**Manufacturing Systematics and Cladistics: State of the Art
and Generic Classification**

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Abstract

Purpose - This paper critically evaluates the state of the art of applications of organisational systematics and manufacturing cladistics in terms of strengths and weaknesses and introduces new generic cladistic and hierarchical classifications of discrete manufacturing systems. These classifications are the basis for a practical web-based expert system and diagnostic benchmarking tool.

Design/methodology - There were two stages for the research methods, with eight re-iterative steps: one for theory building, using secondary and observational data, producing conceptual classifications; the second stage for theory testing and theory development, using quantitative data from 153 companies and 510 manufacturing systems, producing the final factual cladogram. Evolutionary relationships between fifty-three candidate manufacturing systems, using thirteen characters with eighty-four states, are hypothesised and presented diagrammatically. The manufacturing systems are also organised in a hierarchical classification with thirteen genera, six families and three orders under one class of discrete manufacturing.

Findings - This work addressed several weaknesses of current manufacturing cladistic classifications which include the lack of an explicit out-group comparison, limited conceptual cladogram development, limited use of characters and that previous classifications are specific to sectors. In order to correct these limitations, the paper firstly expands on previous work by producing a more generic manufacturing system classification. Secondly, it describes a novel web-based expert system for the practical application of the discrete manufacturing system.

Practical implications - The classifications form the basis for a practical web-based expert system and diagnostic benchmarking tool, but also have a novel use in an educational context as it simplifies and relationally organises extant manufacturing system knowledge.

Originality/value – The research employed a novel re-iterative methodology for both theory building, using observational data, producing the conceptual classification, and through theory testing developing the final factual cladogram that forms the basis for the practical web-based expert system and diagnostic tool.

1. Introduction to Organisational Systematics and Manufacturing Cladistics and a novel application

McKelvey (1978: 1428) first introduced systematics to organisation science, as a 'necessary prerequisite to studies aiming to identify generalizable principles of organisational function and process' and that 'organisation scientists have not developed a widely accepted scheme of classifying observed differences among organisations'. McCarthy (1995) echoed this in the field of production research following a review of the dominant classifications and their limitations, which included specific research biases, researcher subjectivity, inadequate units of analysis, disconnection from other classifications, and a lack of recognition between entities, classes and types.

Systematics, composed of classification, taxonomy and evolution, is the science of diversity (McKelvey 1978). A classification is meant to provide a simple and generalised but authoritative representation of complex phenomena and is the basis for communication and understanding (McCarthy 2005). Haas, Hall, and Johnson (1966) argued that classifications help refine hypotheses, determine validity and utility based on logical and intuitive reasoning, provide a basis for prediction, and specify

populations from which samples could be drawn. Classification is both a process (i.e., classifying) and a product (i.e., classification).

Taxonomy, which, from ancient Greek, means method (-nomia) of arrangement (taxa), is the science of grouping and naming of phenomena on a basis of similarity or shared characteristics. The most notable pioneer in formal taxonomy was Linnaeus (1964 [1735]) who introduced a system of biological classification, arranged in a hierarchy of kingdom, class, order, genus, and variety. Taxa are grouped according to shared physical characteristics in the tradition of the phenetic school of classification. Here any physicality may be used, for example, phenetics in zoology, would compare bones, limbs, organs, etc.

Darwin (1985 [1859]), in contrast, introduced a phylogenetic classification scheme reflecting ancestor-descendent lineages that connect all living things from the origin of species. This in turn led to two further schools of classification – the evolutionary and cladistic – both of which provide methods and techniques that attempt to reconstruct the phylogenetic history of any phenomena that evolves. The evolutionary school, despite its name, recognises evolution but to a limited extent and relies still on some phenetic influence. Cladistics on the other hand is a purist approach, based entirely on ancestor-descendent relationships (Hennig 1966), and where physical similarity is consequential. Cladistics is now considered to underlie the modern system of biological classification. The outcome of a cladistic analysis is a cladogram (see figure 1), a branch and node diagram (from ancient Greek: '*klados*' – '*branch*'). Data, in the form of characters and states, are typically drawn from surviving taxa. This approach investigates the evolutionary links between taxa, through characters and states, and studies common ancestors.

[Figure 1 here]

Since the calls from McKelvey (1978) and McCarthy (2005), many applications of organisational systematics and manufacturing cladistics have now been published. The purpose of this paper is to: a) to critically evaluate the state of the art of applications in terms of strengths and weaknesses; and, building on this, b) introduce a new generic cladistic and hierarchical classification of discrete manufacturing systems, in that sense we define discrete manufacturing systems as separate manufacturing Species which relationships are presented in the cladistic and hierarchical classification, c) the classification to form the basis for a practical web-based expert system and diagnostic bench-marking tool. Thus the system becomes a tool for manufacturing development and change. The ultimate and novel purpose of the research was therefore to produce the practical web-based expert system and diagnostic tool. Applications that could assist manufacturing companies in their effort to improve their manufacturing systems.

The manufacturing literature and manufacturing characters and states were explored in order to assist in defining the discrete manufacturing systems as such. In the hierarchical classifications discrete manufacturing systems are presented at the levels of class, order, family, genus and species. At a more detailed level the cladistics classification presents manufacturing species and their eventual shared character states.

The system of hierarchical biological classification was originally described by Carl Linnaeus in his book, Systema Naturea originally written in 1735 (Linnaeus, 1958). Here Linneaus describes systematics as the scientific inquiry into biological differences. The group into which organisms are placed are referred to as taxa (singular: taxon). The taxa are arranged in a hierarchy. He grouped species according to shared physical characteristic.

The Linnaean hierarchy, however, has its disadvantages as it ranks groups of organisms artificially into a hierarchy. By combining the cladistics and hierarchical classifications a more comprehensive classification of a complex phenomenon is ensured. The level above connects a group of Species. This connecting point is the Genus of this group of Species. The characters shared by these Species are held by the Genus. The level above that connects that group of Species to similar groups of Species. The connecting point is the Family all these Species belong to. In that way more and more Species belonging to the discrete manufacturing sector investigated are connected. Thus the Linnaean hierarchy becomes extremely useful in the process of constructing a phylogenetic tree of the phenomenon (discrete manufacturing sector) that is large and very complex. It is an iterative process where the cladistics informs the Linnaean hierarchy and vice versa. Therefore several "generations" of mutual phylogenetic and Linnaean classifications would be developed.

To achieve the above purpose, the paper sets out to review several published and organizational systematics and cladistics papers, discusses the observable and evolutionary characteristics of manufacturing systems, and presents manufacturing systems in way of layout. Then the paper in the *Methodology* section; a) defines the classification problem, b) determines the clade, c) selects, codes and orders characters and states, and finally d) estimates phylogeny and creates the basis for constructing the conceptual classification.

Based on Popper's (1959) principle of falsification, the hypothesis arrived at represented by the conceptual cladogram can be tested. This search for a better approximation to truth is attempted in the section *Final Nomenclature and Construction of the Factual Cladogram*. This is followed by presenting the *Preliminary results* which includes the *Ancient manufacturing systems – the Out-Group* and the *Conceptual classifications,* in the *Final results* the *Factual classifications* and the *Varieties of Species* are presented. Thereafter the usefulness of the research is demonstrated in the section *Practical Implications*.

2. State of the Art: A Critical Review and the evolutionary choice of organisational development

2.1 The state of the Art

The capability of classifying several aggregations of manufacturing activity is the main strength of manufacturing cladistics with studies conducted at the level of manufacturing and assembly systems in both the automotive and hand-tool industries (McCarthy et al. 1997, Leseure 2000, Rakotobe-Joel, McCarthy, and Tranfield 2002, Allen, Strathern, and Baldwin 2007, Baldwin, Allen, and Ridgway 2010); at the level aggregation above with both eco-industrial parks (Baldwin 2008) and supply chains

within commercial aerospace (Rose-Anderssen et al. 2009, Rose-Anderssen, Baldwin, and Ridgway 2011); as well as at the level of the manufactured artefact including products (ElMaraghy, AlGeddawy, and Azab 2008a) and their associated assembly layouts in view of delayed product differentiation (AlGeddawy and ElMaraghy 2010); machine tools, their capabilities and product features that they produce (AlGeddawy and ElMaraghy 2011b, a, 2012); and for organising product families, variants and modularity (ElMaraghy and AlGeddawy 2012b).

The information contained within the classifications is a second strength. By developing phylogenetic hypotheses, the relationships between manufacturing systems are more easily seen, not just at the species level with the cladistic classification (McCarthy 2005), but also potentially at the genus, family and order level when combining with the hierarchical classification. However, this potential has only been explored in the work of Leseure (2000).

Incidentally, the first two hierarchical classifications of McKelvey (1978) and McCarthy (1995) do not feature cladograms. It is also interesting to note that after these first two studies, the cladistic analyses thereafter are sector specific. Indeed, McCarthy (2005: 83) argues that 'classifications based on industry differentiation are widely used and accepted and are difficult to ignore'. This counters the original organisational systematics attempts of McKelvey (1978) and McCarthy (1995) to develop more generic classifications and perhaps points to a limitation or a potential gap in knowledge.

A strength with regard to practicalities, is the classification's potential utilisation as a 'blueprint' or 'recipe' and/or a system of benchmarking for extant manufacturing systems (McCarthy 1995). The evolutionary relationships give an indication of the

origin of all systems and also the distance and the difficulty of change required to go from one system to another. However, this potential has not been demonstrated beyond theory. That is, it remains at the level of conceptual presentation only. Leseure (2015), however, makes an expansion by producing a more factual classification.

Furthermore, and in terms of potential predictive capability, although classifications are a snapshot of the present, an indication of evolutionary trends and direction can also be glimpsed. With the introduction of the dual cladograms by AlGeddawy and ElMaraghy (2011b), this aspect is considerably enhanced in that the approach models co-evolutionary change of, for example, a machine tool capability and a product feature, and gives an indication of symbioses. When cladograms do not match there is an indication that one side can evolve further until equilibrium is reached.

When analysing the research design, in terms of process and methods employed, it is clear that, although similar, a common approach is still lacking. For example, one inconsistency across studies relates to the process or steps for constructing a classification and cladogram. McKelvey (1978) proposes fourteen 'guidelines' which is adopted by McCarthy (1995) in a manufacturing context. McCarthy et al. (1997), Baldwin (2008), and Rose-Anderssen et al. (2009) reduce this to seven 'steps', as does Leseure (2000) although three of the steps differ. The work that focuses on the manufactured artefact (i.e., ElMaraghy, AlGeddawy, and Azab 2008b, AlGeddawy and ElMaraghy 2010, 2011a, b, 2012, ElMaraghy and AlGeddawy 2012a, ElMaraghy and AlGeddawy 2012b) is less clear in the process with no explicit steps for cladogram construction. However, a similar process appears to be followed.

