

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.

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10 **Keywords:** Evolution, Organisational Systematics, Cladistic Classification, Linnaean
11 Classification, Manufacturing Cladistics, Discrete Manufacturing, manufacturing
12 development and change
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17 **1. Introduction to Organisational Systematics and Manufacturing** 18 **Cladistics and a novel application** 19

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21 McKelvey (1978: 1428) first introduced systematics to organisation science, as a
22 ‘necessary prerequisite to studies aiming to identify generalizable principles of
23 organisational function and process’ and that ‘organisation scientists have not
24 developed a widely accepted scheme of classifying observed differences among
25 organisations’. McCarthy (1995) echoed this in the field of production research
26 following a review of the dominant classifications and their limitations, which included
27 specific research biases, researcher subjectivity, inadequate units of analysis,
28 disconnection from other classifications, and a lack of recognition between entities,
29 classes and types.
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42 Systematics, composed of classification, taxonomy and evolution, is the science
43 of diversity (McKelvey 1978). A classification is meant to provide a simple and
44 generalised but authoritative representation of complex phenomena and is the basis for
45 communication and understanding (McCarthy 2005). Haas, Hall, and Johnson (1966)
46 argued that classifications help refine hypotheses, determine validity and utility based
47 on logical and intuitive reasoning, provide a basis for prediction, and specify
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3 populations from which samples could be drawn. Classification is both a process (i.e.,
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5 classifying) and a product (i.e., classification).
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8 Taxonomy, which, from ancient Greek, means method (-nomia) of arrangement
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10 (taxa), is the science of grouping and naming of phenomena on a basis of similarity or
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12 shared characteristics. The most notable pioneer in formal taxonomy was Linnaeus
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14 (1964 [1735]) who introduced a system of biological classification, arranged in a
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16 hierarchy of kingdom, class, order, genus, and variety. Taxa are grouped according to
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18 shared physical characteristics in the tradition of the phenetic school of classification.
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20 Here any physicality may be used, for example, phenetics in zoology, would compare
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22 bones, limbs, organs, etc.
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4 Darwin (1985 [1859]), in contrast, introduced a phylogenetic classification scheme
5 reflecting ancestor-descendent lineages that connect all living things from the origin of
6 species. This in turn led to two further schools of classification – the evolutionary and
7 cladistic – both of which provide methods and techniques that attempt to reconstruct the
8 phylogenetic history of any phenomena that evolves. The evolutionary school, despite
9 its name, recognises evolution but to a limited extent and relies still on some phenetic
10 influence. Cladistics on the other hand is a purist approach, based entirely on ancestor-
11 descendent relationships (Hennig 1966), and where physical similarity is consequential.
12 Cladistics is now considered to underlie the modern system of biological classification.
13 The outcome of a cladistic analysis is a cladogram (see figure 1), a branch and node
14 diagram (from ancient Greek: '*klados*' – '*branch*'). Data, in the form of characters and
15 states, are typically drawn from surviving taxa. This approach investigates the
16 evolutionary links between taxa, through characters and states, and studies common
17 ancestors.

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

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3 The manufacturing literature and manufacturing characters and states were
4 explored in order to assist in defining the discrete manufacturing systems as such. In the
5 hierarchical classifications discrete manufacturing systems are presented at the levels of
6 class, order, family, genus and species. At a more detailed level the cladistics
7 classification presents manufacturing species and their eventual shared character states.
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14 The system of hierarchical biological classification was originally described by
15 Carl Linnaeus in his book, *Systema Naturea* originally written in 1735 (Linnaeus,
16 1958). Here Linnaeus describes systematics as the scientific inquiry into biological
17 differences. The group into which organisms are placed are referred to as taxa (singular:
18 taxon). The taxa are arranged in a hierarchy. He grouped species according to shared
19 physical characteristic.
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27 The Linnaean hierarchy, however, has its disadvantages as it ranks groups of
28 organisms artificially into a hierarchy. By combining the **cladistics and hierarchical**
29 classifications a more comprehensive classification of a complex phenomenon is
30 ensured. The level above connects a group of Species. This connecting point is the
31 Genus of this group of Species. The characters shared by these Species are held by the
32 Genus. The level above that connects that group of Species to similar groups of Species.
33 The connecting point is the Family all these Species belong to. In that way more and
34 more Species belonging to the discrete manufacturing sector investigated are connected.
35 Thus the Linnaean hierarchy becomes extremely useful in the process of constructing a
36 phylogenetic tree of the phenomenon (discrete manufacturing sector) that is large and
37 very complex. It is an iterative process where the cladistics informs the Linnaean
38 hierarchy and vice versa. Therefore several “generations” of mutual phylogenetic and
39 Linnaean classifications would be developed.
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3 To achieve the above purpose, the paper sets out to review several published and
4 organizational systematics and cladistics papers, **discusses the observable and**
5 **evolutionary characteristics of manufacturing systems, and presents manufacturing**
6 **systems in way of layout.** Then the paper in the *Methodology* section; a) defines the
7 classification problem, b) determines the clade, c) selects, codes and orders characters
8 and states, and finally d) estimates phylogeny and creates the basis for constructing the
9 conceptual classification.
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19 Based on Popper's (1959) principle of falsification, the hypothesis arrived at
20 represented by the conceptual cladogram can be tested. This search for a better
21 approximation to truth is attempted in the section *Final Nomenclature and Construction*
22 *of the Factual Cladogram.* This is followed by presenting the *Preliminary results* which
23 includes the *Ancient manufacturing systems – the Out-Group* and the *Conceptual*
24 *classifications,* in the *Final results* the *Factual classifications* and the *Varieties of*
25 *Species* are presented. Thereafter the usefulness of the research is demonstrated in the
26 section *Practical Implications.*
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37 **2. State of the Art: A Critical Review and the evolutionary choice of** 38 **organisational development**

39 *2.1 The state of the Art*

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42 The capability of classifying several aggregations of manufacturing activity is the main
43 strength of manufacturing cladistics with studies conducted at the level of
44 **manufacturing** and assembly systems in both the automotive and hand-tool industries
45 (McCarthy et al. 1997, Leseure 2000, Rakotobe-Joel, McCarthy, and Tranfield 2002,
46 Allen, Strathern, and Baldwin 2007, Baldwin, Allen, and Ridgway 2010); at the level
47 aggregation above with both eco-industrial parks (Baldwin 2008) and supply chains
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2 within commercial aerospace (Rose-Anderssen et al. 2009, Rose-Anderssen, Baldwin,
3 and Ridgway 2011); as well as at the level of the manufactured artefact including
4 products (ElMaraghy, AlGeddawy, and Azab 2008a) and their associated assembly
5 layouts in view of delayed product differentiation (AlGeddawy and ElMaraghy 2010);
6 machine tools, their capabilities and product features that they produce (AlGeddawy
7 and ElMaraghy 2011b, a, 2012); and for organising product families, variants and
8 modularity (ElMaraghy and AlGeddawy 2012b).

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

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33 Incidentally, the first two hierarchical classifications of McKelvey (1978) and
34 McCarthy (1995) do not feature cladograms. It is also interesting to note that after these
35 first two studies, the cladistic analyses thereafter are sector specific. Indeed, McCarthy
36 (2005: 83) argues that 'classifications based on industry differentiation are widely used
37 and accepted and are difficult to ignore'. This counters the original organisational
38 systematics attempts of McKelvey (1978) and McCarthy (1995) to develop more
39 generic classifications and perhaps points to a limitation or a potential gap in
40 knowledge.

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51 A strength with regard to practicalities, is the classification's potential utilisation
52 as a 'blueprint' or 'recipe' and/or a system of benchmarking for extant manufacturing
53 systems (McCarthy 1995). The evolutionary relationships give an indication of the
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3 origin of all systems and also the distance and the difficulty of change required to go
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5 from one system to another. However, this potential has not been demonstrated beyond
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7 theory. That is, it remains at the level of conceptual presentation only. Leseure (2015),
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9 however, makes an expansion by producing a more factual classification.

