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

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.
Keywords: Evolution, Organisational Systematics, Cladistic Classification, Linnaean Classification, Manufacturing Cladistics, Discrete Manufacturing, manufacturing development and change

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
(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-descendant 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-descendant 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 Linnaeus 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 ElMaraghya (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., ElMaragh, AlGeddawy, and Azab 2008b, AlGeddawy and ElMaragh 2010, 2011a, b, 2012, ElMaragh and AlGeddawy 2012a, ElMaragh 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 descendancy 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 plesiomorphic
(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-

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. Clearly, 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 cellular 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 cellular 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. Dolgai 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).
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., AlGedawy 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 \textit{REMOTE} and the \textit{MINIATURE}) and species levels were less equal (with the \textit{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.

References


Dolgui, A., Guschinsky, N.N., and Levin, G.M. (2009), "Graph approach for optimal
design of transfer machine with rotary table", *International Journal of

configuration of reconfigurable manufacturing systems using GA", International

manufacturing capabilities and application in auto-parts assembly", *Flexible

analogy for integrating product design for variety with market requirements",

ElMaraghy, H., AlGedawy, T., and Azab, A.. (2008a), "Modelling evolution in
manufacturing: A biological analogy", *CIRP Annals-Manufacturing Technology,
Vol.57 No. 1, pp. 467-472.

ElMaraghy, H., AlGedawy, T., and Azab, A. (2008b) "Modelling evolution in
manufacturing: A biological analogy", *CIRP Annals - Manufacturing
Technology* 57 No. 1, pp. 467-472.


process industry using hybrid knowledge based simulation", *International


No. 6, pp. 1799-1819.
Table 1: Manufacturing system literature

<table>
<thead>
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<th>Literature</th>
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<th>Literature</th>
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<td>Jajoda et al (1992)</td>
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<td></td>
<td>Stock and Tatikoda (2000)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Shenbar (1998)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Goodall and Roy (1995)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Brown and Mitchell (1991)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Wulfsberg et al (2010)</td>
</tr>
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<td></td>
<td>Kanan and Gosh (1996)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Smunt and Perkins (1985)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paced / Assembly Line</td>
<td>Akgunduz and Tunali (2011)</td>
<td>Holonic</td>
<td>Lee and Banerjee (2011)</td>
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<td></td>
<td>Amen (2000)</td>
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<td></td>
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<td></td>
<td>Boysen et al (2007)</td>
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<tr>
<td></td>
<td>Freiheit et al (2007)</td>
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<td></td>
<td>Hill (1991)</td>
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Table 2: Primary Species-Defining characters and states for conceptual cladistic classification of discrete manufacturing systems