The inclusion of an out-group is a consistent omission in all studies. The out-group is an important methodological means as it acts as a reference point for deciding

what and why to include or exclude in the group of phenomena under study. It is also

another indicator of descendency and origin. An out-group should reference all

ancestral characters and states, in their most primitive form, which in turn determine,

using out-group comparison, to resolve the polarity (i.e., ancestor-descendent lineage)

of all further characters and states. The first step in basic cladistics analysis is to

determine which character states are plesiomorphic (primitive) and which are

apomorphic (derived). In Out-Group comparison, if a taxon that is not a member of the

group of organisms being classified has a character state that is the same as the

organisms in the Out-Group, then that character state can be considered plesiomorhic

(Lipscomb, 1998). The outside taxon is called the Out-Group and the organism being

classified are the In-Group. The only way a homologous feature could be present in

both an In-Group and an Out-Group would be for it to have been inherited by both

groups from an ancestor older than the ancestor of just the In-Group.

Whereas, previous manufacturing classifications presented the most primitive or

ancient manufacturing form in the cladogram simply as Ancient Craft System

(McCarthy et al, 1997, Leseure, 2001), Rose-Anderssen et al (2016) presents an Out-

Group which represents Self-Production. This was based on their previous work on

cladistics classification of Ancient Manufacturing Forms and Technologies (Rose-

Anderssen et al, 2012).

The treatment of characters differs between most of the studies. The use of

individual characters is evident in studies by McCarthy et al. (1997), Baldwin (2008),

and Rose-Anderssen et al. (2009) whereas Leseure (2000) is the first to experiment with

multi-state characters although never exceeds three and most include a null state.

Although multi-state character use is also a feature in the manufactured artefact studies,

due to additional analytical methods that are employed these are then broken down into binary states.

There are three further limitations associated with characters. The first is an inadequate character representation with taxa early in the cladogram. For example, the *Ancient Craft Systems,* of McCarthy et al. (1997) has no associated character; only one character is used to describe the first system in the studies of Leseure (2000), Rose-Anderssen et al. (2009) and all the manufactured artefact studies; and only two characters to describe the first system in Baldwin (2008). The second limitation is the haphazard numbering of characters, which in all studies seems to follow the order in which they were identified rather than any evolutionary significance or chronological introduction. This is perhaps illustrated by the automotive assembly plant example of McCarthy et al. (1997) in which three of the first six characters introduced are numbered 47, 48 and 50. The third limitation refers to one instance of character reversal and several instances of repeated character insertion (i.e., when one or more of the same characters feature again in the cladogram). For character reversal, see the '(-20)' on the *Intensive Mass Producers* of McCarthy et al. (1997); this incidentally doesn't require introduction or subsequent reversal as it would not affect the cladogram structure or evolutionary 'story', indeed it would increase the consistency of the analysis. Repeated character introductions reduce consistency and are a feature for all of the studies with the exception of Leseure (2000). This is perhaps due to either inappropriate character selection (i.e., evolutionary insignificant) or inappropriate system selection.

A final limitation of the field is that most studies lack a validation step, which typically involves quantitative methods. Only Leseure (2000) has performed a full quantitative validation whereas Rose-Anderssen, Baldwin, and Ridgway (2011) employed semi-structured interviews for partial validation. However, in these studies,

several common problems were experienced and lessons were learnt in research method design, which strongly informed the design taken in this study. These included: incomplete surveys (Leseure 2000); exaggeration of practices to appear operationally better (Leseure 2000, Rose-Anderssen, Baldwin, and Ridgway 2011); easily there could be misunderstanding of questions and their associated characters leading to potential misclassification (Leseure 2000, Rose-Anderssen, Baldwin, and Ridgway 2011); likewise misunderstanding of manufacturing system boundaries and the species definition again leading to potential misclassification (Rose-Anderssen, Baldwin, and Ridgway 2011); and, under- and over-representation of particular manufacturing systems (species in the clade) in the conceptual schema through random sampling procedures (Leseure 2000). In the work presented by Leseure (2015), there is a validation of the conceptual classification which is expanded to produce a more factual classification. However, in the work above by Rose-Anderssen et al (2011) what could lead to misunderstanding of questions, system boundaries and thus lead to misclassification was corrected during the interactive focus group interviews with the aim to collectively construct mutual meanings (Rose-Anderssen et al, 2010). The knowledge observed from this work enhanced the present method design of re-iterative steps for retrieving and validating data.

The clear gap in knowledge between most current manufacturing cladistics in general and the one presented in this paper is the lack of: generic classification, presentation beyond theory, out-group comparison to resolve polarity of further characters and states, evolutionary significant / chronological numbering of states, and validation steps. Also, there is little consistency across studies related to the steps for constructing classification and cladograms.

2.2 Observable and evolutionary characteristics of manufacturing systems

To construct the 1st generation (basic) cladogram, the most evolutionary significant characters and states were selected and refined and this continued throughout the research. These characters are phenotypic in nature. To explain this further it is necessary to look at the distinction between the phenotypic and genotypic nature of the characters identified in the paper. Basically, the term *phenotype* is used to describe the observable characteristics or outward physical manifestations of an organism. The term *genotype* denotes the organism's genetic make-up (Weatherall, 2001). In terms of evolution, it is interesting to know how the phenotype and the genotype are related. Cleary, the genotype defines the phenotype, but how does the phenotype influence the genotype? When it comes to natural selection this acts directly on the phenotype. The differential reproduction and survivorship depend on the phenotype. Therefore the phenotype is the observable expression of the genes and therefore the genotype that affects the traits (Johannsen, 1911).

Similarly, as a cladistics exercise, it is therefore necessary to try and search out the phenotype-genotype duality. That is to search out how a phenotype manifestation is also represented in the history of a Species. As can be argued it is only when characteristic change and are shared we are able to recognize different lineages or groups. Then the characteristics have become more than a phenotype manifestation. In practice, several generations of lineages or groups have to be worked at through testing and refuting in order to approach a more true representation of manufacturing Species relationships.

The observable characteristics from literature and industry are the phenotypes that have been subject to the selection by academics and the industrial environment respectively. The understanding and knowledge of these characteristics are the

genotypes that are made available for developing phenotypes in new situational contexts. This explains the phenotype-genotype duality applied to manufacturing change and evolution in practice. And this is the principle underlying the web-based system in this paper.

2.3 Manufacturing systems in way of layout

At a general level, a manufacturing system is characterised by its layout system. Arguably there are four main basic manufacturing philosophies (Slack et al, 2006), each of which are appropriate for different volume – variety combinations. These layouts are: fixed position, functional or process, cell or group technology, and the product layout.

Workshops is a fixed position layout with a focus on a variety of products (Alizon et al, 2009). *Project* environments follow a fixed position principle, designed to accommodate one-off, special products (Mead and Sakis, 1999). A *Jobshop* can capture situations with large difference in orders. The *Batch* process is implemented when similar items in large volumes are to be made (Brown and Mitchell, 1911). A *Linked Batch* approach capture the benefits of and hybridises both batch and line principles (Hill, 2005). Similarly, a *Nagare* system is a virtual cellular system combining the setup efficiency of celluar manufacturing systems with the routing of a job – and batch setup (Kannan and Gosh, 1996). The idea of *Group Technology* or *Cell* layout is to gain for batch production some of the advantages present in the higher volume line situation (Das and Canel, 2005). *U-Lines* arrange machines around a U-shaped line, thus extending the celluar principle. The idea is to encourage better communication and interaction among workers (Mittenberg, 2001). *FMS* or flexible manufacturing system includes; transformation system, automated material handling system, and computer system in charge of planning and process (Tanquard and Martineau, 2001). Dawande et

al (2005), and Brauner and Finke (2005) also talk about *Robotic cells*, where robots that are placed centrally carry out transfers between machines. However, where quick responses to unpredictable market changes are required, Bruccoleri et al (2006) recommend *Reconfigurable manufacturing* systems. To capture the dynamic characteristics of the manufacturing environment, Lee and Banerjee (2001) describe the evolutionary steps of *Holonic* manufacturing systems. For accurate production of microstructures, Son et al (2010) have described *Desktop* machinery, and Wulfsberg et al (2001) *Square Foot* machinery concepts. Dolgui et al (2009) proposes a method for dealing with the balancing problem for transfer machines with *Rotary* indexer tables. *Unpaced assembly lines* are series of workstations with buffer storage between stations (Smunt and Perkins, 1985). *Assembly lines* with equal cycle time of all workstations are called *Paced* (Boysen et al, 2008). *Transfer lines* are mass production systems consisting of automatic workstations arranged in a serial configuration and linked by automatic transfer mechanisms (Dhoib et al, 2009)

3. Methodology

The aim of this research was to take heed of the strengths and weaknesses of previous cladistics studies and in particular: a) develop complementary cladistic and hierarchical classifications that are generic and span sectors, i.e., focusing on discrete manufacturing systems of all kinds; b) follow a multi-iteration approach to the construction of the conceptual cladogram and finally the factual cladogram; c) include an out-group for comparison; d) develop comprehensive multi-state characters that are ordered and numbered in terms of their evolutionary emergence; e) include an appropriate and relatively equal 'description' or character representation of all manufacturing systems;

and, f) develop a research design, based on observation-assisted surveying, to mitigate the problems experienced in previous validation studies.

Developing a classification that is generic and span sectors facilitates the production of a practical web-based expert system and diagnostic benchmarking tool that could be applicable to manufacturing companies wanting to explore the challenge of improving their systems regardless of which industrial sector they belong to.

Following an evaluation of the guidelines and steps of constructing a cladistic classification, this design adopted an eight-step process – the seven steps used by McCarthy et al. (1997), Baldwin (2008), and Rose-Anderssen et al. (2009) plus an additional, initial step from Leseure (2000) which helps frame the problem. In practice the procedural steps are re-iterative as they essentially overlap, are often concurrent activities and help refine each of the other steps' outcomes.

3.1 Define the Classification Problem (Step 1)

The manufacturing classification process should begin by stating clearly the nature of the problem to be solved which provides the basis to understand the relation between the phenomena under study, here a manufacturing system, and the characters that define it (McKelvey 1975). A proposed definition for this classification problem, or manufacturing system, is as follows:

> *A coherent set of processes which, depending on the complexity of that being manufactured, represents a significant stage in production and produces a coherent, single or family of parts, components, modules or final products. The boundary is not necessarily a whole factory system, which can be set out in modular fashion and contain plant within plants (in effect an ecology of different*

species), but individual workstations, cells or plants, the latter being a relatively

small system of workstations or cells.

3.2 Determine the Clade (Step 2)

A clade is a monophyletic taxon (plural: taxa); that is, a group that consists of all the

potential manufacturing systems under study, along with the common and most recent

ancestors. Candidate manufacturing systems were collected from a variety of sources

including: a) traditional manufacturing system classification studies previously

reviewed; b) the cladistic analyses reviewed in this paper, where appropriate; and, c)

literature concerning individual manufacturing systems, a sample of which is listed in

table 1.