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

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

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53 The inclusion of an out-group is a consistent omission in all studies. The out-
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55 group is an important methodological means as it acts as a reference point for deciding
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3 what and why to include or exclude in the group of phenomena under study. It is also
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5 another indicator of descendency and origin. An out-group should reference all
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7 ancestral characters and states, in their most primitive form, which in turn determine,
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9 using out-group comparison, to resolve the polarity (i.e., ancestor-descendent lineage)
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11 of all further characters and states. The first step in basic cladistics analysis is to
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13 determine which character states are plesiomorphic (primitive) and which are
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15 apomorphic (derived). In Out-Group comparison, if a taxon that is not a member of the
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17 group of organisms being classified has a character state that is the same as the
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19 organisms in the Out-Group, then that character state can be considered plesiomorphic
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21 (Lipscomb, 1998). The outside taxon is called the Out-Group and the organism being
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23 classified are the In-Group. The only way a homologous feature could be present in
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25 both an In-Group and an Out-Group would be for it to have been inherited by both
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27 groups from an ancestor older than the ancestor of just the In-Group.
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32 Whereas, previous manufacturing classifications presented the most primitive or
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34 ancient manufacturing form in the cladogram simply as Ancient Craft System
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36 (McCarthy et al, 1997, Leseure, 2001), Rose-Anderssen et al (2016) presents an Out-
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38 Group which represents Self-Production. This was based on their previous work on
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40 cladistics classification of Ancient Manufacturing Forms and Technologies (Rose-
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42 Anderssen et al, 2012).
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46 The treatment of characters differs between most of the studies. The use of
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48 individual characters is evident in studies by McCarthy et al. (1997), Baldwin (2008),
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50 and Rose-Anderssen et al. (2009) whereas Leseure (2000) is the first to experiment with
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52 multi-state characters although never exceeds three and most include a null state.
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54 Although multi-state character use is also a feature in the manufactured artefact studies,
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3 due to additional analytical methods that are employed these are then broken down into
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5 binary states.
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8 There are three further limitations associated with characters. The first is an
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10 inadequate character representation with taxa early in the cladogram. For example, the
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12 *Ancient Craft Systems*, of McCarthy et al. (1997) has no associated character; only one
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14 character is used to describe the first system in the studies of Leseure (2000), Rose-
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16 Anderssen et al. (2009) and all the manufactured artefact studies; and only two
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18 characters to describe the first system in Baldwin (2008). The second limitation is the
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20 haphazard numbering of characters, which in all studies seems to follow the order in
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22 which they were identified rather than any evolutionary significance or chronological
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24 introduction. This is perhaps illustrated by the automotive assembly plant example of
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26 McCarthy et al. (1997) in which three of the first six characters introduced are
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28 numbered 47, 48 and 50. The third limitation refers to one instance of character reversal
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30 and several instances of repeated character insertion (i.e., when one or more of the same
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32 characters feature again in the cladogram). For character reversal, see the ‘(-20)’ on the
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34 *Intensive Mass Producers* of McCarthy et al. (1997); this incidentally doesn’t require
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36 introduction or subsequent reversal as it would not affect the cladogram structure or
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38 evolutionary ‘story’, indeed it would increase the consistency of the analysis. Repeated
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40 character introductions reduce consistency and are a feature for all of the studies with
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42 the exception of Leseure (2000). This is perhaps due to either inappropriate character
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44 selection (i.e., evolutionary insignificant) or inappropriate system selection.
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50 A final limitation of the field is that most studies lack a validation step, which
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52 typically involves quantitative methods. Only Leseure (2000) has performed a full
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54 quantitative validation whereas Rose-Anderssen, Baldwin, and Ridgway (2011)
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56 employed semi-structured interviews for partial validation. However, in these studies,
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3 several common problems were experienced and lessons were learnt in research method
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5 design, which strongly informed the design taken in this study. These included:
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7 incomplete surveys (Leseure 2000); exaggeration of practices to appear operationally
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9 better (Leseure 2000, Rose-Anderssen, Baldwin, and Ridgway 2011); easily there could
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11 be misunderstanding of questions and their associated characters leading to potential
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13 misclassification (Leseure 2000, Rose-Anderssen, Baldwin, and Ridgway 2011);
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15 likewise misunderstanding of manufacturing system boundaries and the species
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17 definition again leading to potential misclassification (Rose-Anderssen, Baldwin, and
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19 Ridgway 2011); and, under- and over-representation of particular manufacturing
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21 systems (species in the clade) in the conceptual schema through random sampling
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23 procedures (Leseure 2000). In the work presented by Leseure (2015), there is a
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25 validation of the conceptual classification which is expanded to produce a more factual
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27 classification. However, in the work above by Rose-Anderssen et al (2011) what could
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29 lead to misunderstanding of questions, system boundaries and thus lead to
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31 misclassification was corrected during the interactive focus group interviews with the
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33 aim to collectively construct mutual meanings (Rose-Anderssen et al, 2010). The
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35 knowledge observed from this work enhanced the present method design of re-iterative
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37 steps for retrieving and validating data.
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43 The clear gap in knowledge between most current manufacturing cladistics in
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45 general and the one presented in this paper is the lack of: generic classification,
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47 presentation beyond theory, out-group comparison to resolve polarity of further
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49 characters and states, evolutionary significant / chronological numbering of states, and
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51 validation steps. Also, there is little consistency across studies related to the steps for
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53 constructing classification and cladograms.
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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

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3 genotypes that are made available for developing phenotypes in new situational
4 contexts. This explains the phenotype-genotype duality applied to manufacturing
5 change and evolution in practice. And this is the principle underlying the web-based
6 system in this paper.
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10 11 12 2.3 Manufacturing systems in way of layout 13

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15 At a general level, a manufacturing system is characterised by its layout system.
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17 Arguably there are four main basic manufacturing philosophies (Slack et al, 2006), each
18 of which are appropriate for different volume – variety combinations. These layouts are:
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20 fixed position, functional or process, cell or group technology, and the product layout.
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25 *Workshops* is a fixed position layout with a focus on a variety of products
26 (Alizon et al, 2009). *Project* environments follow a fixed position principle, designed to
27 accommodate one-off, special products (Mead and Sakis, 1999). A *Jobshop* can capture
28 situations with large difference in orders. The *Batch* process is implemented when
29 similar items in large volumes are to be made (Brown and Mitchell, 1911). A *Linked*
30 *Batch* approach capture the benefits of and hybridises both batch and line principles
31 (Hill, 2005). Similarly, a *Nagare* system is a virtual cellular system combining the setup
32 efficiency of cellular manufacturing systems with the routing of a job – and batch setup
33 (Kannan and Gosh, 1996). The idea of *Group Technology* or *Cell* layout is to gain for
34 batch production some of the advantages present in the higher volume line situation
35 (Das and Canel, 2005). *U-Lines* arrange machines around a U-shaped line, thus
36 extending the cellular principle. The idea is to encourage better communication and
37 interaction among workers (Mittenberg, 2001). *FMS* or flexible manufacturing system
38 includes; transformation system, automated material handling system, and computer
39 system in charge of planning and process (Tanquard and Martineau, 2001). Dawande et
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3 al (2005), and Brauner and Finke (2005) also talk about *Robotic cells*, where robots that
4 are placed centrally carry out transfers between machines. However, where quick
5 responses to unpredictable market changes are required, Bruccoleri et al (2006)
6 recommend *Reconfigurable manufacturing* systems. To capture the dynamic
7 characteristics of the manufacturing environment, Lee and Banerjee (2001) describe the
8 evolutionary steps of *Holonic* manufacturing systems. For accurate production of
9 microstructures, Son et al (2010) have described *Desktop* machinery, and Wulfsberg et
10 al (2001) *Square Foot* machinery concepts. Dolgui et al (2009) proposes a method for
11 dealing with the balancing problem for transfer machines with *Rotary* indexer tables.
12 *Unpaced assembly lines* are series of workstations with buffer storage between stations
13 (Smunt and Perkins, 1985). *Assembly lines* with equal cycle time of all workstations are
14 called *Paced* (Boysen et al, 2008). *Transfer lines* are mass production systems
15 consisting of automatic workstations arranged in a serial configuration and linked by
16 automatic transfer mechanisms (Dhoib et al, 2009)
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38 **3. Methodology**

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

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3 *species), but individual workstations, cells or plants, the latter being a relatively*
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5 *small system of workstations or cells.*
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8 3.2 Determine the Clade (Step 2)

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10 A clade is a monophyletic taxon (plural: taxa); that is, a group that consists of all the
11 potential manufacturing systems under study, along with the common and most recent
12 ancestors. Candidate manufacturing systems were collected from a variety of sources
13 including: a) traditional manufacturing system classification studies previously
14 reviewed; b) the cladistic analyses reviewed in this paper, where appropriate; and, c)
15 literature concerning individual manufacturing systems, a sample of which is listed in
16 table 1.
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31 3.3 Selecting, Coding and Ordering Characters and States (Steps 3, 4 & 5)

