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The evolution of manufacturing SPECIES

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Abstract

This research aims to develop hierarchical and cladistic classifications of manufacturing system evolution, incorporating evolving and interacting product, process and production system features. The objectives then are to systematically organise manufacturing systems and their characteristics in classifications Forty-six candidate species of manufacturing systems have been identified and organised in a 4th generation hierarchical classification with 14 'genera', 6 'families' 3 'orders' and 1 'class' of discrete manufacturing. The accompanying cladistic classification hypothesises the evolutionary history of manufacturing, using 'descriptors' drawn from a library of 12 characters and 66 states. These are consistent and synthesise many of the established typologies in the literature.

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1. Introduction

The SPECIES working group aims to: *investigate approaches, techniques and methods to determine the most appropriate evolution strategy for production system that must competitively operate in an environment characterised by evolving products and technologies* [1]. The complementary aim of the work reported here is to develop a classification system, incorporating evolving and interacting product, process and production system features, and applicable to discrete manufacturing (www.copernico.co). The main objectives: a) identify a range of discrete manufacturing system characters and states; b) develop both hierarchical and cladistic classifications, c) define the most evolutionary relevant characters and states.

The system of hierarchical classification was originally described by Linnaeus [2] as an inquiry into biological differences. The groups into which organisms are placed are referred to as taxa (singular: taxon). The taxa are arranged in a hierarchy originally limited to Kingdom, Class, Order, Genus, and Variety. The taxon is ranked within this hierarchy (i.e., the Species). The Linnaean hierarchy, ranks entities artificially, and can be misleading suggesting different rankings are equivalent.

Phylogenetic classification incorporates evolutionary history and does not attempt to rank organisms. Phylogenetic classification (or cladistics) groups organisms that share derived characters [3]. Camin and Sokal [4] suggest the term cladogram to distinguish a cladistic (Klados is Greek for 'branch') dendrogram from a phenetic one (phenogram). Cladistics is an evolutionary classification scheme that not only describes the attributes of existing entities but also the ancestral characteristics. Each Species is defined by a list of character states [5], which distinguish one Species from another. Species are grouped based on the similarity of change leading to the cladogram.

'Manufacturing' cladistics has been successfully applied to discrete manufacturing systems and to aerospace supply chains [6] but, to this point, is sector specific (e.g., the automobile industry). The aim here is to develop a general classification system that spans sectors and links to other important co-evolutionary work (e.g., [7] [8] [9]) in the SPECIES working group.

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2. Methodology

Constructing the cladistic classification involves an eight-step re-iterative process [5]: **Problem Definition:** The 'problem' is defined which provides the basis to understand the relation between the Species and their defining characters. **Determine the Clade (Taxon):** The manufacturing systems under study, along with common and most recent ancestors. **Determine the Characters:** A character is any variable, feature or attribute, which forms the basis for classificatory significance. **Code the Characters:** Numbering characters and states, helps with both ordering and making classification decisions. **Ascertain Character Polarity:** To help the distinction between a primitive character or state and a derived character or state. **Estimating Phylogeny and Constructing the Conceptual Cladogram:** Cladograms are constructed by grouping Species that share a common root and evolutionary history. **Construction of the Factual Cladogram:** This step is more quantitative in nature. The aim is to test the hypotheses inherent in the conceptual cladogram. Any conflicts are resolved leading to a full factual cladogram. **Decide Taxa Nomenclature:** Naming should ensure universal communication and binominal (Species and Genus).

3. Results and Discussion

The classification problem, the Species, is defined as: *'A coherent set of product, process and production system features, 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), but individual workstations, cells or plants, the latter being a relatively small set of workstations or cells'.* The forty-six candidate Species are organised in a hierarchical classification with 13 Genera, 6 Families and 3 Orders under 1 'Class' of discrete manufacturing (figure 1). The evolutionary relationships between the Species of manufacturing systems, using 'descriptors' drawn from a library of twelve characters with a total of sixty-six states (table 1), are hypothesized and described.