[Table 1 in here]

3.3 Selecting, Coding and Ordering Characters and States (Steps 3, 4 & 5)

A character is any variable, feature or attribute, which forms the basis for classificatory

significance. Taxonomic characters perform two functions: firstly, they have a

diagnostic aspect uniquely specifying a given taxon and an emphasis on the

differentiating properties of taxa is particularly strong at the level of lower categories

(McKelvey 1978); and, secondly, they function as indicators of relationships; a property

that makes them especially useful in the study of the higher taxa. The character

selection is a manual process involving secondary data (i.e., literature, company

records, annual reports, and technical data such as layout plans, control/scheduling

strategies, etc.).

Candidate characters are considered and then rejected if they are irrelevant or if

they create 'noise' in the data table (Leseure 2000, McCarthy et al. 2000). Qualitative

methods, such as observations, field visits, and interviews and discussions with key

personnel, were also implemented. Initially, 210 characters and 817 possible states were

identified from the literature. The development of the conceptual cladogram proceeded

through several iterations where these characters and states were re-examined and

refined so that manufacturing system evolution could be described in the final

conceptual cladistic classification by twelve multi-state characters (see Table 1). This

involved systematic coding of categories identified. When these categories could not be

developed any further from the literature, it was decided a saturation of categories had

been reached. Subjectivity played a role in each of the 8 steps of constructing a

cladistics classification and not limited to the definition of manufacturing systems; the

selection of candidate manufacturing systems and Species; the selection of characters

and states; the grouping of states under characters; the ordering of states within

characters; the emphasis or weighing of one character over another; and the decision

over whether characters are either primary species-Defining, Variety-Defining, or

secondary product, process and systems characters. In this research, there were 4

generations of iterations of conceptual classification work and refinement.

[Table 2 Here]

Numbering characters, helps with both ordering and decisions concerning whether they

exist in the forms of organisation under study (Leseure 2000). This is a trial and error

process where characters are continuously compared, recoded and/or rejected. Different

states for each character are proposed and an indication given of what species possess

which state. When this cannot be developed any further, a saturation of categories has

been reached. The character itself is shown in the list of characters relevant to the clade.

Each character is then shown with its primitive (1) and derived (2, 3…n) states. It is

important to note here that states are numbered in this study according to their estimated

appearance in the evolutionary scheme and have both an additive and discontinuous

nature. With discontinuous state evolution, one state does not necessarily follow, in

evolutionary terms, the one numbered before. That is, the states within characters also

follow a similar evolutionary pattern and can branch off as shown with the character in

Figure 2. In this example, evolution diverges at state 2 leading down one path to states 3

and 4 and down the other path to states 5 and 6. A change in character state signifies an

evolutionary step.

[Figure 2 Here]

3.4 Estimating Phylogeny, and the basis for Constructing the Conceptual Cladograms and Proposed Nomenclature (Step 6 and 7a)

Cladograms are constructed by grouping species that share a common root and

evolutionary history. The total number of character-state changes necessary to support

the relationship for the species in a cladogram describes the tree length (McCarthy and

Ridgway 2000). The Principle of Parsimony states that the cladogram with the shortest

length i.e., with fewer analogous character-states present, is considered to be the 'best-

fit' or most parsimonious tree (McCarthy 2005). Cladograms may be constructed

manually or through dedicated software such as MacClade: Analysis of Phylogeny and

Character Evolution (Maddison and Maddison 2003), used in this research. This helps

to quickly produce candidate cladograms, and offer manipulation tools, in which

characters and their states can be ordered, weighted and traced; all of which help

construct the most parsimonious and logical phylogeny of the clade.

The naming of the manufacturing systems, which should conform to the

principles of biological nomenclature, is proposed during this conceptual stage and

finalised during the next factual stage. In short, names should convey the essence of the

entity and typically their main character(s), be unambiguous, and ensure universal

communication (McCarthy et al. 1997). Although in the Linnaean tradition, each

species is given a binomial Latinised name relating to the species and the genus it

belongs to, in this study, and to convey understanding, an Anglicised polynomial

system, consistent with previous manufacturing cladistics studies, is preferred and used.

The aim is also to use names that are understandable to practitioners and academics

alike. However, as up to two words are used in genus naming and up to four words in

the species, the genus term, when referring to species, is all capitalised.

*3.5 Final Nomenclature and the basis for construction of the Factual Cladogram
(Step 7b & 8)*

This step largely involves contemporary organisations (i.e., specimens of species), and

is more quantitative in nature (Leseure 2000, 2015), i.e., surveying a representative

sample of species and the specimens within. The aim is to test the hypotheses inherent

in the conceptual cladogram. Any conflicts are then resolved leading to a full factual

cladogram (McCarthy et al. 2000). The approximation to truth is increased through the

mixed-method triangulation approach employed involving three steps in research

methods (Jick 1979).

In a true Popperian tradition, further hypothesis testing, in order to develop

theory, was conducted through observing manufacturing systems. This was applied in

order to try and substantiate the theory so far in terms of the conceptual classification.

Quantitative data, based on 510 manufacturing systems operating in 153 manufacturing

companies, representing a very good spread of both discrete manufacturing sectors and

size, were collected through various data collection and sampling methods and catering

for the lessons learnt from previous factual cladistic analyses. Utilising convenience (or

opportunity) sampling, the first companies surveyed were collaborators on a large European project. This then extended to other willing companies on other European projects along with local UK companies that collaborate with our research centre and university. Chain-referral (or snowball) sampling was then employed in which already participating companies along with other project collaborators introduced other willing companies. Finally, focus samples were used to actively seek out specimens in underrepresented species. The research team observed the various manufacturing systems (between 1 and 9 systems) in operation at these companies.

A survey was completed for each manufacturing system based on the observation of manufacturing system features. The survey was made up of items representing both the species-defining and variety-defining characters and states of the final conceptual cladogram. Additional problems anticipated with this specific cladistic study, which also strongly influenced the data collection and sampling methods, included other potential species and other potential characters and states not included in the conceptual classifications, and the potential reliance on characters and states in the conceptual classification which are not evolutionary significant and thus misleading.

A preliminary clean-up and analysis of data was conducted, which involved an evaluation of useful responses, identification of anomalies in the dataset, and the generation of descriptive statistics using statistical analysis software to provide an overview of the dataset. The clean data were again subjected to a cladistic analysis using MacClade software (Maddison and Maddison 2003) to generate candidate cladograms. A period of evaluation followed with the aim of producing the most consistent cladogram.

4. Preliminary results

4.1 Ancient manufacturing systems and the Out-Group

In order to describe ancient manufacturing or ancient craft system more precisely, the research set out to explore what history can tell us about ancient times. The evolution of manufacturing man in pre-historic or ancient time is about a journey of adaptation to an ever but slowly changing environment. By manufacturing today, it is in general understood to make a product from raw material, and especially large scale operations using machinery (Collins, 2000). However, the term manufacturing comes from Latin; manus = hand, facere = make. The factory is thus where something is made, and originally by hand. This journey of ancient manufacturing man runs through the different Stone Age periods of Palaeolithic, Mesolithic, Neolithic, and from there into Bronze Age and Iron Age. Baraclough (1982) outlines these periods as follows; 1) the lower Palaeolithic period (about 2.5 million years ago) is about individual survival, 2) in the Middle Palaeolithic period (120000 – 24000 years ago) the human population is more organised for hunting, 3) during the Upper Palaeolithic period (35000 – 10000 years ago) simple stone type tools are developed, 4) during the Mesolithic period (10000 – 6000 years ago) man makes stone tools for himself. He is not highly skilled. There is no orientation towards a market, there is no product variation, and man uses a simple hand-tool to make his own tool. He is working alone. He makes his single *product* on his lap, i.e. the general layout character is *fixed position*. He performs his work on the site in the protection of dwellings, his *covered dedicated facility*. He uses his hands in a *single universal process*. He *performs all the processes* of producing his tools. The job is done in one go with no *buffer between processes*. He uses a stone as his *manual hand tool* to hammer / chisel out his new tool. He picks up and carries the material he is going to work on back to his dwellings. This is his important *primary material handling*. He moves the raw stone piece around in his hand while he is

working on it. This is his *secondary material handling.* Based on these findings we have

suggested the following Out-Group character states:

1-1 Fixed position layout

2-1 Covered dedicated facility

3-1 Single universal process

4-1 Operator performs all processes

5-1 No buffer between processes

6-1 Manual / hand tool

7-1 Manual / mechanised primary material handling system

8-1 Manual / mechanised secondary material handling system

4.2 The species

Of the 510 manufacturing systems (specimens), 46 specimens proved difficult to

classify under the conceptual classifications. Of the 46, 20 represented 3 additional

potential species, newly named as the PRODUCT CENTRED *Assembly Plant,* the FIXED

Automated Rotary Indexer, and the ROBOT *Sequenced Cell-Based Line*, belonging in

the PRODUCT CENTRED, TRANSFER and ROBOT genera, respectively (note: the genus

names are according to the conceptual classifications).

The other 26 systems and potential species represented a potential partitioning of an

existing species. Two species in particular were in question: the PROJECT *Matrix* and

the UNPACED *Asynchronous*. The *Matrix* species differed significantly in the project

manager's power over the resources needed for particular projects; some project

managers had very little power, others had appropriate power, and yet others had

power plus a high degree of flexibility in their deployment. This resulted in the

formation of three newer and more adequately described species from the one

Matrix species: the *Weak Matrix Project, Strong Matrix Project* and the *Flexible*

Matrix Project. This introduction of three instead of one species, also held questions

and opportunities at the genus level to differentiate between the groups. Therefore,

the original *PROJECT* genus has been partitioned into the *REMOTE* and

ORGANISATIONAL genera, to represent the nature and location and the projects.

The specimens collected questioned a second species, the *UNPACED Asynchronous*,

which also differed significantly in the configuration of the line. Some had a process

layout which acted as one entire line, others were configured around independent

workstations formed in a line, whilst others, were configured around cells. This

again resulted in the formation of three newer and more adequately described

species from the one *UNPACED Asynchronous:* the *UNPACED Process-Based Line,*

the *UNPACED Asynchronous Workstationed Line* and the *UNPACED Asynchronous*

Cell-Based Line.

Inconsistencies surrounding the characters and states also offered an opportunity for

refinement. The first problem rectified and which was separate from this

quantitative study, was that there were no relevant character to represent the order

level. Therefore the character 'Product Mix and Order Capability' was introduced

(now Character 1). An additional 2 states were added to what is now the 2nd

character 'General Layout Approach': virtual product layout (CS 2-3) and virtual

part-family layout (CS 2-5), which more adequately described both the *SCALE*

Linked Batch and *SCALE Nagare*, respectively. Two additional states were added to

character 3 'Location of Production' to reflect and differentiate between the new

Project species. This also offered another opportunity to combine two characters –

that of Management Style and Project Management Type under one renamed

character 'Management Capability'. The last major change to the characters related to the intention to differentiate between dedicated and flexible material handling types (see Characters 11 and 13 in 3).