32 A character is any variable, feature or attribute, which forms the basis for classificatory
33 significance. Taxonomic characters perform two functions: firstly, they have a
34 diagnostic aspect uniquely specifying a given taxon and an emphasis on the
35 differentiating properties of taxa is particularly strong at the level of lower categories
36 (McKelvey 1978); and, secondly, they function as indicators of relationships; a property
37 that makes them especially useful in the study of the higher taxa. The character
38 selection is a manual process involving secondary data (i.e., literature, company
39 records, annual reports, and technical data such as layout plans, control/scheduling
40 strategies, etc.).
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54 Candidate characters are considered and then rejected if they are irrelevant or if
55 they create 'noise' in the data table (Leseure 2000, McCarthy et al. 2000). Qualitative
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3 methods, such as observations, field visits, and interviews and discussions with key
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5 personnel, were also implemented. Initially, 210 characters and 817 possible states were
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7 identified from the literature. The development of the conceptual cladogram proceeded
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9 through several iterations where these characters and states were re-examined and
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11 refined so that manufacturing system evolution could be described in the final
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13 conceptual cladistic classification by twelve multi-state characters (see Table 1). This
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15 involved systematic coding of categories identified. When these categories could not be
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17 developed any further from the literature, it was decided a saturation of categories had
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19 been reached. Subjectivity played a role in each of the 8 steps of constructing a
20
21 cladistics classification and not limited to the definition of manufacturing systems; the
22
23 selection of candidate manufacturing systems and Species; the selection of characters
24
25 and states; the grouping of states under characters; the ordering of states within
26
27 characters; the emphasis or weighing of one character over another; and the decision
28
29 over whether characters are either primary species-Defining, Variety-Defining, or
30
31 secondary product, process and systems characters. In this research, there were 4
32
33 generations of iterations of conceptual classification work and refinement.
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37 [Table 2 Here]
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41 Numbering characters, helps with both ordering and decisions concerning whether they
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43 exist in the forms of organisation under study (Leseure 2000). This is a trial and error
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45 process where characters are continuously compared, recoded and/or rejected. Different
46
47 states for each character are proposed and an indication given of what species possess
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49 which state. When this cannot be developed any further, a saturation of categories has
50
51 been reached. The character itself is shown in the list of characters relevant to the clade.
52
53 Each character is then shown with its primitive (1) and derived (2, 3...*n*) states. It is
54
55 important to note here that states are numbered in this study according to their estimated
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3 appearance in the evolutionary scheme and have both an additive and discontinuous
4 nature. With discontinuous state evolution, one state does not necessarily follow, in
5 evolutionary terms, the one numbered before. That is, the states within characters also
6 follow a similar evolutionary pattern and can branch off as shown with the character in
7 Figure 2. In this example, evolution diverges at state 2 leading down one path to states 3
8 and 4 and down the other path to states 5 and 6. A change in character state signifies an
9 evolutionary step.

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17 [Figure 2 Here]

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23 *3.4 Estimating Phylogeny, and the basis for Constructing the Conceptual*
24 *Cladograms and Proposed Nomenclature (Step 6 and 7a)*

25
26
27 Cladograms are constructed by grouping species that share a common root and
28 evolutionary history. The total number of character-state changes necessary to support
29 the relationship for the species in a cladogram describes the tree length (McCarthy and
30 Ridgway 2000). The Principle of Parsimony states that the cladogram with the shortest
31 length i.e., with fewer analogous character-states present, is considered to be the ‘best-
32 fit’ or most parsimonious tree (McCarthy 2005). Cladograms may be constructed
33 manually or through dedicated software such as MacClade: Analysis of Phylogeny and
34 Character Evolution (Maddison and Maddison 2003), used in this research. This helps
35 to quickly produce candidate cladograms, and offer manipulation tools, in which
36 characters and their states can be ordered, weighted and traced; all of which help
37 construct the most parsimonious and logical phylogeny of the clade.

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52 The naming of the manufacturing systems, which should conform to the
53 principles of biological nomenclature, is proposed during this conceptual stage and
54 finalised during the next factual stage. In short, names should convey the essence of the

1
2
3 entity and typically their main character(s), be unambiguous, and ensure universal
4
5 communication (McCarthy et al. 1997). Although in the Linnaean tradition, each
6
7 species is given a binomial Latinised name relating to the species and the genus it
8
9 belongs to, in this study, and to convey understanding, an Anglicised polynomial
10
11 system, consistent with previous manufacturing cladistics studies, is preferred and used.
12
13 The aim is also to use names that are understandable to practitioners and academics
14
15 alike. However, as up to two words are used in genus naming and up to four words in
16
17 the species, the genus term, when referring to species, is all capitalised.
18
19
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21 *3.5 Final Nomenclature and the basis for construction of the Factual Cladogram* 22 *(Step 7b & 8)*

23
24
25 This step largely involves contemporary organisations (i.e., specimens of species), and
26
27 is more quantitative in nature (Leseure 2000, 2015), i.e., surveying a representative
28
29 sample of species and the specimens within. The aim is to test the hypotheses inherent
30
31 in the conceptual cladogram. Any conflicts are then resolved leading to a full factual
32
33 cladogram (McCarthy et al. 2000). The approximation to truth is increased through the
34
35 mixed-method triangulation approach employed involving three steps in research
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37 methods (Jick 1979).
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41
42 In a true Popperian tradition, further hypothesis testing, in order to develop
43
44 theory, was conducted through observing manufacturing systems. This was applied in
45
46 order to try and substantiate the theory so far in terms of the conceptual classification.
47
48 Quantitative data, based on 510 manufacturing systems operating in 153 manufacturing
49
50 companies, representing a very good spread of both discrete manufacturing sectors and
51
52 size, were collected through various data collection and sampling methods and catering
53
54 for the lessons learnt from previous factual cladistic analyses. **Utilising convenience (or**
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3 opportunity) sampling, the first companies surveyed were collaborators on a large
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5 European project. This then extended to other willing companies on other European
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7 projects along with local UK companies that collaborate with our research centre and
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9 university. Chain-referral (or snowball) sampling was then employed in which already
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11 participating companies along with other project collaborators introduced other willing
12
13 companies. Finally, focus samples were used to actively seek out specimens in
14
15 underrepresented species. The research team observed the various manufacturing
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17 systems (between 1 and 9 systems) in operation at these companies.
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22 A survey was completed for each manufacturing system based on the
23
24 observation of manufacturing system features. The survey was made up of items
25
26 representing both the species-defining and variety-defining characters and states of the
27
28 final conceptual cladogram. Additional problems anticipated with this specific cladistic
29
30 study, which also strongly influenced the data collection and sampling methods,
31
32 included other potential species and other potential characters and states not included in
33
34 the conceptual classifications, and the potential reliance on characters and states in the
35
36 conceptual classification which are not evolutionary significant and thus misleading.
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38

39
40 A preliminary clean-up and analysis of data was conducted, which involved an
41
42 evaluation of useful responses, identification of anomalies in the dataset, and the
43
44 generation of descriptive statistics using statistical analysis software to provide an
45
46 overview of the dataset. The clean data were again subjected to a cladistic analysis
47
48 using MacClade software (Maddison and Maddison 2003) to generate candidate
49
50 cladograms. A period of evaluation followed with the aim of producing the most
51
52 consistent cladogram.
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55 4. Preliminary results 56 57 58 59 60

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

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2
3 working on it. This is his *secondary material handling*. Based on these findings we have
4
5 suggested the following Out-Group character states:

- 6 1-1 Fixed position layout
- 7
- 8 2-1 Covered dedicated facility
- 9
- 10 3-1 Single universal process
- 11
- 12 4-1 Operator performs all processes
- 13
- 14 5-1 No buffer between processes
- 15
- 16 6-1 Manual / hand tool
- 17
- 18 7-1 Manual / mechanised primary material handling system
- 19
- 20 8-1 Manual / mechanised secondary material handling system
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28 4.2 The species

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31 Of the 510 manufacturing systems (specimens), 46 specimens proved difficult to
32
33 classify under the conceptual classifications. Of the 46, 20 represented 3 additional
34
35 potential species, newly named as the *PRODUCT CENTRED Assembly Plant*, the *FIXED*
36
37 *Automated Rotary Indexer*, and the *ROBOT Sequenced Cell-Based Line*, belonging in
38
39 the *PRODUCT CENTRED*, *TRANSFER* and *ROBOT* genera, respectively (note: the genus
40
41 names are according to the conceptual classifications).
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44
45 The other 26 systems and potential species represented a potential partitioning of an
46
47 existing species. Two species in particular were in question: the *PROJECT Matrix* and
48
49 the *UNPACED Asynchronous*. The *Matrix* species differed significantly in the project
50
51 manager's power over the resources needed for particular projects; some project
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53 managers had very little power, others had appropriate power, and yet others had
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55 power plus a high degree of flexibility in their deployment. This resulted in the
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1
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3 formation of three newer and more adequately described species from the one
4
5 *Matrix* species: the *Weak Matrix Project*, *Strong Matrix Project* and the *Flexible*
6
7 *Matrix Project*. This introduction of three instead of one species, also held questions
8
9 and opportunities at the genus level to differentiate between the groups. Therefore,
10
11 the original *PROJECT* genus has been partitioned into the *REMOTE* and
12
13 *ORGANISATIONAL* genera, to represent the nature and location and the projects.

14
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16 The specimens collected questioned a second species, the *UNPACED Asynchronous*,
17
18 which also differed significantly in the configuration of the line. Some had a process
19
20 layout which acted as one entire line, others were configured around independent
21
22 workstations formed in a line, whilst others, were configured around cells. This
23
24 again resulted in the formation of three newer and more adequately described
25
26 species from the one *UNPACED Asynchronous*: the *UNPACED Process-Based Line*,
27
28 the *UNPACED Asynchronous Workstationed Line* and the *UNPACED Asynchronous*
29
30 *Cell-Based Line*.