<table>
<thead>
<tr>
<th>Character States</th>
<th>Character States</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. General layout approach</td>
<td>7. Primary material handling system (PMHS)</td>
</tr>
<tr>
<td>1-1. Fixed position layout</td>
<td>7-1. Manual/mechanised PMHS</td>
</tr>
<tr>
<td>1-3. Product layout</td>
<td>8. Secondary material handling</td>
</tr>
<tr>
<td>1-4. Group technology layout</td>
<td>8-1. Manual/mechanised</td>
</tr>
<tr>
<td>2. Location of production</td>
<td>8-2. Combined with PMHS</td>
</tr>
<tr>
<td>2-1. Covered dedicated facility</td>
<td>8-3. Automated</td>
</tr>
<tr>
<td>3. General machine/process type and number</td>
<td></td>
</tr>
<tr>
<td>3-1. Single universal processes</td>
<td></td>
</tr>
<tr>
<td>3-2. Limited universal processes</td>
<td>9-3. Agile project managed</td>
</tr>
<tr>
<td>3-3. Extensive universal processes</td>
<td>9-4. Centralised</td>
</tr>
<tr>
<td>4. Operator capability</td>
<td></td>
</tr>
<tr>
<td>4-1. Operator performs all processes</td>
<td>10-1. Intra-organisational project resource pool</td>
</tr>
<tr>
<td>4-2. Operator performs significant processes</td>
<td>10-2. Functional manager is project manager</td>
</tr>
<tr>
<td>4-3. Operator performs limited processes</td>
<td>10-3. Power over functional resource secondment</td>
</tr>
<tr>
<td>4-4. Operator oversees processes</td>
<td>10-4. Inter-organisational project resource pool</td>
</tr>
<tr>
<td>4-5. Operator performs product family processes</td>
<td>11. Automated PMH type</td>
</tr>
<tr>
<td>4-6. One operator performs all cell processes</td>
<td></td>
</tr>
<tr>
<td>4-7. Two or more operators share cell zones</td>
<td>11-1. Intermittent</td>
</tr>
<tr>
<td>4-8. Three or more operators share cell ‘legs’</td>
<td>11-2. Continuous: operator processes in motion</td>
</tr>
<tr>
<td>5. In-process buffer</td>
<td>11-4. Continuous: operator feeds other conveyor</td>
</tr>
<tr>
<td>5-1. No buffer between processes</td>
<td>11-5. Continuous: operators walk with in-line cart</td>
</tr>
<tr>
<td>5-2. Buffer between processes</td>
<td>11-6. Continuous: operators ‘slide’ past others</td>
</tr>
<tr>
<td>5-3. Line balanced</td>
<td>11-7. Continuous cycle with automated processes</td>
</tr>
<tr>
<td>5-4. In process buffer is removed</td>
<td>11-8. Intermittent cycling with automated process</td>
</tr>
<tr>
<td>6-1. Manual/hand-tool</td>
<td>11-10. Intermittent closed loop bypass</td>
</tr>
<tr>
<td>6-3. Modular mechanised machines</td>
<td>11-12. Bidirectional</td>
</tr>
<tr>
<td>6-4. Automated machines (non CNC)</td>
<td>11-13. Multidirectional</td>
</tr>
<tr>
<td>6-5. CNC Machine tool</td>
<td>11-14. Mobile, automated</td>
</tr>
<tr>
<td>6-7. Modular CNC machine tool</td>
<td>11-16. Robotic</td>
</tr>
<tr>
<td>6-9. Modular flexible robot</td>
<td>12-1. Decoupling cell buffer</td>
</tr>
<tr>
<td>6-10. Autonomous industrial robot</td>
<td>12-2. No buffer between cells</td>
</tr>
<tr>
<td>6-11. Precision micro machining unit</td>
<td>12-3. No buffer between lines</td>
</tr>
<tr>
<td>6-12. Modular precision micro machining unit</td>
<td></td>
</tr>
<tr>
<td>6-13. Modular universal micro machining unit</td>
<td></td>
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</table>
Table 3: Primary Species-Defining characters and states for factual cladistic classification of discrete manufacturing systems

<table>
<thead>
<tr>
<th>Character States</th>
<th>Character States</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Product mix and order capability</strong></td>
<td><strong>7. Primary material handling (PMH) capability</strong></td>
</tr>
<tr>
<td>1-1. Multi-product capability</td>
<td>7-1. Manual/mechanised PMH</td>
</tr>
<tr>
<td>1-3. Single/mixed model product</td>
<td>7-3. Flexibly automated PMH system</td>
</tr>
<tr>
<td>1-4. Part-family</td>
<td><strong>8. Management capability</strong></td>
</tr>
<tr>
<td><strong>2. General layout approach</strong></td>
<td></td>
</tr>
<tr>
<td>2-1. Fixed position layout</td>
<td>8-1. Entrepreneurial</td>
</tr>
<tr>
<td>2-2. Process layout</td>
<td>8-2. Centralised non-routine task scheduling</td>
</tr>
<tr>
<td>2-4. Product layout</td>
<td>8-4. Inter-organisationally project</td>
</tr>
<tr>
<td>2-5. Virtual part-family layout</td>
<td>8-5. Agile project managed</td>
</tr>
<tr>
<td>2-6. Part-family layout</td>
<td>8-6. Functionally project managed</td>
</tr>
<tr>
<td><strong>3. Location of production</strong></td>
<td>8-7. Weak, cross-functional project</td>
</tr>
<tr>
<td>3-1. Covered dedicated facility</td>
<td>8-8. Strong, cross-functional project</td>
</tr>
<tr>
<td>3-2. Outside dedicated facility</td>
<td>8-9. Flexible cross-functional project</td>
</tr>
<tr>
<td>3-3. Remote location</td>
<td>8-10. Centralised routine resource scheduling</td>
</tr>
<tr>
<td>3-4. Site specific</td>
<td>8-11. Decentralised teams</td>
</tr>
<tr>
<td><strong>4. Process capability</strong></td>
<td>8-12. Decentralised cells</td>
</tr>
<tr>
<td>4-1. Limited universal processes</td>
<td></td>
</tr>
<tr>
<td>4-2. Extensive universal processes</td>
<td>9-1. Process based</td>
</tr>
<tr>
<td>4-3. Dedicated automated processes</td>
<td>9-2. Workstation based</td>
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<td>4-4. Dedicated industrial robots</td>
<td>9-3. Cell based</td>
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<tr>
<td>4-5. Limited modular universal processes</td>
<td>9-4. Autonomous industrial robots</td>
</tr>
<tr>
<td>4-6. Extensive modular universal processes</td>
<td>10-1. Cyclical</td>
</tr>
<tr>
<td>4-7. Limited universal, flexibly-automated</td>
<td>10-2. Unidirectional</td>
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<tr>
<td><strong>5. Operator capability</strong></td>
<td>10-4. Automated PMH type</td>
</tr>
<tr>
<td>5-1. Operator performs all processes</td>
<td>11-1. Intermittent</td>
</tr>
<tr>
<td>5-2. Operator performs significant tasks</td>
<td>11-2. Continuous: operator processes in motion</td>
</tr>
<tr>
<td>5-3. Operator performs significant processes</td>
<td>11-3. Continuous: operator removes and returns</td>
</tr>
<tr>
<td>5-4. Operator performs limited processes</td>
<td>11-4. Continuous: operator feeds other conveyor</td>
</tr>
<tr>
<td>5-5. Operator oversees processes</td>
<td>11-5. Continuous: operators walk with in-line cart</td>
</tr>
<tr>
<td>5-6. Operator performs product family processes</td>
<td>11-6. Continuous: operators ‘slide’ past others</td>
</tr>
<tr>
<td><strong>6. In-process work-in-progress</strong></td>
<td>11-7. Non-CNC bidirectional rotary index table</td>
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<tr>
<td>6-1. No buffer between processes</td>
<td>11-8. Continuous cycle with automated processes</td>
</tr>
<tr>
<td>6-2. Buffer between processes</td>
<td></td>
</tr>
<tr>
<td>6-4. In process buffer is removed</td>
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http://mc.manuscriptcentral.com/jmtm
Table 4: Primary, Variety-Defining Characters and States