More generally, several characters and states were renamed to more adequately describe the species which can be seen when comparing Table 2 and Table 3. Similar refinement was also made in terms of the naming of orders, families, genera and species and can be seen when comparing Figure **4** and Figure 9.

With the data now aligned to the classifications, in terms of the above initial refinements, the spread specimens between orders (see Figure **5**), families (see Figure **7**), and genera (see Figure **7**) can be seen. This spread was achieved from a combination of convenience sampling first, then combined with both the 'snow-ball' sampling (making enquiries to already collected participants about further potential participants) and focussed sampling. This latter technique involves actively seeking out specimens in under- or non-represented genera and species.

5   [Figure **5** Here]

6   [Figure **6** Here]

7   [Figure **7** Here]

At the level of the order, all three are represented adequately with the Single/Mixed Model order accounting for the highest number of specimens (i.e., 222). There is also a very good representation at the level of the family with an average of 85 and range of 56 and 120 specimens. In terms of the level of the genera, two genera in particular suffer from under-representation: the *REMOTE* and the *MINIATURE*. The first is perhaps due to the re-classification and partitioning of the old *PROJECT* genus into two new genera – the *REMOTE* and *ORGANISATIONAL*; and, the re-classification and partitioning of the old *Matrix Project* species into three new species: the *Weak*

Matrix Project, Strong Matrix Project and the *Flexible Matrix Project*. These are discussed and justified above. The second genus, the *MINIATURE,* is arguably due to the species' recency.

There are several notable points to be made concerning the spread at the species level and representation of these with the specimens collected. Firstly, the average representation of species is just under 10 specimens, with 18 species having more than this. Secondly, 4 of the 53 species are represented by 30 or more specimens with the highest representation belonging to the *FIXED Cycle Transfer* with 87 Species. Thirdly, 20 of the species are represented by only 5 or less specimens, with the *MINIATURE Square Foot* only represented by one specimen. This last point can be seen as a weakness of this factual classification and thus more research and data collection, using the focussed sampling technique, is needed. Arguably, 100 specimens per species would increase confidence above any doubt.

Two main candidate factual cladograms emerged in this work, which differed at the order level with Candidate A (the eventual final candidate) having an emphasis more on both the Product Mix and Order Capability (character 1) and General Layout Approach (character 2), whereas Candidate B emphasised Process Capability (character 4) and Primary Material Handling Capability (character 7). In order to select the final candidate two measures are used – tree length (Principle of Parsimony) and a consistency index (CI) score. The length of a tree is the total number of character state changes necessary to support the relationship of the configurations in the cladogram. Thus, the tree with the minimum length is considered to have fewer instances of character re-introduction and as a consequence is the best-fit tree. The CI serves to measure the relative degree of inconsistency in a cladogram and the level of difficulty in fitting a given data set to

a given tree. The CI is calculated with the following formula: CI = M/S; where M is the total number of character changes expected, given the data set and where S is the actual number of changes that occur in the tree. Candidate A had a tree length of 87 (the minimum) and a CI score of 1 (perfect fit), whereas Candidate B had a tree length of 96 and a CI score of 0.915. Given both the tree length and consistency index scores, Candidate A is the most likely candidate.

4.2 The conceptual classification

To fully determine the clade, the conceptual classifications were developed through stages of logical testing, validation and reflection. The final conceptual classifications can be seen in Figure 3 and Figure 4.

(Figure 3 here)

(Figure 4 here)

5   Final results

The final factual cladogram, which achieved the perfect tree length and consistency index, includes 53 manufacturing systems (see Figure 8 and Table), also organised in a hierarchical classification with thirteen genera, six families and three orders under one class of discrete manufacturing (see Figure 9).

[Figure 8 Here]

[Table 3 Here]

[Figure 9 Here]

In general, we have defined our Species by a single character state distinguishing it

from its sister Species, however, sharing character states with the Species of the same

Genus. As such these sister Species are Varieties within the same Genus. The greatest

innovation by Linnaeus was the general use of binominal nomenclature. That is the

combination of a Genus name and a second term to identify the Species. This research

has proposed Varieties of all the Species of the classification. Basically, what

distinguishes one Sister Species from another in Figure 8 is one character state.

However, in the research Varieties add to the potential of more character states that can

distinguish between Sister Species. These are grouped together due to a recent

evolutionary split. Due to the space limitations of the paper, the example presented is of

the first Species of the Product Centred Genus, namely the hierarchical classification of

the Product Centred Workshop (see Figure 10).

(Figure 10 Here)

(Table 4 Here)

The first Species of the *Product Centred* Genus is the *Product Centred Workshop*

(Alizon et al. 2009); the primary difference from the *Out-Group* is that an

entrepreneurial spirit (CS 8-1) has emerged where the manufactured products are sold to

customers. That is, the multi-product capability is retained but is complemented with a

multi-order capability (CS 1-2) and capable of make-to-order, make-to-stock, engineer-

to-order, assemble/configure-to-order, and assemble-to-stock.

To elaborate, the *Workshop*, *Assembly Plant* and the *Assembly/Fabrication Yard* may

exhibit one of all states of the Variety-Defining, Specific Order Type character (see

Table 3) such as make-to-order (CS 14-1), make-to-stock (CS 14-2), engineer-to-order

(CS 14-3), assemble/configure-to-order (CS 14-4) or assemble-to-stock (CS 14-5).

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5.2 Practical Implications

This work underlies a web-based expert system for automating the identification,

diagnosis and improvement of manufacturing systems and complements a larger

software system architecture of the research project, which simplifies and makes

accessible essential modelling tools for the rapid design, simulation and virtual

prototyping of factories.

Figure 11 is a screenshot of the identification and diagnostics web-based tool

based on the factual classifications. The classifications are then used to reveal the

change process that connects the development of processes and technologies, to their

overarching manufacturing system, and can be used as a benchmarking tool that enable

users to view manufacturing systems in an evolutionary landscape, gauge performance,

and identify strategies and tools for improvement.

[Figure 11 Here]

An additional practical use is in an educational context. The cladistic

classification not only sheds light on the possible origin of manufacturing and its

historical development (see Box 1 for an example of how to 'read' the cladogram), but

also offers a tool to both compare and contrast similarities and dissimilarities, and gauge

the 'distance' and the relative difficulty of change required to transform from one

system to another. Relationships between manufacturing systems are evident not just at

the manufacturing system level with the cladistic classification, but also at the genus,

family and order level when referring to the hierarchical classification. The promise of

the 'blueprint' or 'recipe' for a manufacturing system, with which to benchmark is now

much more evident.

[Box 1 Here]

6. Discussion and conclusions

6.1 Discussions

This research returned to the original systematics work of McKelvey (1978) and McCarthy (1995) with the aim of completing the unfinished work of developing a generic cladistic classification of discrete manufacturing systems which spans sectors unlike McCarthy et al. (1997), Leseure (2000, 2015) and Rose-Anderssen (2009, 2011). In terms of further advancing the state of the art, this is the first reported research of its kind that: a) refines the phylogenetic hypotheses through multiple iterations of the conceptual work; b) includes an explicit out-group, which reveals further evolutionary history and the potential origin of manufacturing; and, c) extends the use of multi-state characters, with one character having a total of fifteen states.

Extended multi-state characters also give an indication of the co-evolutionary processes made explicit in the manufactured artefact works (e.g., AlGeddawy and ElMaraghy 2011b). That is, the ordering/numbering of characters reflects their evolutionary introduction and how the evolution of states within a character has an evolutionary impact at the level of aggregation higher – the manufacturing system. In addressing the limitation of character representation with early species, this work includes the out-group with a representation of seven characters. All other species have at least eight characters as is the case with the *Multi-Product* order and up to eleven characters as is the case with both the *Single/Mixed Model* and *Part-Family* orders.

Finally, and in the mitigation of previous research design weaknesses (i.e., Leseure 2000, Rose-Anderssen, Baldwin, and Ridgway 2011), this research employed a novel methodology based on observation-assisted surveying. However, problems did

emerge in the data coverage, i.e., the spread of the 510 specimens between orders, families, genera and species. Although there was good specimen representation of manufacturing systems at the order and family levels, the genera (particularly the *REMOTE* and the *MINIATURE)* and species levels were less equal (with the *MINIATURE Square Foot* only represented by one specimen). This problem is in part exacerbated firstly by the reclassification process from the conceptual to the factual at the genera level, and to the relative recency of some of the species. Arguably, future work should consider at least 100 specimens per species, which would increase confidence above any doubt.

Additional limitations must also be highlighted. The very nature of classification work, particularly in the social sciences, is inherently subjective. Despite claims to the contrary by McCarthy (1995), subjectivity plays a role in each of the procedural steps of constructing a cladistic classification. The definition of a manufacturing system (Leseure 2000) was not an easy process and although most work on this was performed during the first iteration there were refinements made throughout the iterations. The most difficult problem here was to achieve the most appropriate level of granularity. For example, should the focus be on the entire manufacturing company, which could include several manufacturing sites, or on a single factory or on a factory sub-system? Or should it relate to a product, part or component and a stage of production? The outcome attempted to cater to all of these and could include a company with one 'factory' making one product or to a subsystem of a factory of a multi-factory company.

A further limitation, when compared to biological classifications, is that the species concept should be related to reproductive isolation, which in relation to manufacturing systems equates to the sharing of information and practices through people (McKelvey 1978). It is possible that the manufacturing systems at the species

level in this scheme are just varieties and perhaps the species level should be what is the class (e.g., discrete manufacturing) or perhaps higher (e.g., the manufacturing sector). Additional challenges included deciding what to include and exclude as a species in the clade, what should be treated at a higher level of aggregation (genus, family, etc.), and what to treat as a variety (McKelvey 1975). This challenge is highlighted not only by the variation in species numbers included throughout the classification iterations, but also, the final number of varieties (which totalled 1,586, and beyond the scope of this paper). Clear delineations and boundaries are needed in future work to definitively justify not only a species but also a variety, genus, family, order, etc.

There are also challenges concerned with the selection of appropriate characters and states; the grouping of states under characters; the ordering of states within characters; the emphasis or weighting of one character over another; and, the decision over whether characters are either primary species-defining, variety-defining, or secondary characters, all of which are a matter of subjectivity. Furthermore, both candidate cladograms should be seen in the 'light of subjectivity'. Thus, one drastic change would be to attempt a re-description and weighting of characters and states in favour of and emphasising, in candidate B's case, process capability and primary material handling capability.

6.2 Conclusions

The paper set out to:

a) Critically evaluate the state of the art of applications of organisational systematics and manufacturing cladistics in terms of strength and weaknesses.