31
32
33 Inconsistencies surrounding the characters and states also offered an opportunity for
34
35 refinement. The first problem rectified and which was separate from this
36
37 quantitative study, was that there were no relevant character to represent the order
38
39 level. Therefore the character 'Product Mix and Order Capability' was introduced
40
41 (now Character 1). An additional 2 states were added to what is now the 2nd
42
43 character 'General Layout Approach': virtual product layout (CS 2-3) and virtual
44
45 part-family layout (CS 2-5), which more adequately described both the *SCALE*
46
47 *Linked Batch* and *SCALE Nagare*, respectively. Two additional states were added to
48
49 character 3 'Location of Production' to reflect and differentiate between the new
50
51 *Project* species. This also offered another opportunity to combine two characters –
52
53 that of Management Style and Project Management Type under one renamed
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3 character 'Management Capability'. The last major change to the characters related
4
5 to the intention to differentiate between dedicated and flexible material handling
6
7 types (see Characters 11 and 13 in 3).

8
9 More generally, several characters and states were renamed to more adequately
10
11 describe the species which can be seen when comparing Table 2 and Table 3.

12
13 Similar refinement was also made in terms of the naming of orders, families, genera
14
15 and species and can be seen when comparing Figure 4 and Figure 9.

16
17 With the data now aligned to the classifications, in terms of the above initial
18
19 refinements, the spread specimens between orders (see Figure 5), families (see
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21 Figure 7), and genera (see Figure 7) can be seen. This spread was achieved from a
22
23 combination of convenience sampling first, then combined with both the 'snow-ball'
24
25 sampling (making enquiries to already collected participants about further potential
26
27 participants) and focussed sampling. This latter technique involves actively seeking
28
29 out specimens in under- or non-represented genera and species.
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33 5 [Figure 5 Here]

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35 6 [Figure 6 Here]

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37 7 [Figure 7 Here]

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40 At the level of the order, all three are represented adequately with the Single/Mixed
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42 Model order accounting for the highest number of specimens (i.e., 222). There is
43
44 also a very good representation at the level of the family with an average of 85 and
45
46 range of 56 and 120 specimens. In terms of the level of the genera, two genera in
47
48 particular suffer from under-representation: the *REMOTE* and the *MINIATURE*. The
49
50 first is perhaps due to the re-classification and partitioning of the old *PROJECT* genus
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52 into two new genera – the *REMOTE* and *ORGANISATIONAL*; and, the re-classification
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54 and partitioning of the old *Matrix Project* species into three new species: the *Weak*
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3 *Matrix Project, Strong Matrix Project* and the *Flexible Matrix Project*. These are
4 discussed and justified above. The second genus, the *MINIATURE*, is arguably due to
5 the species' recency.
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9 There are several notable points to be made concerning the spread at the species
10 level and representation of these with the specimens collected. Firstly, the average
11 representation of species is just under 10 specimens, with 18 species having more
12 than this. Secondly, 4 of the 53 species are represented by 30 or more specimens
13 with the highest representation belonging to the *FIXED Cycle Transfer* with 87
14 Species. Thirdly, 20 of the species are represented by only 5 or less specimens, with
15 the *MINIATURE Square Foot* only represented by one specimen. This last point can
16 be seen as a weakness of this factual classification and thus more research and data
17 collection, using the focussed sampling technique, is needed. Arguably, 100
18 specimens per species would increase confidence above any doubt.
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32 Two main candidate factual cladograms emerged in this work, which differed at the
33 order level with Candidate A (the eventual final candidate) having an emphasis
34 more on both the Product Mix and Order Capability (character 1) and General
35 Layout Approach (character 2), whereas Candidate B emphasised Process
36 Capability (character 4) and Primary Material Handling Capability (character 7). In
37 order to select the final candidate two measures are used – tree length (Principle of
38 Parsimony) and a consistency index (CI) score. The length of a tree is the total
39 number of character state changes necessary to support the relationship of the
40 configurations in the cladogram. Thus, the tree with the minimum length is
41 considered to have fewer instances of character re-introduction and as a
42 consequence is the best-fit tree. The CI serves to measure the relative degree of
43 inconsistency in a cladogram and the level of difficulty in fitting a given data set to
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3 a given tree. The CI is calculated with the following formula: $CI = M/S$; where M is
4 the total number of character changes expected, given the data set and where S is the
5 actual number of changes that occur in the tree. Candidate A had a tree length of 87
6 (the minimum) and a CI score of 1 (perfect fit), whereas Candidate B had a tree
7 length of 96 and a CI score of 0.915. Given both the tree length and consistency
8 index scores, Candidate A is the most likely candidate.
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20 4.2 The conceptual classification

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

31
32 (Figure 4 here)

33 5 Final results

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

49 [Table 3 Here]

50 [Figure 9 Here]

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3 In general, we have defined our Species by a single character state distinguishing it
4 from its sister Species, however, sharing character states with the Species of the same
5 Genus. As such these sister Species are Varieties within the same Genus. The greatest
6 innovation by Linnaeus was the general use of binominal nomenclature. That is the
7 combination of a Genus name and a second term to identify the Species. This research
8 has proposed Varieties of all the Species of the classification. Basically, what
9 distinguishes one Sister Species from another in Figure 8 is one character state.
10 However, in the research Varieties add to the potential of more character states that can
11 distinguish between Sister Species. These are grouped together due to a recent
12 evolutionary split. Due to the space limitations of the paper, the example presented is of
13 the first Species of the Product Centred Genus, namely the hierarchical classification of
14 the Product Centred Workshop (see Figure 10).

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29 (Figure 10 Here)

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60 (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

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3 This work underlies a web-based expert system for automating the identification,
4 diagnosis and improvement of manufacturing systems and complements a larger
5 software system architecture of the research project, which simplifies and makes
6 accessible essential modelling tools for the rapid design, simulation and virtual
7 prototyping of factories.
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14 Figure 11 is a screenshot of the identification and diagnostics web-based tool
15 based on the factual classifications. The classifications are then used to reveal the
16 change process that connects the development of processes and technologies, to their
17 overarching manufacturing system, and can be used as a benchmarking tool that enable
18 users to view manufacturing systems in an evolutionary landscape, gauge performance,
19 and identify strategies and tools for improvement.
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26 [Figure 11 Here]
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30 An additional practical use is in an educational context. The cladistic
31 classification not only sheds light on the possible origin of manufacturing and its
32 historical development (see Box 1 for an example of how to ‘read’ the cladogram), but
33 also offers a tool to both compare and contrast similarities and dissimilarities, and gauge
34 the ‘distance’ and the relative difficulty of change required to transform from one
35 system to another. Relationships between manufacturing systems are evident not just at
36 the manufacturing system level with the cladistic classification, but also at the genus,
37 family and order level when referring to the hierarchical classification. The promise of
38 the ‘blueprint’ or ‘recipe’ for a manufacturing system, with which to benchmark is now
39 much more evident.
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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

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2
3 emerge in the data coverage, i.e., the spread of the 510 specimens between orders,
4
5 families, genera and species. Although there was good specimen representation of
6
7 manufacturing systems at the order and family levels, the genera (particularly the
8
9 *REMOTE* and the *MINIATURE*) and species levels were less equal (with the *MINIATURE*
10
11 *Square Foot* only represented by one specimen). This problem is in part exacerbated
12
13 firstly by the reclassification process from the conceptual to the factual at the genera
14
15 level, and to the relative recency of some of the species. Arguably, future work should
16
17 consider at least 100 specimens per species, which would increase confidence above
18
19 any doubt.
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23 Additional limitations must also be highlighted. The very nature of classification
24
25 work, particularly in the social sciences, is inherently subjective. Despite claims to the
26
27 contrary by McCarthy (1995), subjectivity plays a role in each of the procedural steps of
28
29 constructing a cladistic classification. The definition of a manufacturing system
30
31 (Leseure 2000) was not an easy process and although most work on this was performed
32
33 during the first iteration there were refinements made throughout the iterations. The
34
35 most difficult problem here was to achieve the most appropriate level of granularity. For
36
37 example, should the focus be on the entire manufacturing company, which could
38
39 include several manufacturing sites, or on a single factory or on a factory sub-system?
40
41 Or should it relate to a product, part or component and a stage of production? The
42
43 outcome attempted to cater to all of these and could include a company with one
44
45 'factory' making one product or to a subsystem of a factory of a multi-factory company.
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50 A further limitation, when compared to biological classifications, is that the
51
52 species concept should be related to reproductive isolation, which in relation to
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54 manufacturing systems equates to the sharing of information and practices through
55
56 people (McKelvey 1978). It is possible that the manufacturing systems at the species
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3 level in this scheme are just varieties and perhaps the species level should be what is the
4 class (e.g., discrete manufacturing) or perhaps higher (e.g., the manufacturing sector).

