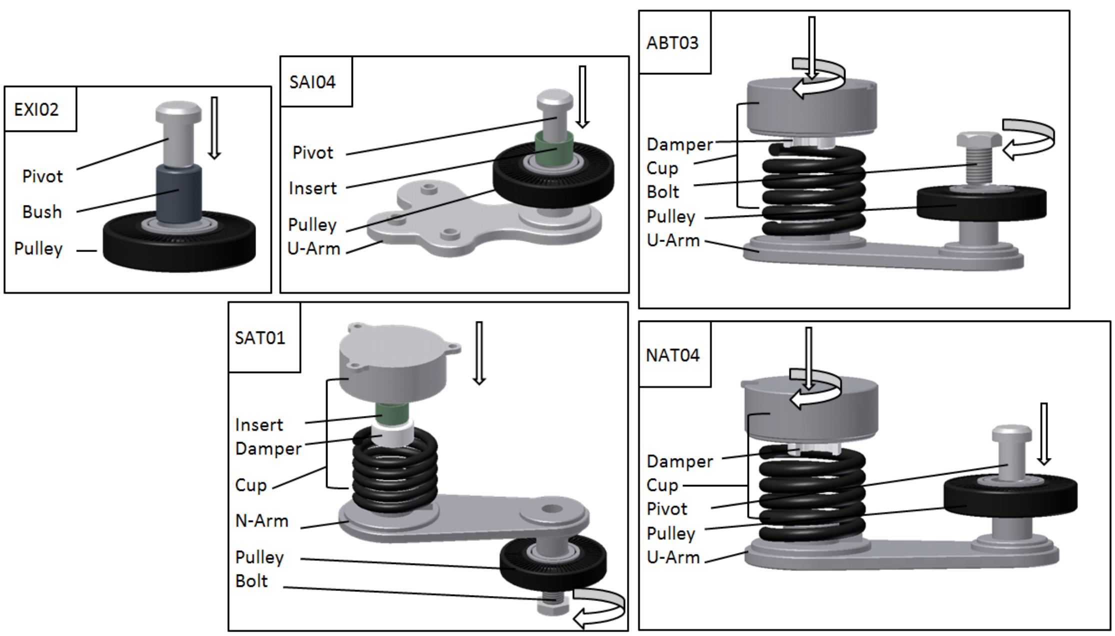


Figure 6.1 The Group of studied engine accessories

Table 12. The assembly processes of the studied products

	Place Pulley	Insert Bushing	Fastening		Arm Positioning		Twist Cup Assembly	Insert Damper	Align	
			Bolt	Pivot	U	N			Self	Fixed
	1	**2**	**3.1**	**3.2**	**4.1**	**4.2**	**5**	**6**	**7.1**	**7.2**
EXI02	1	1	0	1	0	0	0	0	0	0
SAI04	1	0	0	1	1	0	0	0	1	0
SAT01	1	0	1	0	0	1	1	1	1	0
ABT03	1	0	1	0	1	0	1	1	0	1
NAT04	1	0	0	1	1	0	1	1	0	1

A pulley assembly (1) is placed in the pallet then a bushing (2), which exits in some variants, is inserted in the pulley. The pulley assembly is held together by driving a bolt (3.1) or pressing a pivot (3.2). Different engine belt-tensioners may have U (4.1) or N-shaped (4.2) arms - the latter needs to be inverted upside down for further operations. The damper (6) is placed inside the arm housing and secured by pressing and twisting the cup and spring assembly (5) into the arm housing. If the product is self-aligning; an insert (7.1) is placed on top of the damper before the cup and spring are assembled.

For products requiring accurate alignment (7.2); a CNC machine is used to make a final precision surface machining of the arm housing where it gets assembled to the engine. The required production rates for each product and the production capacity of the assembly stations used for each process are given in Table 13. The precedence constraints of these assembly processes are represented by a group of precedence graphs as shown in Figure 6.2. These constraints are converted to a precedence matrix (Table 14) representing the pair wise relationships between the different assembly processes. A ‘1’ value indicates the existence of a precedence relationship; while a ’0’ value means its absence.

Table 13. Required production rates and stations production capacities

Product	EXI02	SAI04	SAT01	ABT03	NAT04
Required Rate (unit/min)	1.1	0.8	1.1	1.1	1.2

Assembly Station	1	2	3.1	3.2	4.1	4.2	5	6	7.1	7.2
Capacity Q (unit/min)	2.1	1.9	1.2	1.2	1.6	2.1	2.7	1.5	1.5	1.4