The paper argues that the gap between the most current manufacturing cladistics in general and the one presented in this paper is the lack of: generic classification, presentation beyond theory, out-group comparison to resolve polarity of further characters and states, evolutionary significant / chronological numbering of states, and validations steps. Further there is little consistency across classifications and cladograms.

   b) Building on the above introduce a new generic cladistics and hierarchical classification of discrete manufacturing systems

This paper introduced generic cladistic and hierarchical classifications of discrete manufacturing systems following a review, and building on strengths and weaknesses, of the state of the art of organisational systematics and manufacturing cladistics. The research employed a novel re-iterative methodology for both theory building, using secondary and observational data, producing the conceptual classifications, and theory testing producing the final factual cladogram, based on the observation-assisted surveying of 510 manufacturing systems within 153 companies. Phylogenetic hypotheses of the evolutionary emergence of fifty-three manufacturing systems, described by thirteen characters and eighty-four states were presented diagrammatically. This was accompanied by a hierarchical classification containing thirteen genera, six families and three orders under one class of discrete manufacturing. Regarding practicalities, the classifications form the basis of a web-based diagnostic and benchmarking tool, but also has significance in an educational context as it provides an alternative system of knowledge to that traditionally found in the literature and textbooks.

   c) The classification to form the basis for a practical web-based expert system and diagnostic bench-marking tool.

The web-based expert system allows for the identification, diagnosis and improvement of manufacturing systems. It can be used as a bench-marking tool that enable users to view manufacturing systems in an evolutionary landscape, gauge performance, and identify strategies and tools for improvement.

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Table 1: Manufacturing system literature

Layout species	Literature	Layout species	Literature
Workshops	Alizon et al (2009) Burbridge (1978) McCarthy et al (1997) Slack et al (2006) Wild (1989)	Cells / Group Technology	Burbridge (1970) Das and Canel (2005) Mansouri et al (2000) Shambu et al (1996) Womack et al (1990) Jajoda et al (1992)
Projects	Bruke (2003) Lancaster et al (2007) Mafakheri et al (2008) Meade and Sarkis (1999) Stock and Tatikoda (2000) Shenbar (1998)	U-Line	Kara and Tekin (2009) Miltenburg (2001) Ozcean et al (2011) Sparling and Miltenberg (1998)
Jobshops	Betrand et al (2008) Ham et al (2011) Uzsoy and Wang (2011) Vinod and Sridharan (2011)	FMS	Devise and Pierreval (2000) Liu and MacCarthy (1999) Tacquard and Martineau (2001) Rajotia et al (1998)
Batchshop	Chen et al (2002) Goodall and Roy (1995) Brown and Mitchell (1991)	Desktop	Son et al (2010)
Linked Batch	Hill (2005)	Square Foot	Redlich et al (2009) Wulfsberg et al (2010)
Nagare	Hill (2005) Kanan and Gosh (1996)	Rotary Indexer	Dolgui et al (2009)
Unpaced Line	Bulgak (2006) Lau and Martin (1986) Martin (1993) Pike and Martin (1994) Smunt and Perkins (1985)	Reconfigurable	Abdi and Labib (2011) Bi et al (2008) Bruccoleri et al (2006) Dou et al (2010)
Paced / Assembly Line	Akgunduz and Tunali (2011) AlGeddawy and ElMaraghy (2010) Amen (2000) Boysen et al (2007) Boysen et al (2008) Freiheit et al (2007) Hill (1991)	Holonic	Lee and Banerjee (2011) Cheung et al (2000)
Transfer Lines	Dhoib et al (2009) Inman and Leon (1994) Lavoie et al (2010) Mourani et al (2007)	Robotic Cell	Brauner and Finke (2001) Dawande et al (2005) Gultekin et al (2008) Shafiei-Monfared et al (2001)

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Table 2: Primary Species-Defining characters and states for conceptual cladistic classification of discrete manufacturing systems

Character States	Character States
1. General layout approach	**7. Primary material handling system (PMHS)**
1-1. Fixed position layout	7-1. Manual/mechanised PMHS
1-2. Process layout	7-2. Automated PMHS
1-3. Product layout	**8. Secondary material handling**
1-4. Group technology layout	8-1. Manual/mechanised
2. Location of production	8-2. Combined with PMHS
2-1. Covered dedicated facility	8-3. Automated
2-2. Remote location	**9. Management style**
3. General machine/process type and number	9-1. Entrepreneurial
3-1. Single universal processes	9-2. Project Managed
3-2. Limited universal processes	9-3. Agile project managed
3-3. Extensive universal processes	9-4. Centralised
3-4. Single dedicated-machine/process types	**10. Project management type**
4. Operator capability	10-1. Intra-organisational project resource pool
4-1. Operator performs all processes	10-2. Functional manager is project manager
4-2. Operator performs significant processes	10-3. Power over functional resource secondment
4-3. Operator performs limited processes	10-4. Inter-organisational project resource pool
4-4. Operator oversees processes	**11. Automated PMH type**
4-5. Operator performs product family processes	11-1. Intermittent
4-6. One operator performs all cell processes	11-2. Continuous: operator processes in motion
4-7. Two or more operators share cell zones	11-3. Continuous: operator removes and returns
4-8. Three or more operators share cell 'legs'	11-4. Continuous: operator feeds other conveyor
4-9. Programs and oversees/monitors processes	11-5. Continuous: operators walk with in-line cart
5. In-process buffer	11-6. Continuous: operators 'slide' past others
5-1. No buffer between processes	11-7. Continuous cycle with automated processes
5-2. Buffer between processes	11-8. Intermittent cycling with automated process
5-3. Line balanced	11-9. Intermittent progressive bypass
5-4. In process buffer is removed	11-10. Intermittent closed loop bypass
6. Process technology type	11-11. Bidirectional CNC rotary indexing
6-1. Manual/hand-tool	11-12. Bidirectional
6-2. Mechanised machines	11-13. Multidirectional
6-3. Modular mechanised machines	11-14. Mobile, automated
6-4. Automated machines (non CNC)	11-15. Mobile, autonomous
6-5. CNC Machine tool	11-16. Robotic
6-6. Flexible industrial robot	**12. Cellular work-in-progress**
6-7. Modular CNC machine tool	12-1. Decoupling cell buffer
6-8. Autonomous CNC machine tool	12-2. No buffer between cells
6-9. Modular flexible robot	12-3. No buffer between lines
6-10. Autonomous industrial robot	
6-11. Precision micro machining unit	
6-12. Modular precision micro machining unit	
6-13. Modular universal micro machining unit	

Table 3: Primary Species-Defining characters and states for factual cladistic
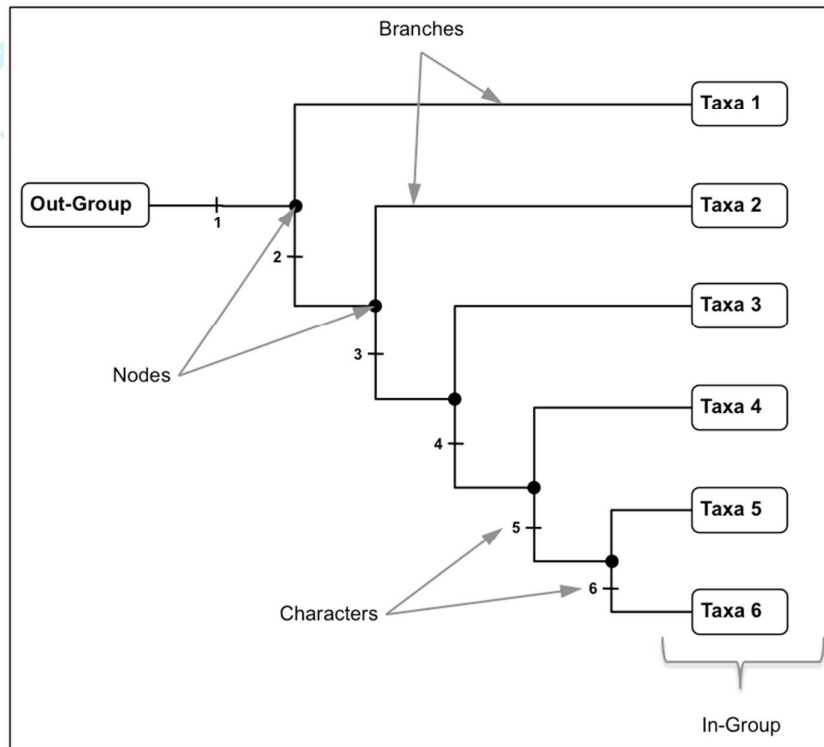classification of discrete manufacturing systems

Character States	Character States
1. Product mix and order capability	**7. Primary material handling (PMH) capability**
1-1. Multi-product capability	7-1. Manual/mechanised PMH
1-2. Multi-product and multi-order capability	7-2. Automated PMH system
1-3. Single/mixed model product	7-3. Flexibly automated PMH system
1-4. Part-family	**8. Management capability**
2. General layout approach	8-1. Entrepreneurial
2-1. Fixed position layout	8-2. Centralised non-routine task scheduling
2-2. Process layout	8-3. Intra-organisationally project
2-3. Virtual product layout	8-4. Inter-organisationally project
2-4. Product layout	8-5. Agile project managed
2-5. Virtual part-family layout	8-6. Functionally project managed
2-6. Part-family layout	8-7. Weak, cross-functional project
3. Location of production	8-8. Strong, cross-functional project
3-1. Covered dedicated facility	8-9. Flexible cross-functional project
3-2. Outside dedicated facility	8-10. Centralised routine resource scheduling
3-3. Remote location	8-11. Decentralised teams
3-4. Site specific	8-12. Decentralised cells
4. Process capability	**9. Asynchronous line configuration**
4-1. Limited universal processes	9-1. Process based
4-2. Extensive universal processes	9-2. Workstation based
4-3. Dedicated automated processes	9-3. Cell based
4-4. Dedicated industrial robots	**10. Fixedly-automated robot line configuration**
4-5. Limited modular universal processes	10-1. Cyclical
4-6. Extensive modular universal processes	10-2. Unidirectional
4-7. Limited universal, flexibly-automated	10-3. Sequenced cell-based
4-8. Modular, universal, flexibly-automated	**11. Automated PMH type**
4-9. Autonomous CNC machine tool	11-1. Intermittent
4-10. Flexible industrial robots	11-2. Continuous: operator processes in motion
4-11. Modular flexible industrial robots	11-3. Continuous: operator removes and returns
4-12. Autonomous industrial robots	11-4. Continuous: operator feeds other conveyor
4-13. Precision micro machining units	11-5. Continuous: operators walk with in-line cart
4-14. Modular precision micro machining units	11-6. Continuous: operators 'slide' past others
4-15. Modular universal micro machining units	11-7. Non-CNC bidirectional rotary index table
5. Operator capability	11-8. Continuous cycle with automated processes
5-1. Operator performs all processes	11-9. Intermittent cycling with automated process
5-2. Operator performs significant tasks	**12. Cellular work-in-progress**
5-3. Operator performs significant processes	12-1. Decoupling cell buffer
5-4. Operator performs limited processes	12-2. No buffer between cells
5-5. Operator oversees processes	12-3. No buffer between lines
5-6. Operator performs product family processes	**13. Flexibly PMH type**
5-7. One operator performs all cell processes	13-1. Intermittent progressive bypass
5-8. Two or more operators share cell zones	13-2. Intermittent closed loop bypass
5-9. Three or more operators share cell 'legs'	13-3. Bidirectional CNC rotary indexing
5-10. Operator programs and oversees processes	13-4. Bidirectional
6. In-process work-in-progress	13-5. Multi-directional
6-1. No buffer between processes	13-6. Mobile, automated
6-2. Buffer between processes	13-7. Mobile, autonomous
6-3. Line balanced	13-8. Robotic
6-4. In process buffer is removed	