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6
7 Additional challenges included deciding what to include and exclude as a species in the
8 clade, what should be treated at a higher level of aggregation (genus, family, etc.), and
9 what to treat as a variety (McKelvey 1975). This challenge is highlighted not only by
10 the variation in species numbers included throughout the classification iterations, but
11 also, the final number of varieties (which totalled 1,586, and beyond the scope of this
12 paper). Clear delineations and boundaries are needed in future work to definitively
13 justify not only a species but also a variety, genus, family, order, etc.
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23 There are also challenges concerned with the selection of appropriate characters
24 and states; the grouping of states under characters; the ordering of states within
25 characters; the emphasis or weighting of one character over another; and, the decision
26 over whether characters are either primary species-defining, variety-defining, or
27 secondary characters, all of which are a matter of subjectivity. Furthermore, both
28 candidate cladograms should be seen in the 'light of subjectivity'. Thus, one drastic
29 change would be to attempt a re-description and weighting of characters and states in
30 favour of and emphasising, in candidate B's case, process capability and primary
31 material handling capability.
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44 *6.2 Conclusions*

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46 The paper set out to:

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

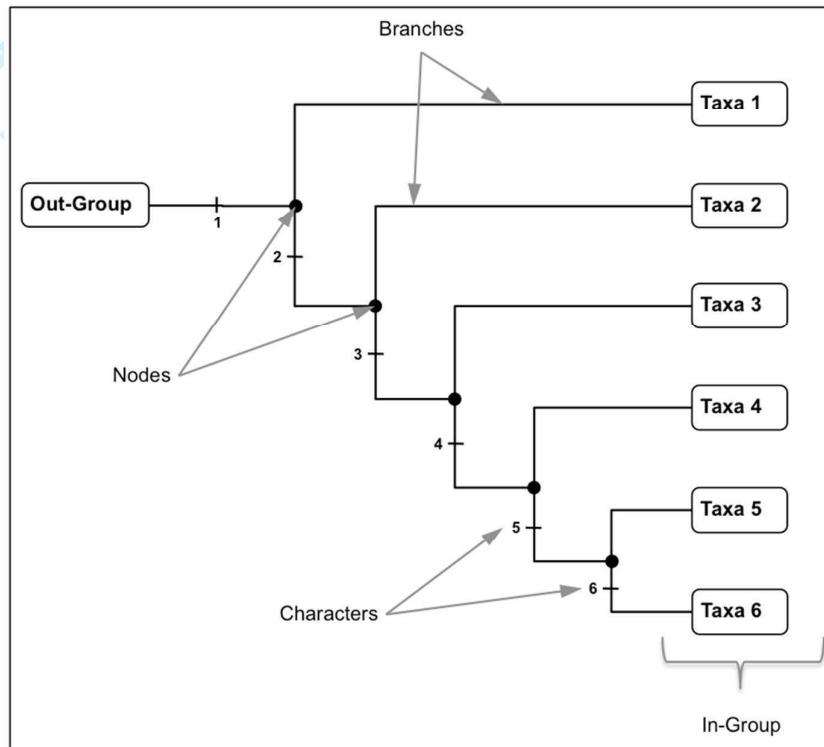
Character States	Character States
1. Product mix and order capability	7. Primary material handling (PMH) capability
1-1. Multi-product capability	7-1. Manual/mechanised PMH
1-2. Multi-product and multi-order capability	7-2. Automated PMH system
1-3. Single/mixed model product	7-3. Flexibly automated 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	U/L Line Layout	SECONDARY PRODUCT C&SS	SECONDARY PROCESS C&SS	SECONDARY SYSTEM C&SS
14 Specific Order Type	22-1 Multi-lined single U	25 Order Volume	30-1 High priority	41 Raw Materials Inventory
14-1 Make-to-order	22-2 Embedded U	25-1 One	30-2 Medium priority	41-1 Low
14-2 Make-to-stock	22-3 Double dependent U	25-2 Low	30-3 Low priority	41-2 Moderate
14-3 Engineer-to-order	22-4 Figure 8	25-3 High	31-1 Compete on Development Speed (NPI)	41-3 High
14-4 Assembly/configure-to-order	23 Ladder Layout	25-4 Very high	31-1 High priority	42 WIP Inventory
14-5 Assemble-to-stock	23-1 Double rung	25-5 Very high	31-2 Medium priority	42-1 Low
15 Universal Process Capability	23-2 Triple rung	26 Product Variety	31-3 Low priority	42-2 Moderate
15-1 Manual and/or hand/power tool	23-3 Multi rung	26-1 Unique	32 SECONDARY PROCESS C&SS	42-3 High
15-2 Mechanised machine tool	24 Robot Centred Layout	26-2 High	32 Machine Mobility	43-1 Low
15-3 CNC machine tool/centre	24-1 Line	26-3 Medium	32-1 Fully mobile	43-2 Moderate
16 Modular Universal Process Capability	24-2 Double Line	26-4 Low	32-2 Temporarily fixed	43-3 High
16-1 Modular mechanised machine tool	24-3 Rectangle	26-5 Very low	32-3 Permanently fixed	44 Definition of Capacity
16-2 (primarily)	24-4 Circular	27 Standard/custom	33 Process Flexibility	44-1 Well-defined
17 Product Centred Layout	24-5 L-form	27-1 Non-standard	33-1 Flexible	44-2 Moderately defined
17-1 Standalone production	24-6 U-form	27-2 Standard	33-2 Semi-flexible	45 Compete on Production Cost
17-2 Parallel production	24-7 Matrix	27-3 Customised	33-3 Inflexible	45-1 Low priority
18 Shop Layout		27-4 Mass customised	34 Process Change Ability	45-2 Medium priority
18-1 Standalone shop		27-5 Competitive on Product Cost	34-1 High	45-3 High priority
18-2 Parallel shops		28 Compete on Product Consistent	34-2 Medium flexible	46 Compete on Consistent Production Quality
19 Product Line Layout		28-1 Low priority	34-3 Low	46-1 Low priority
19-1 Space constrained		28-2 Medium priority	35 New Process Introduction Ability	46-2 Medium priority
19-2 Line shape		28-3 High priority	35-1 High	46-3 High priority
19-3 U-shape		29 Quality	35-2 Medium flexible	47 Compete on Fast Delivery Time
19-4 S-shape		29-1 Low priority	35-3 Low	47-1 Low priority
19-5 Serpentine		29-2 Medium priority	36 Number of bottlenecks	47-2 Medium priority
19-6 Segmented L		29-3 High priority	36-1 Key process	47-3 High priority
19-7 Segmented U		29-4 Daily Scheduling Difficulty	36-2 Few	48 Compete on On-Time Delivery
19-8 Rectangle		30 Compete on Performance Design	36-3 None	48-1 Low priority
19-9 Loop		30-1 High priority	37 Nature of bottlenecks	48-2 Medium priority
20 Product Line Configuration		30-2 Medium priority	37-1 Fixed (short and medium term)	48-3 High priority
20-1 Standalone line		30-3 Low priority	37-2 Moveable	49 Compete on Volume Flexibility
20-2 Parallel line		31 Machine Mobility	38 Number of Setups	49-1 Low priority
20-3 Sub-cell line		31-1 Fully mobile	38-1 High	49-2 Medium priority
20-4 Multi-sub-cell line		31-2 Temporarily fixed	38-2 Moderate	50 Compete on Customisation (one-offs)
20-5 Sub-line line		31-3 Permanently fixed	38-3 Low	50-1 High priority
20-6 Multi-sub-line line		32 Process Flexibility	39 Cost of Setups	50-2 Medium priority
20-7 Parallel sub-cell line		32-1 Flexible	39-1 Low	51 Compete on Mass Customisation
20-8 Parallel multi-sub-cell line		32-2 Semi-flexible	39-2 Moderate	51-1 Low priority
20-9 Parallel sub-line line		32-3 Inflexible	39-3 High	51-2 Medium priority
20-10 Parallel multi-sub-line line		33 Process Change Ability	40 Daily Scheduling Difficulty	51-3 High priority
21 Cell Layout		33-1 Flexible	40-1 Easy	52 Unique Selling Point
21-1 Chase U		33-2 Semi-flexible	40-2 Complex	52-1 High priority
21-2 Chase shared X		33-3 Inflexible	40-3 Very complex	52-2 Product
21-3 Zonal U		34 Process Change Ability	40-4 Moderate	
21-4 Zonal S		34-1 High		
21-5 Zonal M		34-2 Medium flexible		
21-6 Split U		35 New Process Introduction Ability		
21-7 Split Y		35-1 High		

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Figure 1: Illustrative cladogram



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Figure 2: Character evolution and state numbering