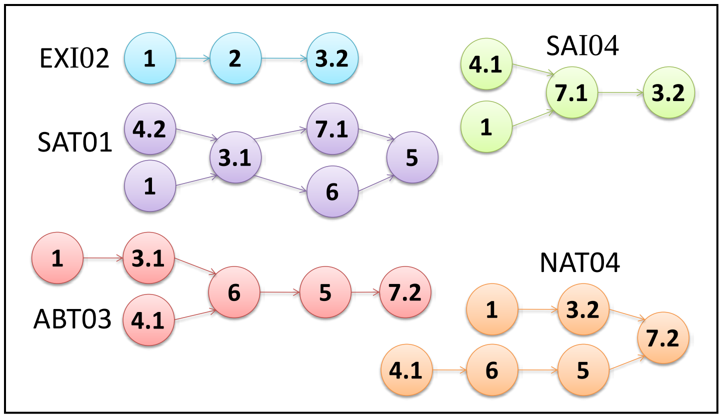


Figure 6.2 The precedence graphs of the automobile engine belt-tensioners

Table 14. The precedence matrix of engine accessories

	Successor Process									
Predecessor Process	1	2	3.1	3.2	4.1	4.2	5	6	7.1	7.2
1	0	1	1	1	0	0	1	1	1	1
2	0	0	0	1	0	0	0	0	0	0
3.1	0	0	0	0	0	0	1	1	1	1
3.2	0	0	0	0	0	0	0	0	0	1
4.1	1	0	1	1	0	0	1	1	1	1
4.2	1	0	1	0	0	0	1	1	1	0
5	0	0	0	0	0	0	0	0	0	1
6	0	0	0	0	0	0	1	0	0	1
7.1	0	0	0	1	0	0	1	0	0	0
7.2	0	0	0	0	0	0	0	0	0	0

For a set of five end product variants; there exist seven different Cladistic topologies and 5! = 120 end products-to-terminals combinations. The complete solution space contains 7x120 = 840 possible cladograms, which is feasible to search exhaustively given its small size. The optimum cladogram (see Appendix for the used Algorithm) was found to have a length of 22 steps land two differentiation points after station ‘1’ (3 parallel stations) - where pulleys are assembled - and station ‘4.1’ (2 parallel stations) - where the U-shaped arms are positioned in the assembly. The optimum cladogram is shown in Figure 6.3 (a). This graph can be readily converted to a schematic assembly line layout by deleting the arcs that do not possess characters, and rejoining their end nodes (Figure 6.3 (b)). This schematic layout is then converted to the physical assembly line layout shown in Figure 6.4.

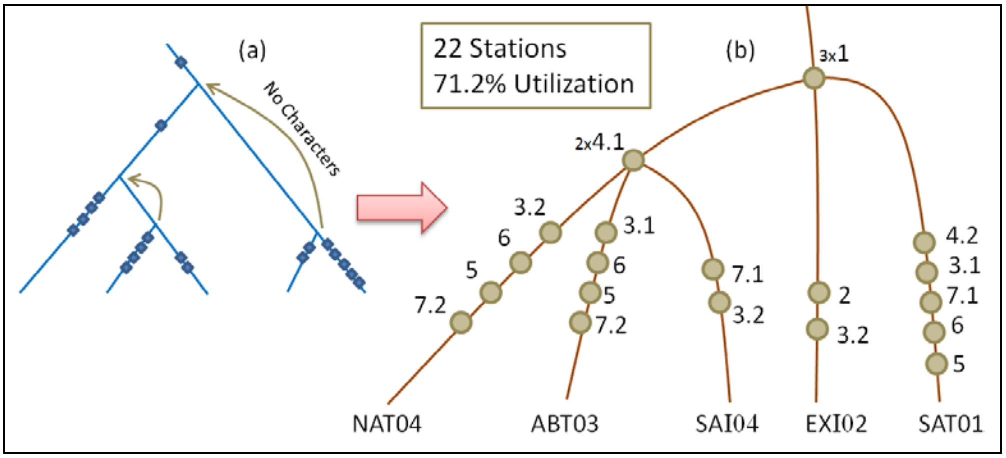


Figure 6.3 The optimum assembly line schematic
(a) Cladistic representation (b) Schematic representation
(AlGeddawy and ElMaraghy 2010c)