Table 4: Primary, Variety-Defining Characters and States

PRIMARY VARIETY-DEFINING C&Ss

Code	State
14 Specific Order Type	
14-1	Make-to-order
14-2	Make-to-stock
14-3	Engineer-to-order
14-4	Assembly/configure-to-order
14-5	Assemble-to-stock
15 Universal Process Capability	
15-1	Manual and/or hand/power tool
15-2	Mechanised machine tool
15-3	CNC machine tool/centre
16 Modular Universal Process Capability	
16-1	Modular mechanised machine tool (primarily)
16-2	Modular CNC machine tool (primarily)
17 Product Centred Layout	
17-1	Standalone production
17-2	Parallel production
18 Shop Layout	
18-1	Standalone shops
18-2	Parallel shops
19 Product Line Layout	
19-1	Space constrained
19-2	Line shape
19-3	U-shape
19-4	S-shape
19-5	Serpentine
19-6	Segmented L
19-7	Segmented U
19-8	Rectangle
19-9	Loop
20 Product Line Configuration	
20-1	Standalone line
20-2	Parallel line
20-3	Sub-cell line
20-4	Multi-sub-cell line
20-5	Sub-line line
20-6	Multi-sub-line line
20-7	Parallel sub-cell line
20-8	Parallel multi-sub-cell line
20-9	Parallel sub-line line
20-10	Parallel multi-sub-line line
21 Cell Layout	
21-1	Chase U
21-2	Chase shared X
21-3	Zonal U
21-4	Zonal S
21-5	Zonal M
21-6	Split U
21-7	Split Y

Code	State
22 U-Line Layout	
22-1	Multi-lined single U
22-2	Embedded U
22-3	Double dependent U
22-4	Figure 8
23 Ladder Layout	
23-1	Double rung
23-2	Triple rung
23-3	Multi rung
24 Robot Centred Layout	
24-1	Line
24-2	Double Line
24-3	Rectangle
24-4	Circular
24-5	L-form
24-6	U-form
24-7	Matrix

SECONDARY PRODUCT C&Ss

Code	State
25 Order Volume	
25-1	One
25-2	Low
25-3	Medium
25-4	High
25-5	Very high
26 Product Variety	
26-1	Unique
26-2	High
26-3	Medium
26-4	Low
26-5	Very low
27 Standard/custom	
27-1	Non-standard
27-2	Standard
27-3	Customised
27-4	Mass customised
28 Compete on Product Cost	
28-1	Low priority
28-2	Medium priority
28-3	High priority
29 Compete on Product Consistent Quality	
29-1	Low priority
29-2	Medium priority
29-3	High priority

Code	State
30 Compete on Performance Design	
30-1	High priority
30-2	Medium priority
30-3	Low priority
31 Compete on Development Speed (NPI)	
31-1	High priority
31-2	Medium priority
31-3	Low priority

SECONDARY PROCESS C&Ss

Code	State
32 Machine Mobility	
32-1	Fully mobile
32-2	Temporarily fixed
32-3	Permanently fixed
33 Process Flexibility	
33-1	Flexible
33-2	Semi-flexible
33-3	Inflexible
34 Process Change Ability	
34-1	High
34-2	Medium flexible
34-3	Low
35 New Process Introduction Ability	
35-1	High
35-2	Medium flexible
35-3	Low
36 Number of bottlenecks	
36-1	Key process
36-2	Few
36-3	None
37 Nature of bottlenecks	
37-1	Fixed (short and medium term)
37-2	Moveable
38 Number of Setups	
38-1	High
38-2	Moderate
38-3	Low
39 Cost of Setups	
39-1	Low
39-2	Moderate
39-3	High
40 Daily Scheduling Difficulty	
40-1	Easy
40-2	Complex
40-3	Very complex
40-4	Moderate

SECONDARY SYSTEM C&Ss

Code	State
41 Raw Materials Inventory	
41-1	Low
41-2	Moderate
41-3	High
42 WIP Inventory	
42-1	Low
42-2	Moderate
42-3	High
43 Finished Goods Inventory	
43-1	Low
43-2	Moderate
43-3	High
44 Definition of Capacity	
44-1	Well-defined
44-2	Moderately defined
44-3	Ill-defined
45 Compete on Production Cost	
45-1	Low priority
45-2	Medium priority
45-3	High priority
46 Compete on Consistent Production Quality	
46-1	Low priority
46-2	Medium priority
46-3	High priority
47 Compete on Fast Delivery Time	
47-1	Low priority
47-2	Medium priority
47-3	High priority
48 Compete on On-Time Delivery	
48-1	Low priority
48-2	Medium priority
48-3	High priority
49 Compete on Volume Flexibility	
49-1	Low priority
49-2	Medium priority
49-3	High priority
50 Compete on Customisation (one-offs)	
50-1	High priority
50-2	Medium priority
50-3	Low priority
51 Compete on Mass Customisation	
51-1	Low priority
51-2	Medium priority
51-3	High priority
52 Unique Selling Point	
52-1	Capability
52-2	Product

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Figure 1: Illustrative cladogram

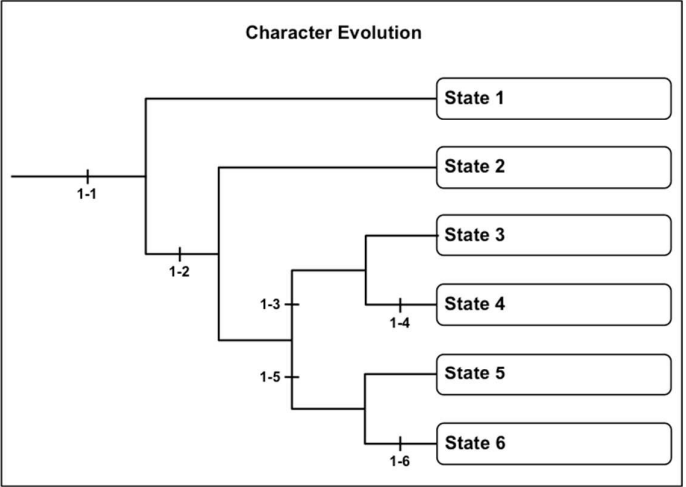Figure 2: Character evolution and state numbering