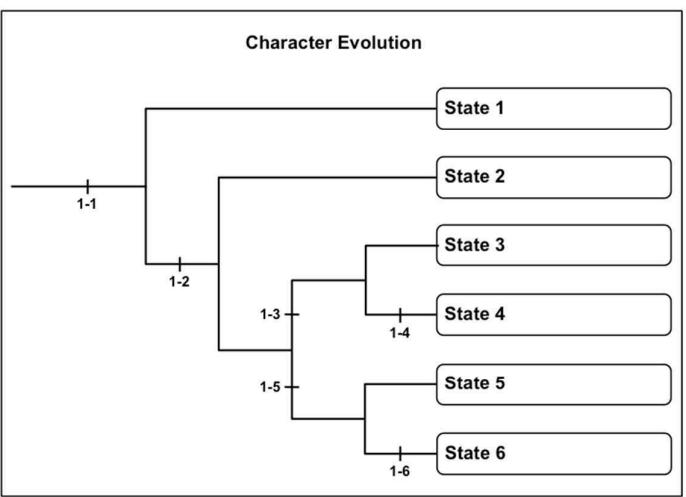


Figure 3: Conceptual cladistic classification of discrete manufacturing systems (see Table for the characters and states)

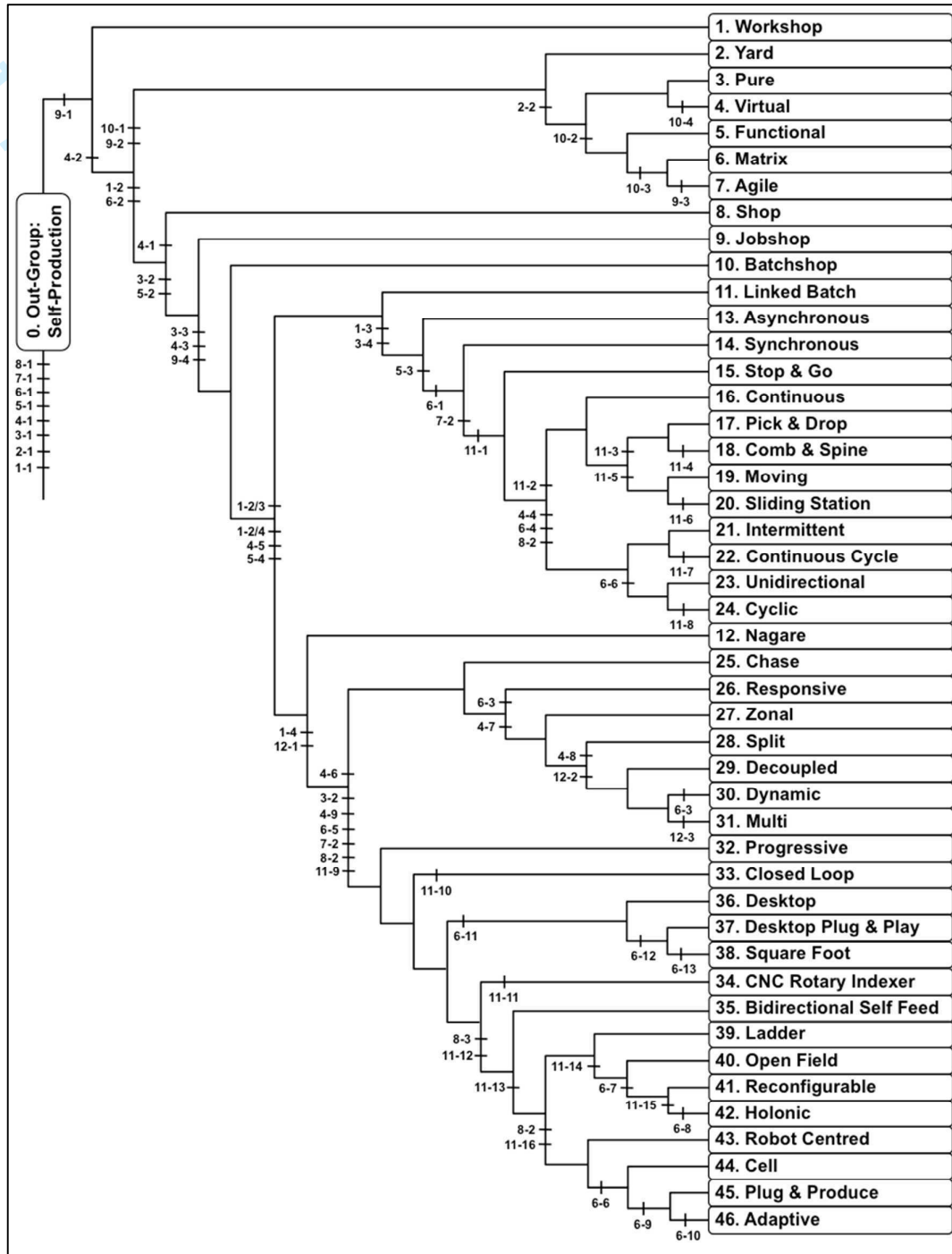


Figure 4: Conceptual hierarchical classification of discrete manufacturing systems

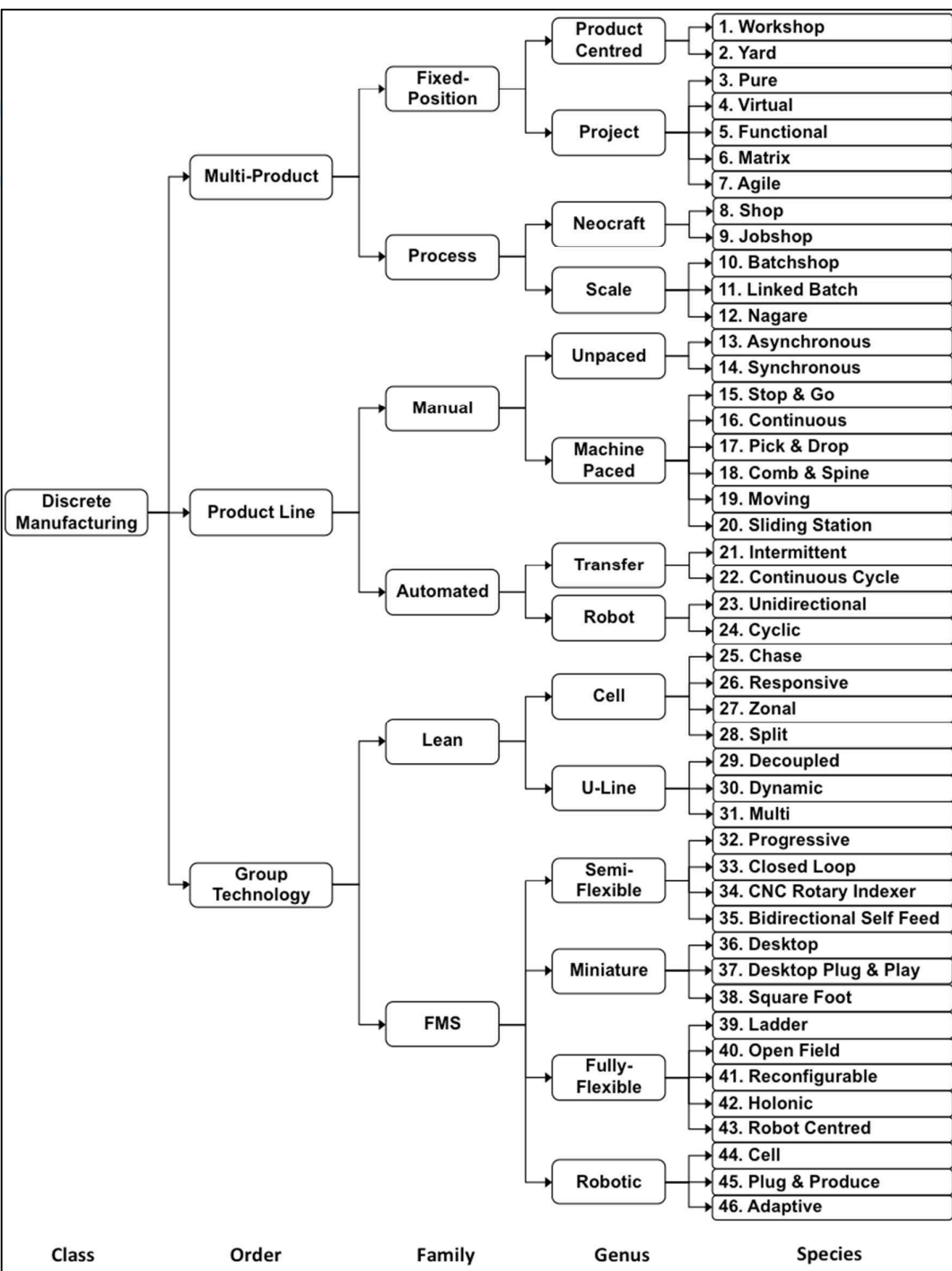
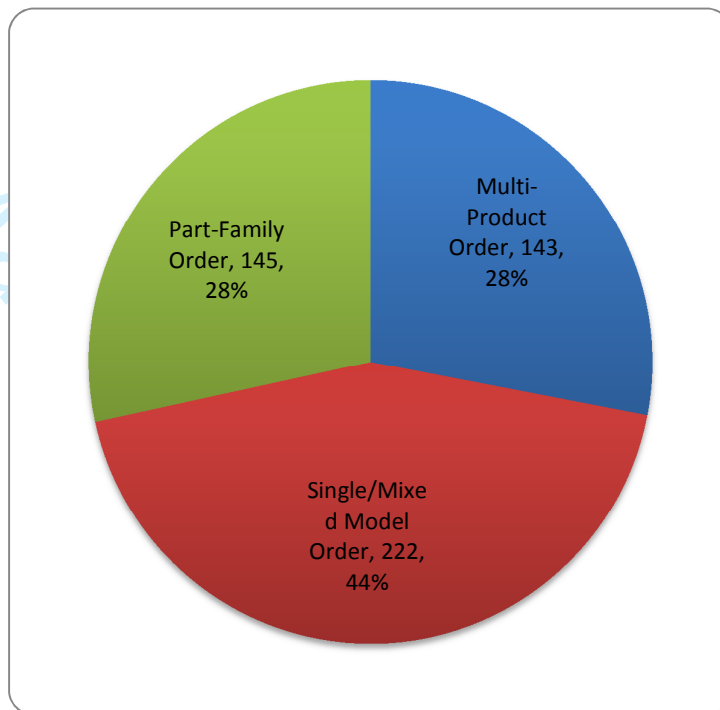