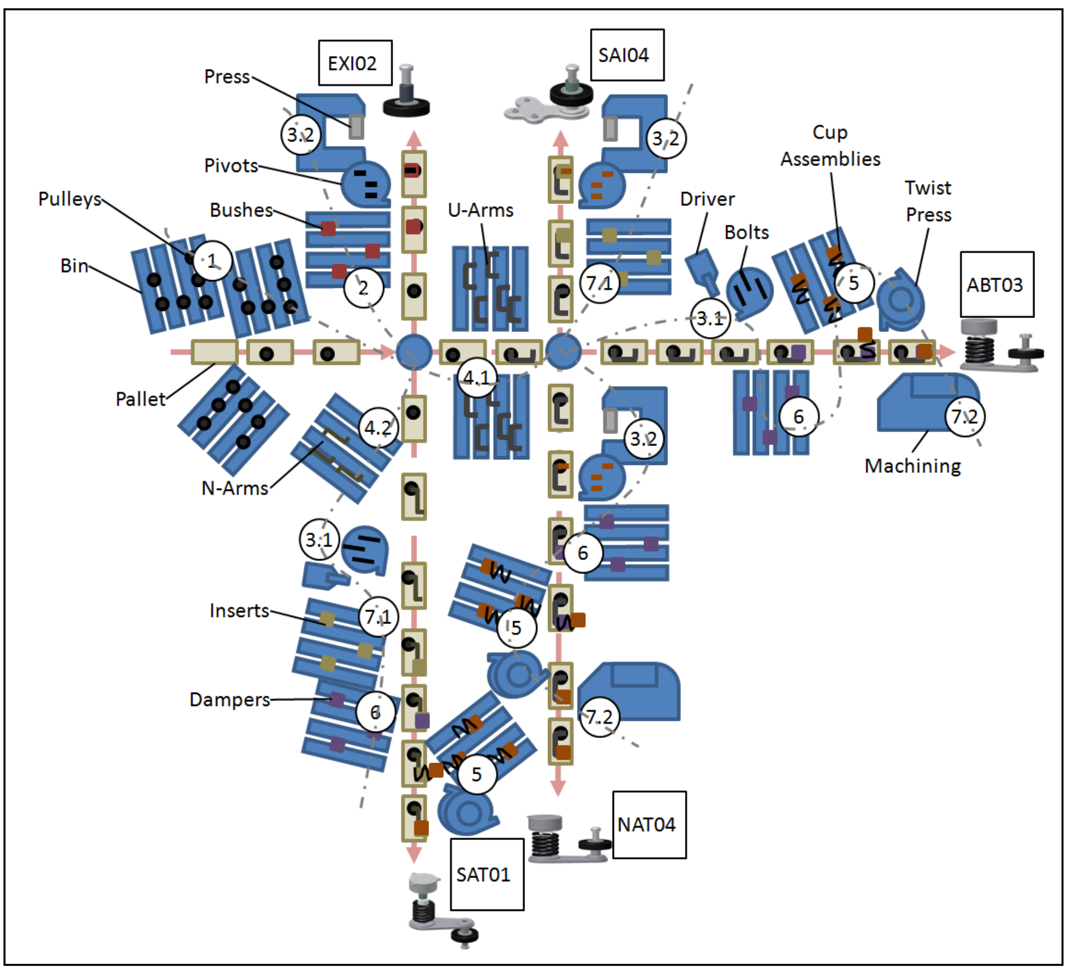


Figure 6.4 The optimum and balanced delayed differentiation layout of the 5 auto-engine accessories assembly system (AlGeddawy and ElMaraghy 2010c)

6.2 Design Sustainability

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 product design. An in depth cladogram analysis is presented (ElMaraghy *et al.* 2008, AlGeddawy and ElMaraghy 2009d), 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.

A set of cylinder blocks that consists of six different instances is used as an example to demonstrate this analysis and its merits. The cylinder block variants belong to automotive engines of different makes and materials. 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 15 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 6.5 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 Table 16.

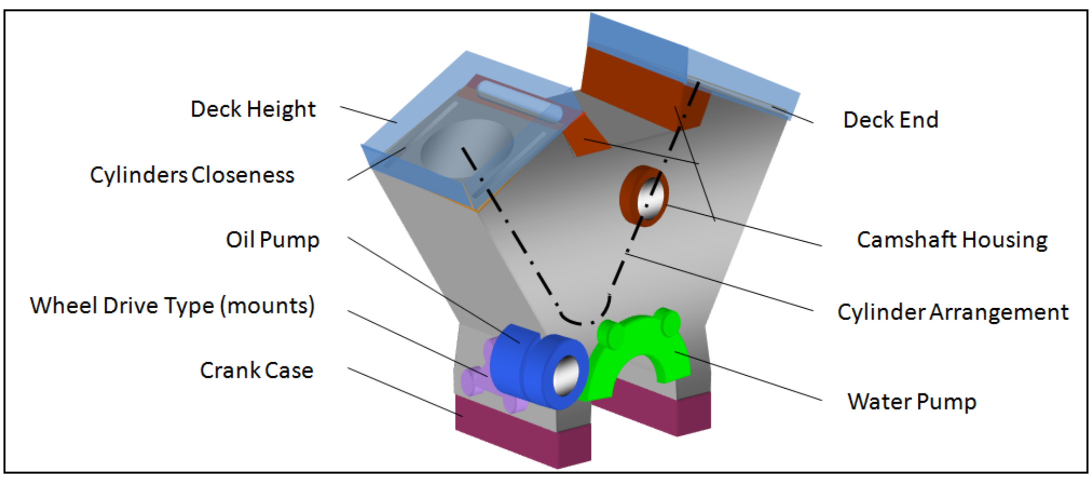


Figure 6.5 All-Derived Characters of a Cylinder Block (ElMaraghy et al. 2008)

Table 15. Identifying studied characters and their states

Characters		States	Description
1	Material	0	Aluminum
		1	Cast Iron
2	Cylinders Arrangement	0	Inline with Ø=0
		1	V-Banks with Ø=60˚ or 90˚
3	Wheel Drive Type	0	Front- mounts on block sides (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 diameter

Table 16. Characters' States in the studied cylinder blocks.

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

Commercial package ('WinClada') was used to perform Cladistics analysis on the given data set. The Cladogram in Figure 6.6 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 given 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 came late in the evolution path of this trend.