<table>
<thead>
<tr>
<th>Character</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety</td>
<td>Primary, variety-defining characters and states</td>
</tr>
</tbody>
</table>

- **Primary Variety-Defining Characters**:
  - **Make-to-stock**: Production that waits for inventory to be made.
  - **Make-to-order**: Production that waits for orders to be made.
  - **Mix Model in Production Line**: Production that involves a mix of different models.
  - **Mix Product/Process Capability**: Production that involves a mix of different product and process capabilities.
  - **Mix Line Shape**: Production that involves a mix of different line shapes.
  - **Mix Machine Time**: Production that involves a mix of different machine times.
  - **Mix Production Line**: Production that involves a mix of different production lines.

- **Secondary Product Classes**:
  - **High-mix**: High variety of products.
  - **Medium-mix**: Medium variety of products.
  - **Low-mix**: Low variety of products.
  - **Very complex**: Very complex product mix.
  - **Complex**: Complex product mix.
  - **Moderate**: Moderate product mix.

- **Secondary System Classes**:
  - **High priority**: High priority for production.
  - **Medium priority**: Medium priority for production.
  - **Low priority**: Low priority for production.

- **Secondary Performance Data**:
  - **High availability**: High availability of system.
  - **Medium availability**: Medium availability of system.
  - **Low availability**: Low availability of system.

- **Secondary Personnel Data**:
  - **High capacity**: High capacity for production.
  - **Medium capacity**: Medium capacity for production.
  - **Low capacity**: Low capacity for production.

- **Secondary Material Data**:
  - **High inventory**: High inventory levels.
  - **Medium inventory**: Medium inventory levels.
  - **Low inventory**: Low inventory levels.

- **Secondary Machine Data**:
  - **High quality**: High quality of machine.
  - **Medium quality**: Medium quality of machine.
  - **Low quality**: Low quality of machine.

- **Secondary Schedule Data**:
  - **High scheduling effort**: High scheduling effort.
  - **Medium scheduling effort**: Medium scheduling effort.
  - **Low scheduling effort**: Low scheduling effort.

- **Secondary Control Data**:
  - **High control**: High control over the system.
  - **Medium control**: Medium control over the system.
  - **Low control**: Low control over the system.

- **Secondary Environment Data**:
  - **High environment**: High environment conditions.
  - **Medium environment**: Medium environment conditions.
  - **Low environment**: Low environment conditions.
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

- Single/Mixed Model Order, 222, 44%
- Part-Family Order, 145, 28%
- Multi-Product Order, 143, 28%
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.