Figure 5: Number of manufacturing systems within each order



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Figure 6: Number of manufacturing systems within each family

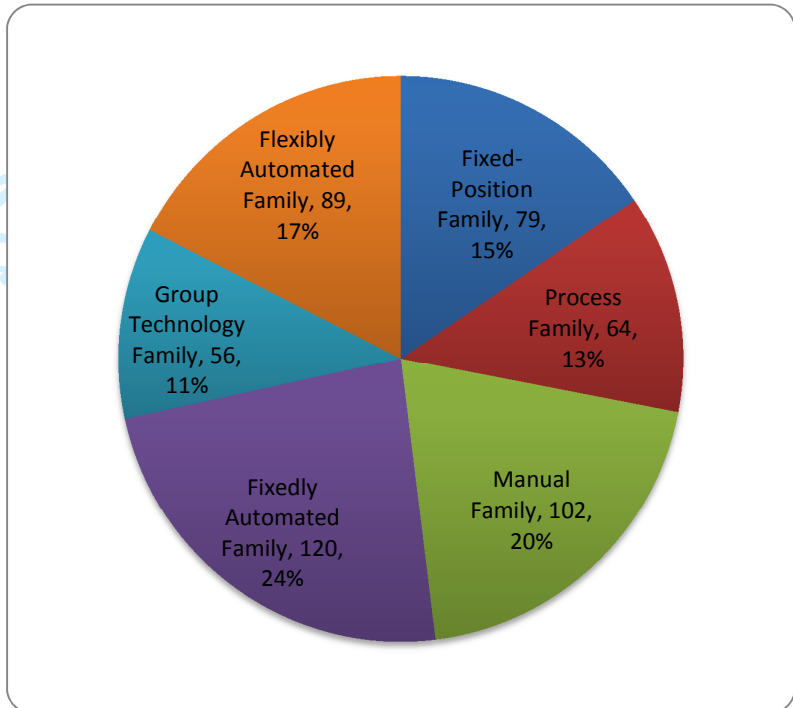


Figure 7: Number of manufacturing systems within each genus

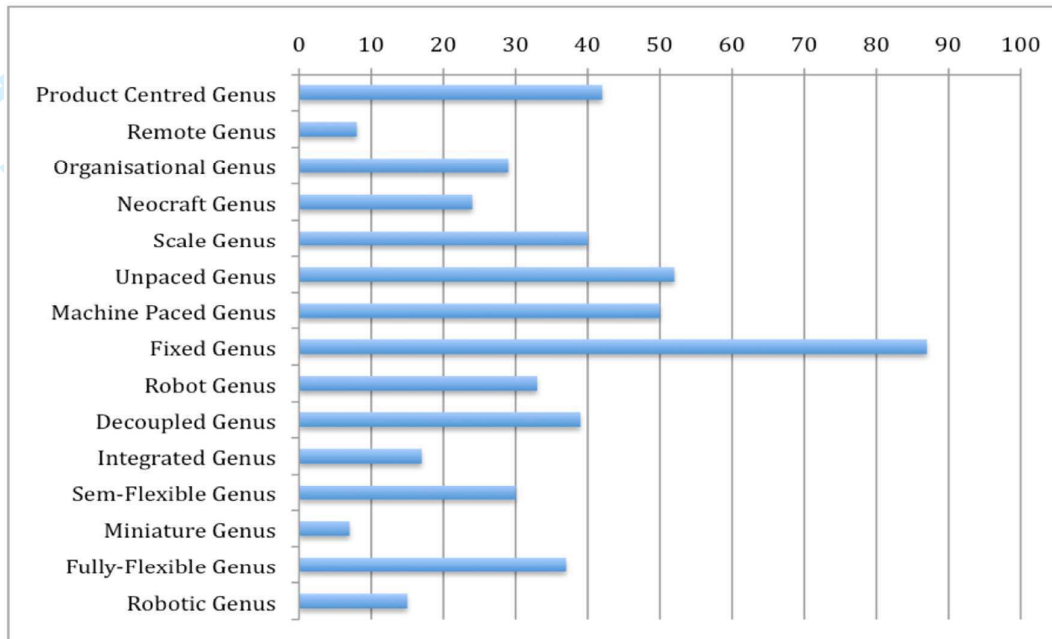


Figure 8: Factual cladistic classification of discrete manufacturing systems (see Table for the characters and states)