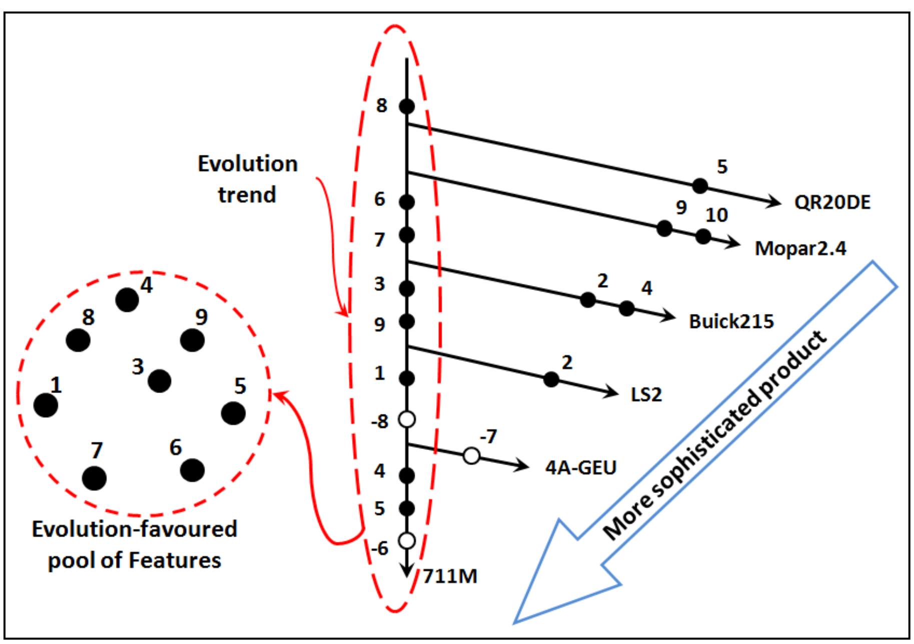


Figure 6.6 Cladistics Depth Analysis of Cylinder Blocks
(AlGeddawy and ElMaraghy 2009c)

6.3 Product Family Redesign: Promoting Modularity

This research introduces a novel cladogram breadth analysis (AlGeddawy and ElMaraghy 2009c) that can be used to understand how product families split into different variants, and find the logical basis for that splitting. The gathered data should only correspond to the currently produced families of products, with the goal of improving the different variants' design to find potentials for modularity and components integration and to manage the effect of product diversification on the manufacturing systems. Examining the resulting cladogram should reveal the features that can be unified and grouped into integral designs in single variants and modules in multiple variants. Features that connect two consecutive nodes on a cladogram are candidates for such transformation, since these are common in the variants that lie at the end of the connected branches. However, the proposed design features / characters integration must not interfere with the functionality of the product.

A family of five household appliances (Figure 6.7) is used to illustrate the proposed breadth analysis. The product variants are all used for heating water / food. They have both common and different components; hence their family is a candidate for further improvements through modularization and components integration. Product A is a water kettle with a fixed side coil, Product B is a water kettle with a detachable base, Product C is also a water kettle but with a temperature control unit instead of an on/off switch as in A, and B. Product D has a metallic body compared to the plastic kettles A, B, and C, and finally product E is a table top burner to prepare food.

The components and their existence in the different variants are identified in Table 17, (0) means the variant does not possess the component, and (1) means otherwise. A cladogram of 20 steps length is found to be the optimum and the most parsimonious (Figure 6.8). Components are represented by solid circles. For the purpose of studying variety, the disappearance of features is disabled (i.e. no negative signs). It can be noticed that products (A, B and C) and products (D and E) form two main sub-groups.

Table 17. States of characters and character definitions of products family of products

Variants \ Components	Plastic Body 1	Metal Body 2	Plastic Handle 3	Metal Handle 4	Boiling Checker 5	On-Off Switch 6	Temperature Control Unit 7	Side Coil Unit 8	Bottom Coil Unit 9	Door Unit 10	Steam Valve 11	Burner Surface 12	Detachable Base 13	Base Plug 14	Body Plug 15
A) COR-HL	I	0	I	0	I	I	0	I	0	I	0	0	0	I	0
B) DET-HL	I	0	I	0	I	I	0	0	I	I	0	0	I	0	I
C) THR-HL	I	0	I	0	0	0	I	0	I	I	0	0	0	0	I
D) POD-HL	0	I	0	I	0	0	0	0	I	0	I	0	I	0	0
E) BUR-H0	0	0	0	0	0	0	I	0	I	0	0	I	0	0	0

Scanning the cladogram for a breadth analysis (see Appendix for the used Algorithm) shows many potential areas for integral designs; (1-3-10), (5-6), (8-14), (7-9-15), 13-9-15), (7-12) and (2-4-11-13). However; feature 10 'the door' module cannot be integrated since this would lead to loss of functionality. Also feature 13, which represents a cladogram conflict since it exists in product B as well as D, cannot be integrated with those components in product D. Features 7 and 12 do not qualify for integration as feature 7 is a cladogram conflict, it exists in both product E and C. Consequently, only (1-3), (5-6), (8-14) and (2-4-11) can be integrated. Also many modularization opportunities exist since there are common features shared by more than one product. These are modules (1-3-10), (5-6) and (9). Although features (9-15) are cladogram conflicts and do not exist on a single branch, they are shared by products B and C. Consequently; (9-15) also qualify for modularization (Figure 6.8).