Figure 3: Conceptual cladistic classification of discrete manufacturing systems (see Table   for the characters and states)
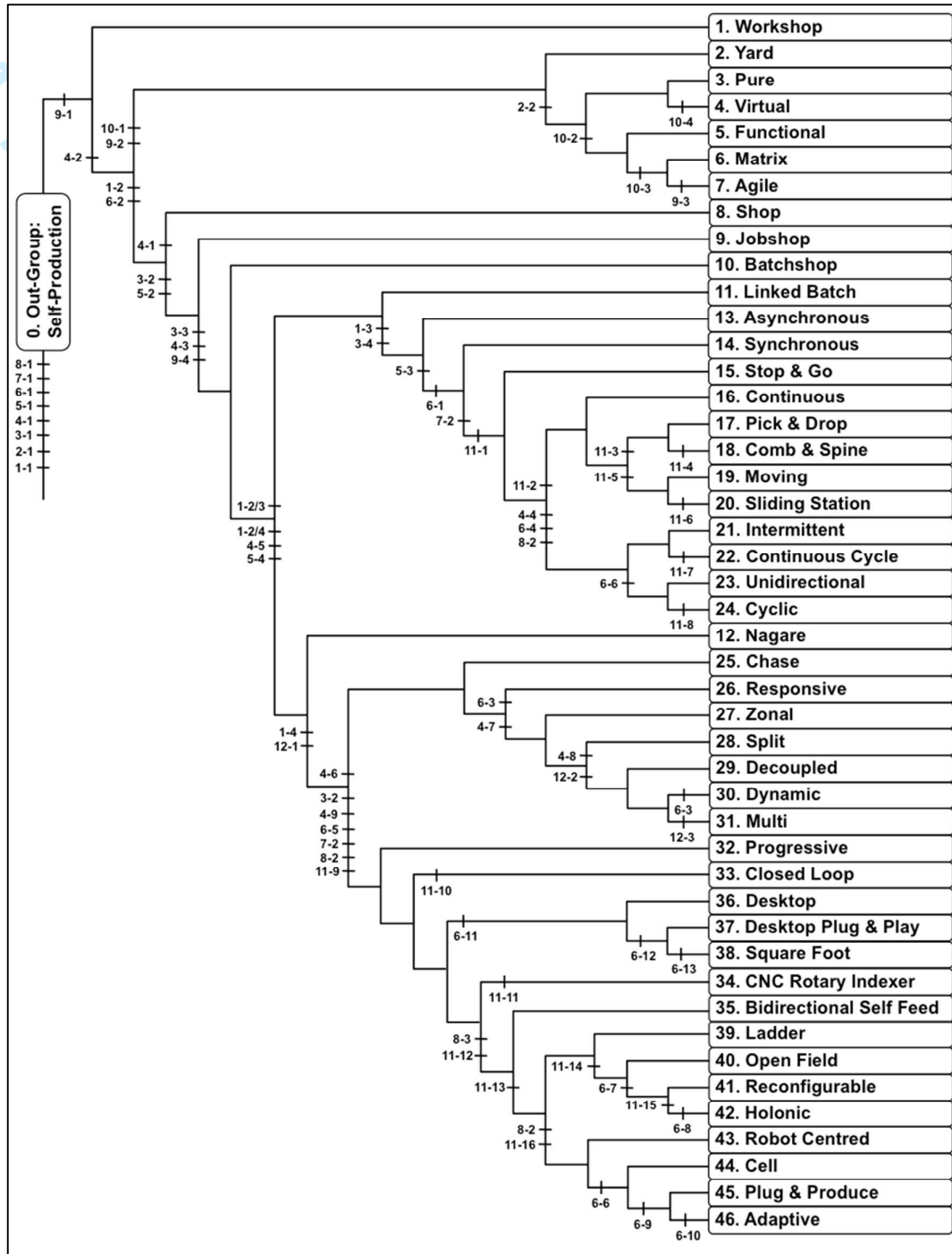
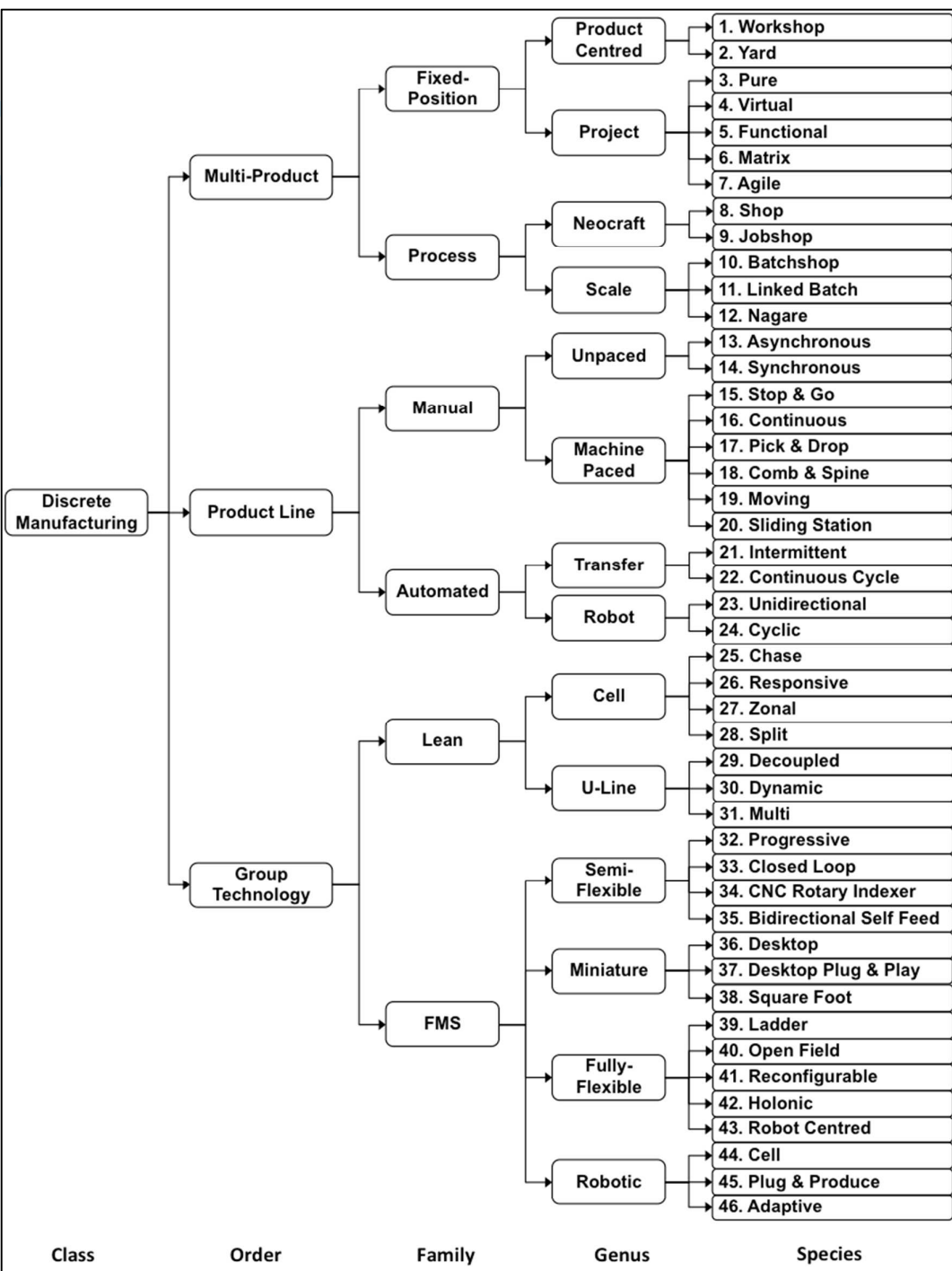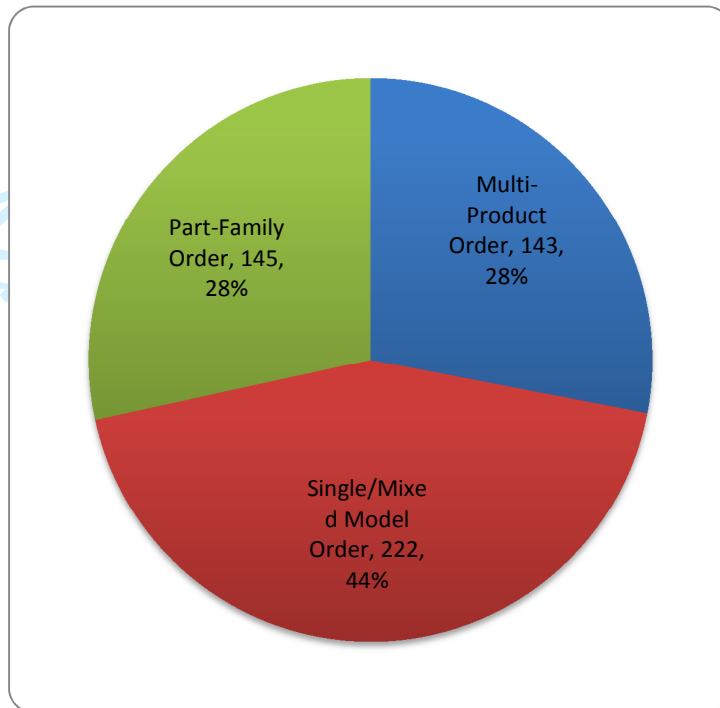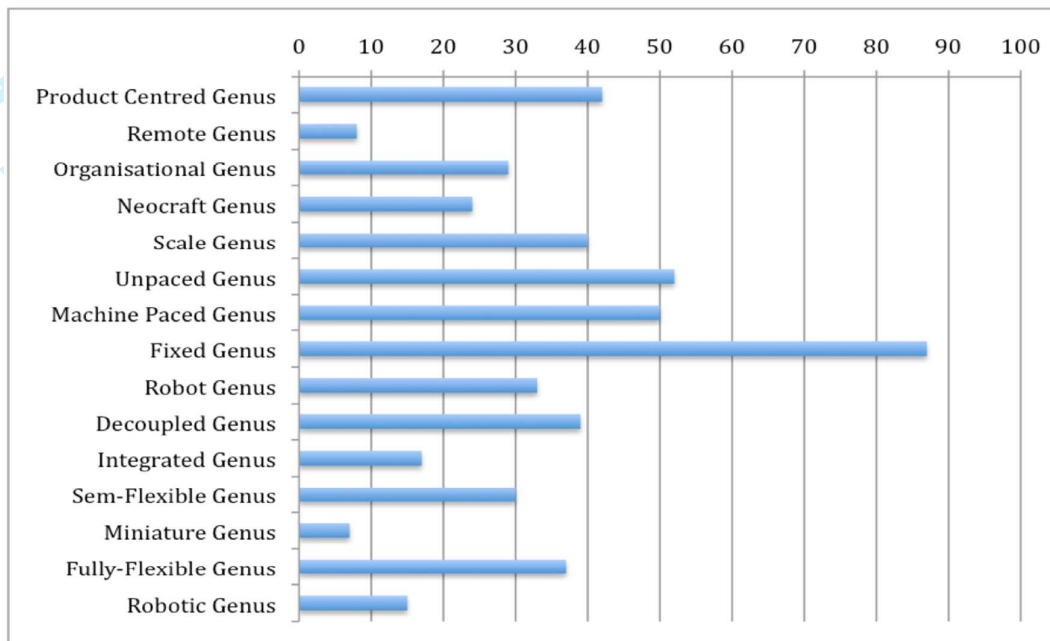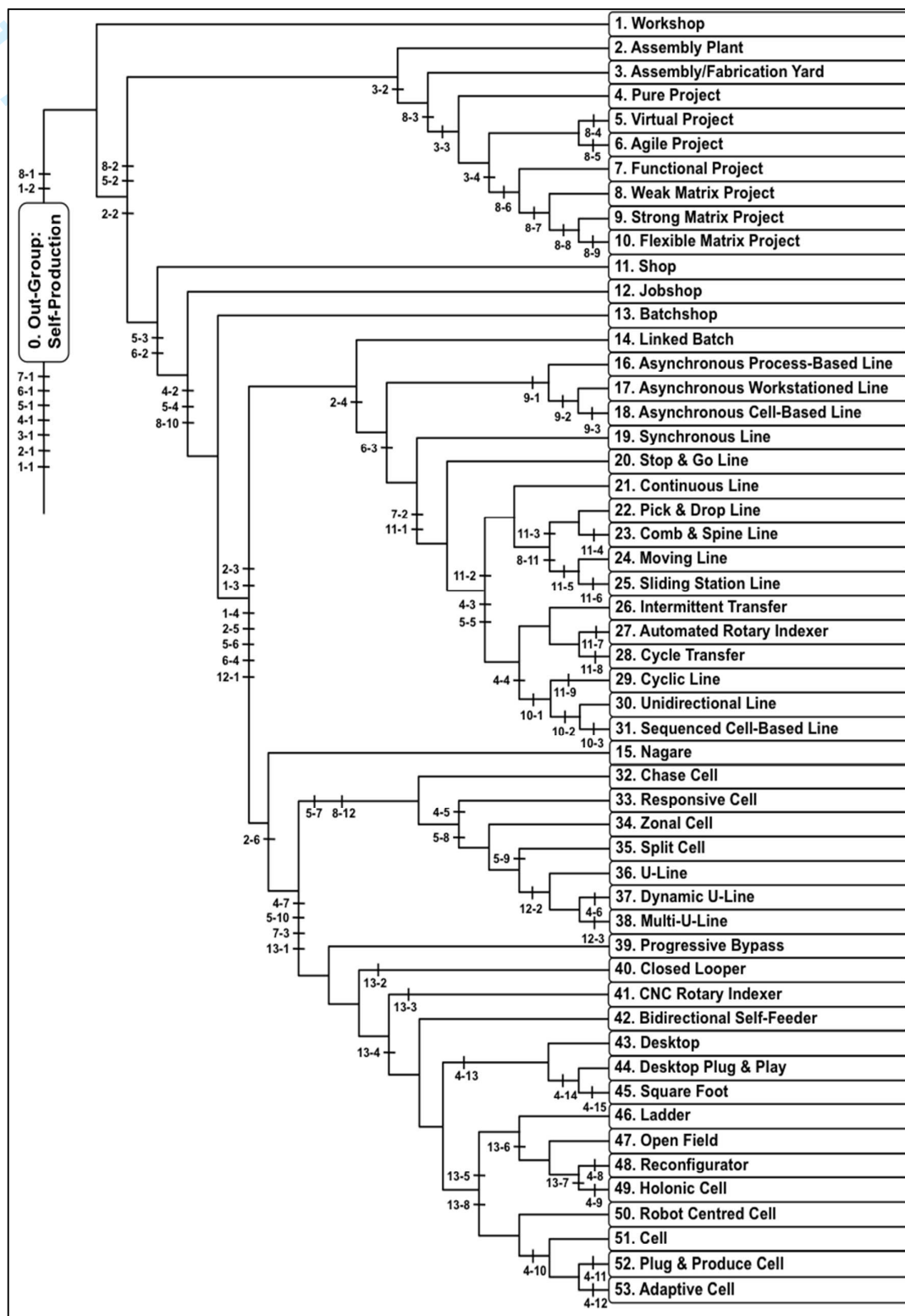Figure 4: Conceptual hierarchical classification of discrete manufacturing systems