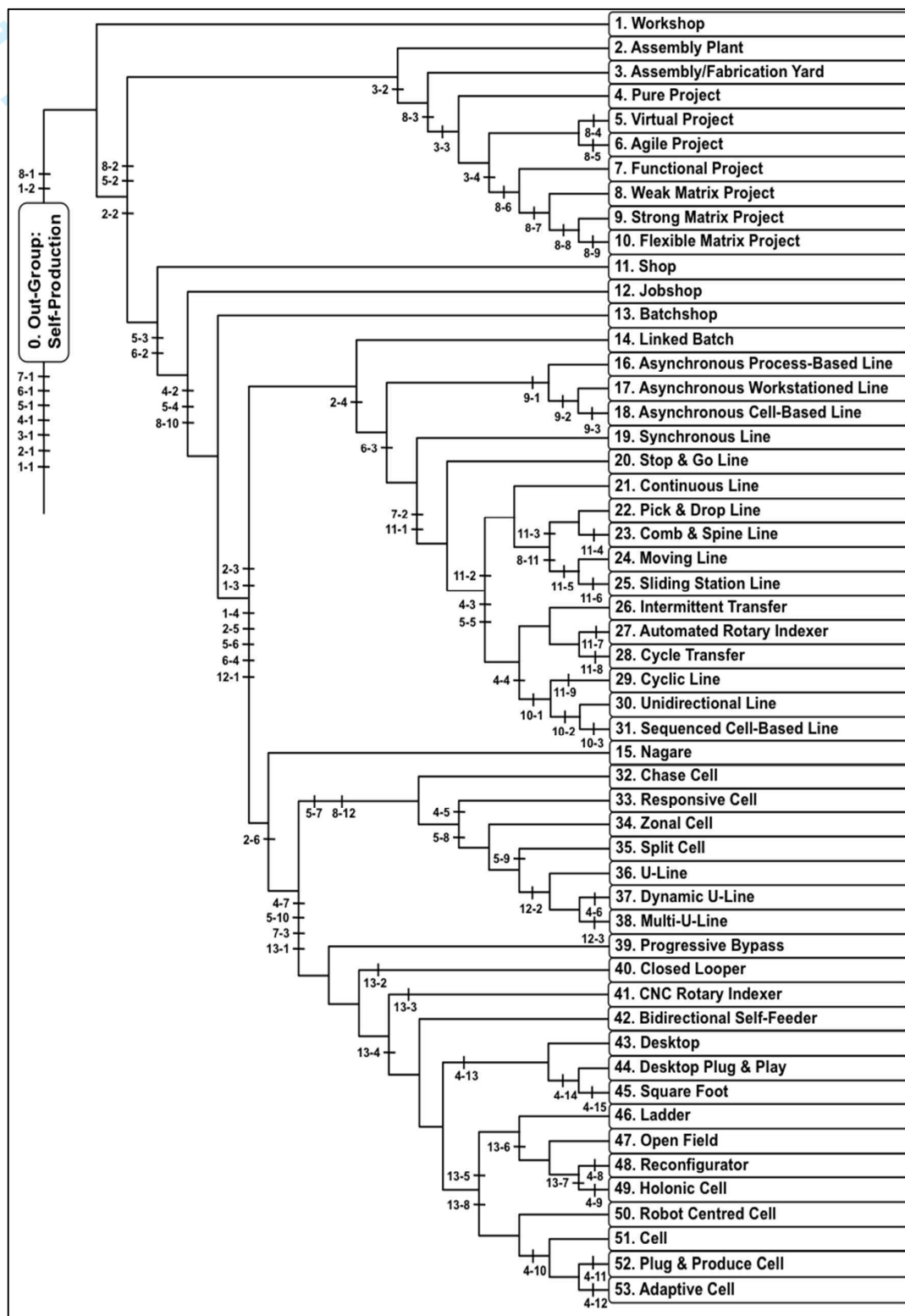


Figure 9: Factual hierarchical classification of discrete manufacturing systems

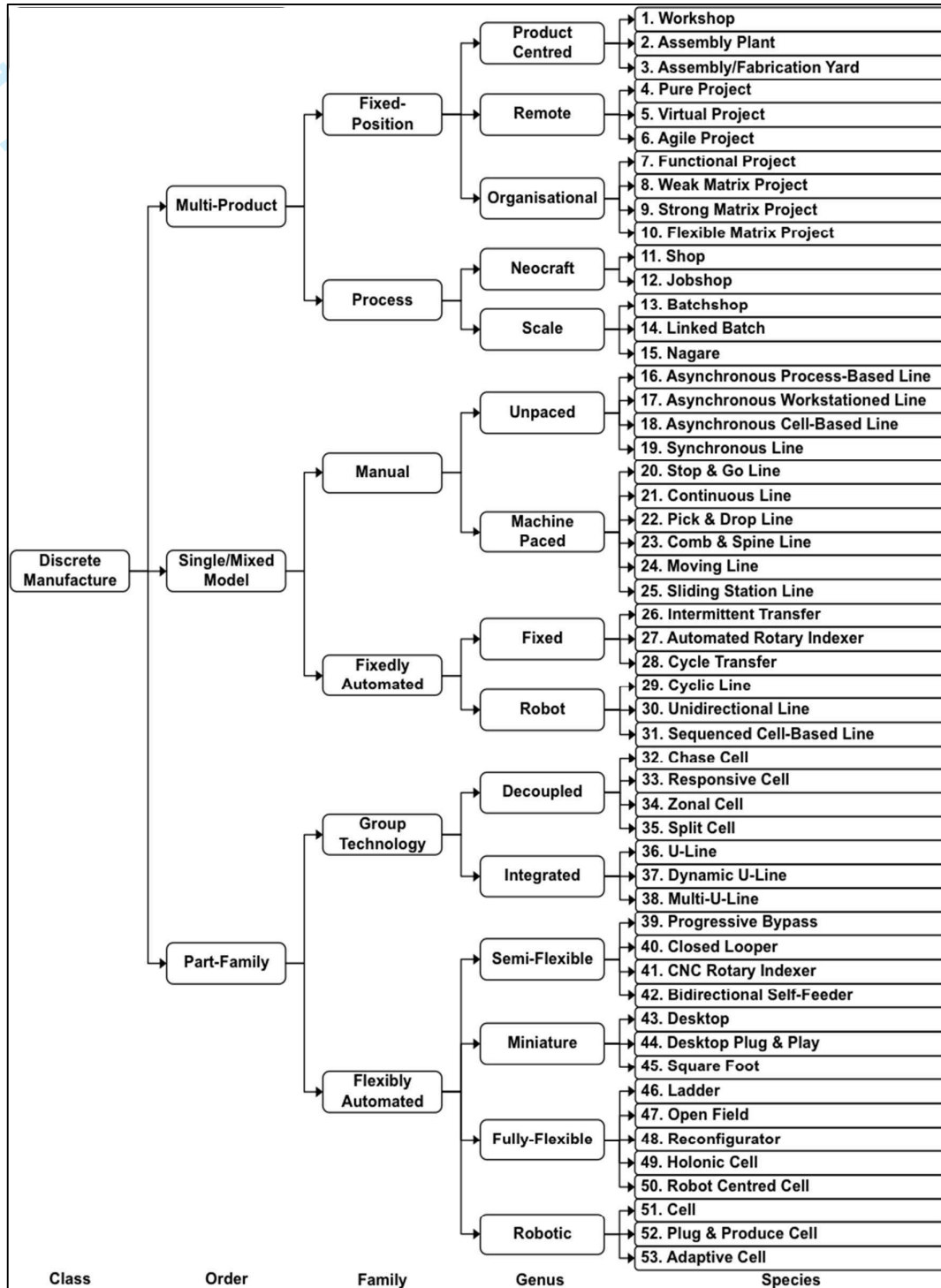


Figure 10: Varieties of the species of the Product Centred Genus

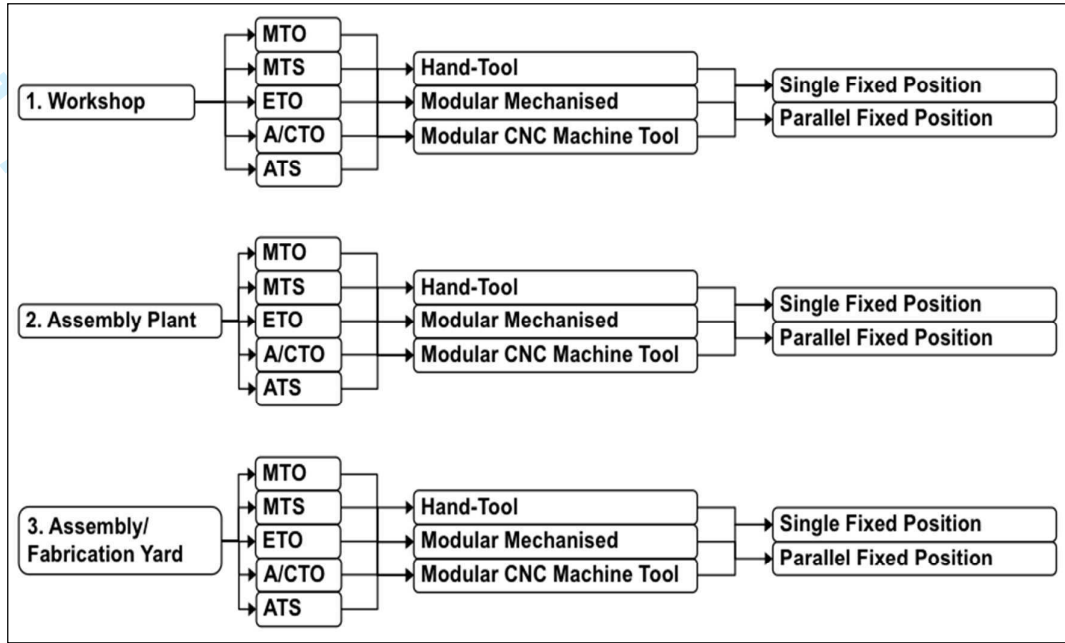


Figure 11: Identification and diagnostics software tool based on factual classifications

The screenshot displays the Copernico software interface. At the top, there is a navigation bar with the Copernico logo and two menu items: 'TOOLBOX' and 'MANAGE USER PROFILE'. Below the navigation bar, a breadcrumb trail indicates the current location: 'You are here: diagnostics results and status'.

The main content area is titled 'Based on your answers your manufacturing system can be described as a' and features a large heading: 'Fully-Flexible Robot Centred Cell'.

Below the heading, a section titled 'This information was elicited by your answers so far:' lists several configuration items, each with a dropdown menu and a green checkmark icon:

- General Layout Approach: Part-family layout
- Process Capability: Limited universal, automated, flexible process capability (i.e., CNC machin
- Primary Material Handling Capability: Flexibly automated primary material handling system
- Flexibly-Automated Primary Material Handling Type: Robotic primary material handling

A note below this section states: 'If you want to change one of this settings please restart the diagnostics, as it may influence the resulting manufacturing system.'

The interface is divided into two columns for additional specifications:

- Left Column: 'The information marked in blue is assumed as it is typical for a Fully-Flexible Robot Centred Cell:'**
 - Product Mix and Order Capability: Part-family capability and limited order capability (make-to-order, assembl
 - Location of Production: On-site (covered dedicated facility)
 - Operator Capability: Operator programmes and oversees/monitors processes
 - In-Process Buffer (Work-in-Progress): In-process buffer (work-in-progress) is removed
 - Management Capability: Centralised with routine production resource scheduling
 - Cell Buffer (Work-in-Progress): Decoupling cell buffer (work-in-progress; i.e. creating independent cells)
- Right Column: 'This information helps to specify your system additionally:'**
 - Robot Centred Layout: Circular

At the bottom of the interface, a section titled 'Your next steps' provides three options:

- (1) Please check and amend above
- (2) Save and continue (highlighted in green)
- (3) Discard all data and restart diagnostics

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.