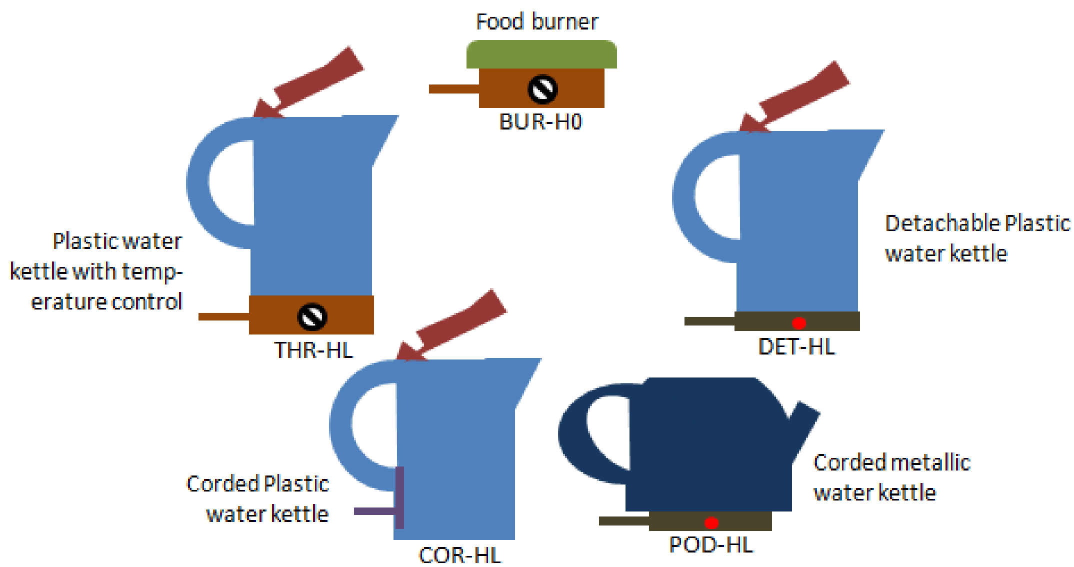


Figure 6.7 The five members of the studied family of products

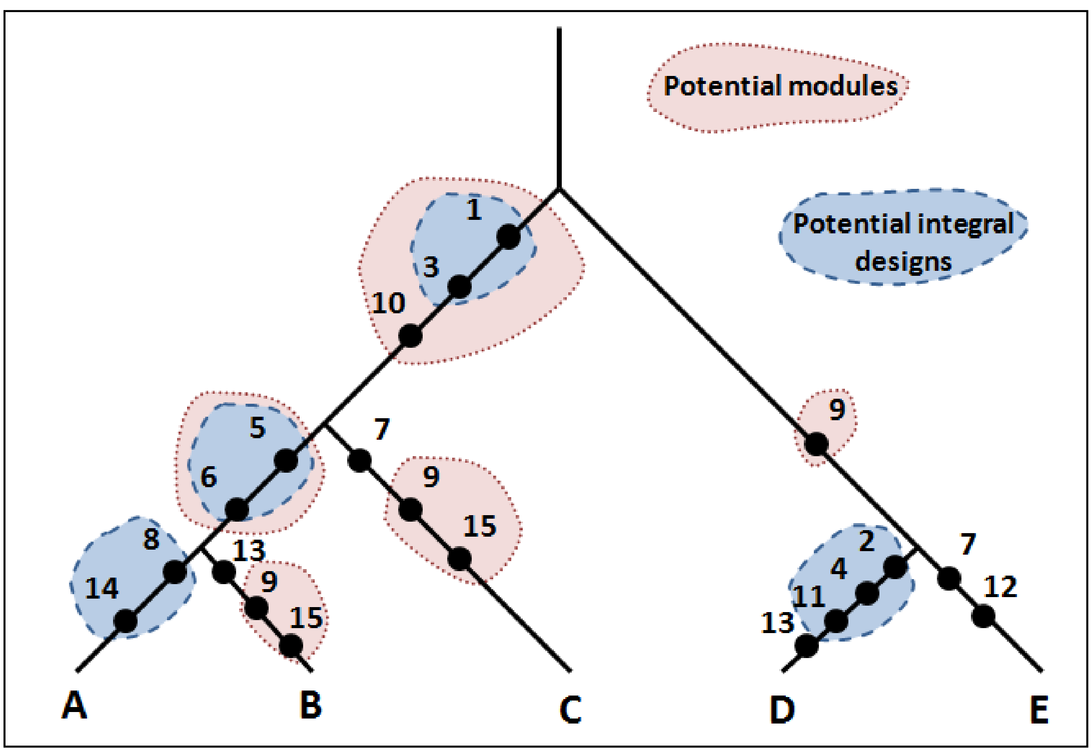


Figure 6.8 Breadth Analysis for the Household Products Family

6.4 Computational Complexity and Modelling Issues

All the used techniques in these applications are extension and modification of the original parsimony analysis problem. As mentioned in chapter 5; this problem is divided into two sub-problems to further reduce the computational complexity; tree topology construction with (N-1)! topologies and taxa arrangement of N! possible combinations for N products.

For the application of promoting modularity in a family of products by discovering the areas that are worth redesigning and integration in a single module; features loss was suppressed since in this application product evolution and change are not the objective but rather rearranging present information content of the product family design. For N products there exist $(N-1)!\times N!$ cladograms with N-1 nodes per cladogram. Consequently solution algorithm has to check the commonality of $C\times(N-1)$ characters per cladogram; where C is the number of those characters (product features). Computation time to search all cladograms and check features commonality in a family of 5 products was typically 30 seconds using a 3GHz, 4G RAM PC.