Figure 5: Number of manufacturing systems within each order

Multi-Product Order, 143, 28%

Part-Family Order, 145, 28%

Single/Mixed Model Order, 222, 44%

Figure 6: Number of manufacturing systems within each family
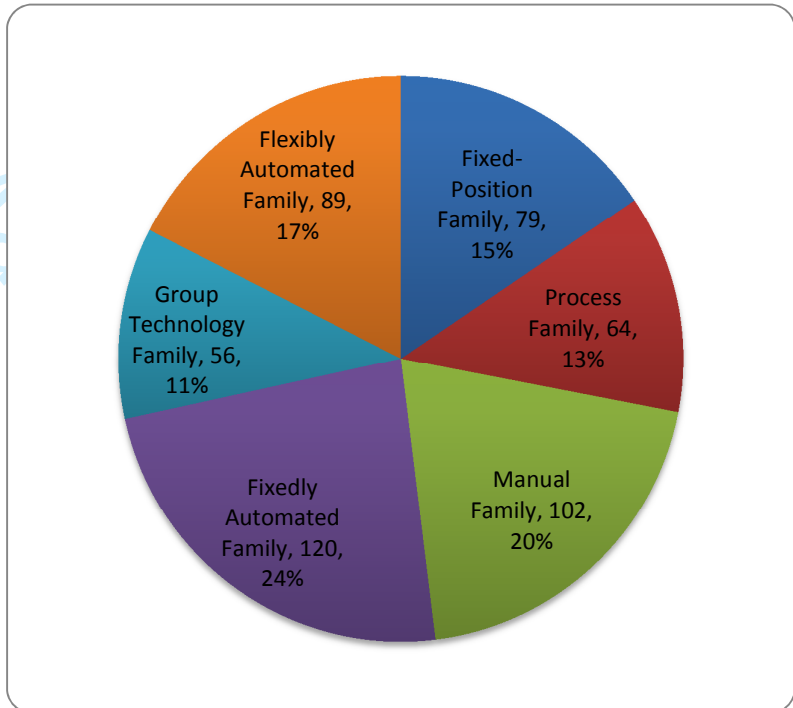
Figure 7: Number of manufacturing systems within each genus

Figure 8: Factual cladistic classification of discrete manufacturing systems (see Table for the characters and states)

Figure 9: Factual hierarchical classification of discrete manufacturing systems
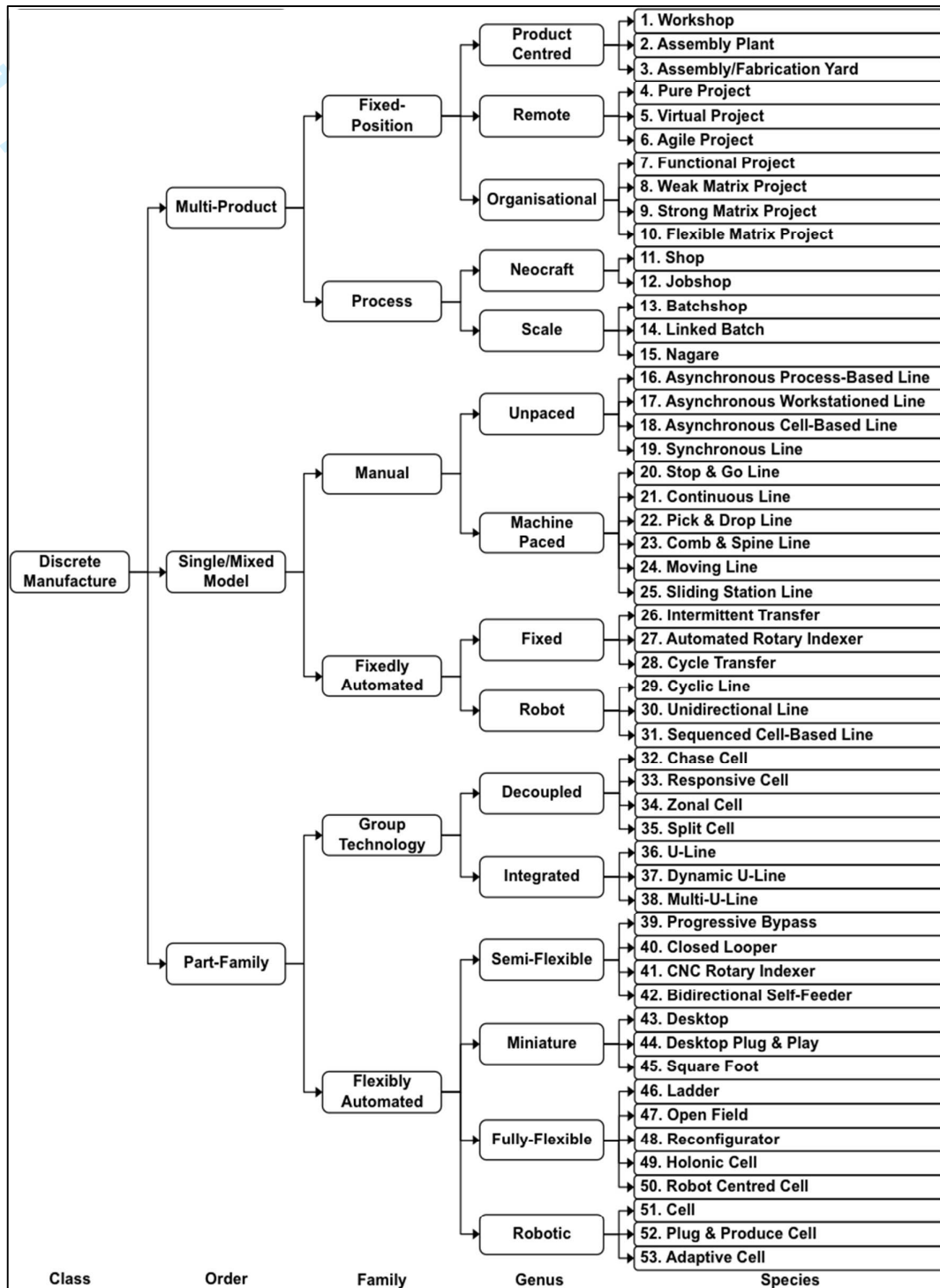
Figure 10: Varieties of the species of the Product Centred Genus
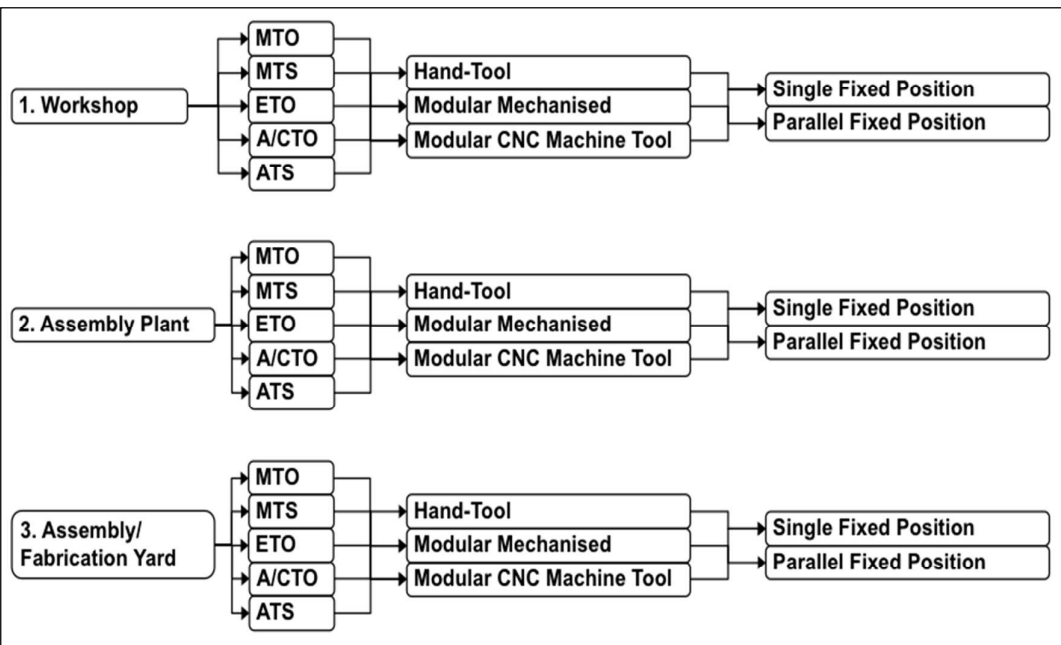
Figure 11: Identification and diagnostics software tool based on factual classifications

Box 1: An example of how to 'read' the cladogram

The first manufacturing system 'species' to evolve from the common ancestor starting what is now the class of *Discrete Manufacturing* is the **PRODUCT CENTRED Workshop** and belongs to the *Multi-Product* order. This manufacturing system processes in a fixed position (character-state or CS 2-1) in an undercover dedicated site (CS 3-1). Simple, universal, processing techniques and tools are employed, in the form of manual or hand tool manipulation (CS 4-1). All the necessary processes are performed, and the full article produced, by the one person (CS5-1) in one go, i.e., without WIP or 'buffer' between the processes (CS 6-1). All material handling is primarily manual (CS 7-1) and, in some instances, mechanised (primitive pulleys, winches, etc.).

The primary difference from the **Out-Group** (**Self-Production)** is that an entrepreneurial spirit (CS 8-1) has emerged where the manufactured products are sold to customers; that is, the multi-product capability is retained but is complemented with a multi-order capability (CS 1-2) and capable of make-to-order, make-to-stock, engineer-to-order, assemble/configure-to-order, and assemble-to-stock. Specimens include jewelry makers, carpet weavers, clockmakers, along with a lot of other handicrafts.

The second species in the *Product Centred* genus is the **PRODUCT CENTRED Assembly Plant** where products are more complex, require more workers, who still perform significant product tasks, but only produce part of the product (CS 5-2) albeit a significant part. With more workers and more complex products and production sequences, a more centralised management capability is evident where skilled resources are scheduled according to non-routine tasks at hand (CS 8-2). Final assembly of cars around the turn of the twentieth century is a good specimen of this species whereas the final assembly of large aircraft such as the A380 and Boeing 787 are more recent examples.

The third and final species in the *Product Centred* genus is the **PRODUCT CENTRED Assembly/Fabrication Yard**. Here, a change in the Location of Production character is evident featuring an on-site but uncovered (or external) dedicated facility (CS 3-2). This also represents a variation in the size and nature of the resource pool. Shipyards are good example specimens of this species.