For assembly system layout commonalities of processes at each cladogram node has to be checked; then compared to precedence constraints to check compliance. Consequently solution algorithm has to check $C\times P\times (N-1)$ assembly processes per cladogram; where C is the number of characters (product features) and P is the number of precedence constraints of a maximum of C-1. Then the largest solution space of this problem is $C\times(C-1)\times(N-1)\times (N-1)!\times N!$ assembly processes to check. This indicates a problem with highly combinatorial nature and exponential growth of computational complexity. Since the solved case studies only considered families of 5 products; the exhaustive search technique was possible. Computation time to search all cladograms and check all assembly processes was typically 50 seconds.

Using meta-heuristic search techniques could be useful to solve problems of these two applications by dealing only with small portions of the cladogram topologies and taxa arrangements. Genetic Algorithms (GA) is one example; where strings of random topologies and taxa arrangements can be initially provided and then improved by consecutive crossovers and mutations. Cladogram matrix representation in the co-evolution model provides a platform for GA strings and easy data handling.

For the application of design sustainability and promoting evolution-proven product design features; features loss was allowed, without constraints on sequences or precedence. For this application; commercial cladogram construction software has been used. ‘WinClada’ is a Windows based application that connects other command-based applications (such as ‘Nona’) to provide a visual presentation of the resulted cladograms. Although many cladograms share the same most parsimonious length; the ones with the least features loss (minimum negative signs) were selected to emphasise the idea of preserving human knowledge in artifacts innovation.

CHAPTER 7
DISCUSSION AND CONCLUSIONS

7.1 Research Significance

The presented manufacturing co-evolution model in this research has closed the loop that connects manufacturing systems synthesis and product design, which has not been done mathematically before. The model showed graphically and mathematically how systems and product co-evolve and how to direct their future co-development. Moreover, the discovered relationships between product features and manufacturing capabilities represent how changes in systems and products sides are proportionate and can be used for synthesizing the model predicted species of systems and products.

7.2 Research Contributions

7.2.1 Understanding Symbiosis between Systems and Products

Models and design methodologies of products and manufacturing systems are primarily used at present to respond in a reactive mode to changes in the current requirements and modify them for the next design interval. These approaches do not take advantage of the symbiosis between the product and the corresponding manufacturing systems or benefit from their inter-related historical development. However, it can be shown that the symbiosis of product design and manufacturing capabilities of the system can be strongly correlated for most of the observed examples from manufacturing world, and hence can improve their future co-development.

The impact of capturing and understanding such symbiosis is to develop a mathematical model that is able to simulate the real world interaction between systems and products, plan their future efficiently and predict their co-development. Such a model would be helpful for using available manufacturing capabilities efficiently and increasing economic sustainability of manufacturing systems considerably when adapting to different generations of products.

7.2.2 Innovative Modelling

a) Biological analogy

The general proposition of this research is that changes observed in the artificial world of manufacturing, either on the product side or the manufacturing system side regarding product features and / or manufacturing capabilities, are analogous to evolutionary changes in the natural world. Nevertheless, evolution is more than a simple change. Evolution is the change that is driven by the surrounding stimuli for the sake of adaptation to these stimuli, which can be observed in both nature and the artificial world of manufacturing. Natural evolution marks the modifications occurring over time, which can be inherited by descendants, in the process of developing new species.

The notion of developing new species is also consonant with the need of products families to adapt to customers and market requirements. The boundaries of those families are no longer rigid; they are constantly repositioned to gain new features and lose others. This process of change of boundaries of products families is similar to the natural evolution process when developing new species of products.

Natural evolution is analyzed and modeled using comparative data analysis to find similarities among living beings. The same technique was used in this research to study evolution of products and extended for manufacturing systems. Cladistics, which is borrowed from biological sciences, is capable of determining the logical representation of a group of variants and showing their path of evolution, in the most efficient way using parsimony analysis.

b) Co-evolution of Systems and Products

In addition to the general proposition that both products and manufacturing systems evolve in a manner analogous to the evolution observed in nature, this research also has proven that symbiotic relationships between products and manufacturing systems exist. Those relationships drive systems/products co-evolution and progressive co-development of new classes of products and systems akin to the co-evolution of biological species.

c) Novel Systems - Products Co-evolution Hypotheses

Based on observations and examples from both the natural and the artificial worlds; a series of hypotheses were introduced, mathematically formulated and validated. This set of hypotheses is:

1) Changes on both products and systems sides are symbiotic.

2) Products and systems tend to reach an equilibrium state (perfect co-evolution) where all entities have already reacted to each other change.

3) Perfect co-evolution guides products and systems future planning.

4) New products and systems species can be predicted while arriving at a co-evolution equilibrium state.

d) Innovative Mathematical Co-evolution Model

This research also presented a mathematical model that translated those hypotheses formally. The manufacturing co-evolution model in the artificial world of manufacturing has been divided into four IDEF0 activities; history realization of systems and products, establishing their association, preserving their perfect co-evolution for future planning, and restoring equilibrium state if co-evolution is out-of-equilibrium.

In the first model activity, history realization, an optimization algorithm has been developed to perform parsimony analysis on the studied products and systems (akin to host and parasite in nature) and keep a fair amount of their equally parsimonious cladograms. That analysis is performed independently on the data of both sides, resulting in two sets of evolution hypotheses that describe their historical progression. Then in the model second activity; the associated history of both systems and products is realized by reconciling their cladograms. The idea of trees reconciliation is also borrowed from biology to develop an algorithm that searches for the cladograms' pair of the minimum cladistic difference in both systems and products. In this part of the model the present situation of both sides co-evolution is established. The results show if co-evolution has been perfectly established and is in an equilibrium state, or else there are discrepancies that have been causing imperfect co-evolution.

The co-evolution model also proposes that achieving, preserving and restoring that perfect co-evolution, is the target of systems and products co-existence. The model third activity introduces the algorithm of that preservation among different systems and products generations. It keeps the constructed symmetrical tanglegram of systems and products and appends both cladograms at the desired locations, thus keeping co-evolution perfection intact. In this way manufacturing systems can live longer since manufacturing technologies and capabilities are to be maximally exploited by multiple generations of artifacts.

However; if the associated history of systems and products shows discrepancies, the fourth model activity predicts the path of their perfect co-evolution recovery. Discrepancies are represented in the form of shifted branches that do not connect at the similar locations on the tanglegram left and right cladograms. The algorithm identifies those branches and appends both cladograms to look the same by predicting the missing manufacturing systems and artifacts. If these predictions are to be considered; the current manufacturing systems would be totally exploited by the predicted products and current products would fully exploit the manufacturing boundaries of the predicted systems, thus achieving equilibrium state in manufacturing co-evolution. The model does not synthesize systems or products from scratch, but uses the already gained synthesis experience over their associated history to establish relationships between manufacturing capabilities and product features. These relationships are converted to a linear system of equations and reduced to the most basic capabilities/features relationships. Those irreducible relationships are then used to synthesize species of systems and products that are needed to restore the perfect co-evolution state.

7.3 Co-evolution Model Benefits

a) Better Manufacturing Capabilities Exploitation

The manufacturing co-evolution model has been applied to many case studies in machining and in assembly. Studying the co-evolution of turning machine tools with machined rotational parts through history, from manual control to the CNC era, has proven the hypothesis of manufacturing symbiotic changes of systems and products.

b) Guiding Manufacturing Future Plans

Analyzing the co-evolution in an assembly facility for engine accessories showed how to use the model for future planning in manufacturing, and how to identify product features that can be targeted for modification to re-use the already available capabilities in a manufacturing facility for longer economic sustainability of manufacturing systems.

c) Knowledge Discovery for System Synthesis

The case study of milling machine tools and machined prismatic parts showed how to use the inherent knowledge of classification codes, of parts and systems, to discover the relationships between product features and manufacturing capabilities.

d) New products/systems species prediction

The reduced relationships - obtained in the milling machines case study between machining capabilities and parts features - are used to synthesize new systems and products. Those new species of parts and machines have been predicted by the model to restore the out-of-equilibrium state of co-evolution found in this case study. This provides guidance for developing future products/features and manufacturing systems capabilities.

e) System Layout Design for Delayed Assembled Products Differentiation

Symbiosis of systems and products also affects the layout of manufacturing systems. Form postponement in manufacturing is an efficient strategy to deal with product variety proliferation; and affects the physical layout of the manufacturing system that applies that strategy. Cladistics was modified and used in this research to design assembly system layout for delayed products differentiation and improving modularity in products families.

f) Preserving Successful Product Design Features

Cladistics was also used to identify design features of parts and products that were proven fit by their evolution. Those features are grouped and suggested for future successful product designs.

g) Product Family Redesign

Modularity and modular design are main design enablers for dealing with product variety increase. Cladistics in this research was used to analyze families of products and identify potential modules made of their components for easier and faster assembly.

7.4 Modelling and Computational Considerations

The extracted knowledge is subject to the quality of the human experience and intellect in systems and products associated design history, hence the quality of model results depends on the quality of the used historical data.

Sometimes data of products experience cross, hierarchal and/or complex relationships for BOMs. Data preparation is needed for the co-evolution model; where cross-relationships are separated, hierarchal information are suppressed and tabulated and complex BOM possibilities are sorted out. This can increase the number of studied entities and consequently problem size and hence computational time.

To increase confidence in model results; more data is needed. Larger number of studied products and systems entities and more inclusive encoded features and capabilities leads to better representative results. However; more data and larger problems require longer computation time. This is not a real hurdle since synthesis of manufacturing systems is not performed frequently, and extracted data are based on a long history of systems / products co-existence. The modeling and computation effort is negligible compared to the benefits of discovering the embedded knowledge gained in so many years and using that knowledge for future planning and prediction.

7.5 Concluding Remarks

In summary, the following conclusions are drawn based on this research:

- Evolutionary behaviour of products and manufacturing systems exists.
- Changes of manufacturing systems symbiotically affect product design and vice-versa.

- Symbiosis in manufacturing always seeks an equilibrium state.
- Seeking co-evolution equilibrium beneficially guides future planning of products and manufacturing systems.
- Cladistics can be utilized to obtain more detailed systems and products classification.
- Trees Reconciliation can be utilized to relate systems and products evolution history to understand their co-development.
- The formulation and application of "Cladistics" Classification can be modified and extended beyond its traditional use in Biological evolution.

7.6 Future Work

a) Extension to enterprise boundaries

The manufacturing co-evolution model opens the door for more complex modelled integration modelling in the artificial world. The same concept of associated history and symbiosis can be extended to be applied on different frontiers. Customer needs, market niches, processing operations, supply chains are some of the other enterprise components that might be considered for modelling a more comprehensive economic systems.

b) Predicting new technologies trend

The developed model has the potential to predict new technological trends within their scope of applications. For example, there is an increasing interest in producing mini and micro-mechanics such as motors, turbines, gear boxes and mechanical actuators. The need to produce those miniaturized products led to advancing Ultra-precision and Micromachining. In turn; the emergence of those new technologies has affected the configuration of the manufacturing system; from cutting tools fabrication to machine configurations. The manufacturing co-evolution model can be applied to identify the enablers of micromachining and product miniaturization technologies in machine-tools and manufacturing systems to synthesize future micromachining systems and predict manufacturing requirements of miniaturization in product design.

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APPENDIX

Algorithm - Design of a Balanced Assembly system that Delays Product Differentiation

1. Require:
   S; the set of processing stations
   Q; the set of production capacities of assembly stations
   R; the set of required production rates of the product mix
2. Recall:
   A; an arrangement of products
   T; a specific assembly line topology (known X_{ij} $\forall$ i,j = 1,….n)
3. N_{min} ← very large positive integer. Initiate optimization. N_{min} is the minimum number of required processing stations
4. C_{ij} ← Ø. Initiate the set C_{ij} that will contain derived characters of level i, and position j, i=1,…n, j=1,…n+1-i
5. C_{nj} ← S_{Aj}. Determine characters at nodes X_{nj} by placing associated stations S_{Aj} with each product in A to position j of level n. j=1,…n
6. i = n-1. Consider next level
7. j = 1. Consider 1st node in the current level.
8. If $X_{ij} \neq 0$: $X_{ij} \in T$. A node exists at position j in level i for topology T
   Then C_{com} ← $C_{i-1\,j} \cap C_{i-1j+1}$. Search for common stations in the connected nodes to the current one
9. If stations in $C_{i-1\,j} \cup C_{i-1j+1} - \{C_k : C_k \in C_{com}\}$ do not precede C_k (k refers to a specific character)
   Then:
   - C_{ij} ← $C_{ij} + C_k$. Add precedence conforming common characters to the current node.
   - $C_{i-1\,j}$ ← $C_{i-1\,j} - C_k$, C_{i-1j+1} ← $C_{i-1j+1} - C_k$. Remove precedence conforming characters from lower level related nodes
   - m_{ijk}←Largest integer (R_k/Q_k). Calculate the number of required in parallel stations of type (k) at current node
   - Repeat $\forall$ $C_k \in C_{com}$.
10. M_{ij}←$\sum_{\forall k} m_{ijk}$. Calculate the number of required stations at current node
11. j ← j+1. Proceed to the next node in the current level
12. If j = i+1
    Then Go to step 13. All nodes of current level are tested
    Otherwise repeat from step 8
13. i ← i -1. Proceed to the next upper level
14. If i = 0
    Then Go to 15. All levels are tested
    Otherwise repeat from step 6
15. N ←$\sum_{\forall i,j} M_{ij}$. Calculate the total number of required stations.
16. If $N<N_{min}$ (optimizing line balance)
    Then:
    - $N_{min} = N$
    - Store T and A as best layout
17. Repeat from 2 until all required T and A are tested

Algorithm - Promoting Modularity in a family of Products

1. $X_{ij} \leftarrow \emptyset$. Initiate Set X_{ij} that will contain characters of level i, and node j, i=1,…N, j=1,…N+1-i.
2. Require A: an arrangement of end-taxa, and S: a specific cladogram shape.
3. $X_{1j} \leftarrow \{ C_j \}$. Assign characters C_j of each end-taxa in A to node j of level 1, j=1,…N.
4. i = 2. Consider 2nd level.
5. j = 1. Consider 1st node in the current level.
6. If $S_{ij} \neq 0$: $S_{ij} \in S$. A node exists at position j in level i for cladogram shape S
   Then:
   $C \leftarrow X_{i-1\,j} \cap X_{i-1j+1}$. Search for common characters in the related nodes.
7. $j \leftarrow j+1$. Proceed to the next node in the current level.
8. If j = N+1- i
   Then Go to step 9. All nodes of current level are tested.
   Otherwise Repeat from step 6
9. $i \leftarrow i+1$. Proceed to the next level.
10. If i < N+1
    Then Repeat from step 5
    Otherwise End. All levels are tested.

VITA AUCTORIS

Tarek AlGeddawy was born in Giza, Egypt in 1977. He graduated in Production and Mechanical engineering in 1999 from Cairo University, Egypt, where he also received the M.Sc. degree in Industrial engineering in 2004. He joined the Intelligent Manufacturing systems Centre (IMSC) as a Ph.D. student in 2006, at the University of Windsor in Ontario, Canada. In 2008, he received a 3-years post-graduate research grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), and nominated for F.W. Taylor CIRP (International Academy for Production Engineering) medal 2011. His research activities are focused on management of products variety/change and synthesis of manufacturing systems. He has published 7 journal papers, one edited book chapter and 10 conference papers.