What is not included in the scheme and the table of character states is the product order type (e.g. *make-to-order*), which governs the ensuing evolutionary development. However, this is reflected in hierarchical classification at the Order level. That is, the hierarchical scheme has three Orders directly related to the multi-product and order capability (Multi-Product Order), single or mixed-model capability (Product Line Order) and part-family capability (Group Technology Order).

The evolutionary history must begin with an *Out-group*, which is *Self-Production*. This primitive system of manufacturing shares many of the characters to the in-group or clade passed on from a common ancestor. *Self Production* manufactures articles for personal use, in a fixed position (SYSTEM or S/CS1-1), in one site (S/CS2-1) and usually in or around the place of living. Simple, universal, processing techniques and tools (PROCESS or P/CS3-1) are employed, in the form of manual or hand tool manipulation (P/CS6-1). All the necessary processes are performed and the full article produced, by the one person (P/CS4-1) in one go, i.e., without WIP or 'buffer' between the processes (S/CS5-1). All material handling (i.e., both primary (between processes) and secondary (within processes) is primarily manual (P/CS7-1; P/CS8-1) and sometimes mechanised.

The first Species to evolve, with an entrepreneurial spirit (S/CS9-1), starting the Class of *Discrete Manufacturing* is the *Product Centred Workshop* and belongs to the *Multi-Product* Order. In this Order, two new characters emerge: the style of management and the power over resources. The most significant change is the General Layout Approach with the fixed position layout (S/CS1-1) being the most defining CS for the *Fixed-Position* Family and the process layout (S/CS1-2) the most defining CS for the *Process* Family.

The *Fixed-Position* Family comprises two Genera, the *Product Centred* and the *Project*. With the *Product Centred Yard* a variation of the Management Style Character is evident as the products are more complex, and require more workers, who still perform significant product processes, but only produce part of the product (P/CS4-2) albeit a significant part. A more project-managed (S/CS9-2) environment is required in order for the project manager (PM) to get the best out of the resource pool (S/CS10-1).

The *Project Genus* explore variations in the location of production (defining the *Project Pure*), management style and resource power. The most defining CS is with the production taking place at a remote location (S/CS2-2) where all resources are brought to a specific one-off location, i.e., the customer. The *Project Virtual* spans different companies and has an inter-organisational resource pool (S/CS10-4). The *Project Functional* represents those systems in which one-off products are produced within a certain organisational function (typically engineering). Here the functional manager is the PM (S/CS10-2) and has responsibility over both the function (department or division) and the project. The *Project Matrix*, represents projects in which cross-functional resources are needed, requiring a specialised PM who has power to second specific functional resources (S/CS10-3). The *Project Agile* employ agile techniques (S/CS9-3) tackling the inflexibility associated with formal PM techniques.

The second Family of the *Multi-Product* Order is the *Process* Family. The *Neocraft Shop* evolved from a common ancestor of the *Product Centred Workshop* and shares the majority of CSs except the implementation of a process layout (S/CS1-2), where the product moves to each machine or process. This change was primarily due to the size and weight of the mechanised machines introduced (P/CS6-2), which would be placed and fixed in certain areas. The second Species, the *Neocraft Jobshop*, changes with a scaling up of the same key machines and processes (P/CS3-2). More workers are employed who concentrate on their process expertise and perform significant product processes but only produce part of the product (P/CS4-2). This system creates significant WIP between processes (S/CS5-2).

The *Scale* Genus takes this further with large-scale additions of most or all machines (P/CS3-3). The *Scale Batchshop*, exhibits two other fundamental changes. The first is a deskilling in the production process where workers perform single or a very limited set of processes (P/CS4-3). With more workers, a requirement for a change in management style leading to a more centralised approach (S/CS9-4). The next two Species in the Genus, the *Scale Linked Batch* and the *Scale Nagare*, lead to a major bifurcation in the evolutionary scheme with the ancestor of the former leading to the *Product Line* Order around the turn of last century, and the other making way for the *Group Technology* Order; both Species still have the process layout but some machines are 'virtually' linked either to form a product line (S/CS1-2/3; this Species exhibits two states of the character 'general layout approach'; both the process layout (S/CS1-2) and the product layout (S/CS1-3)) as with the *Scale Linked Batch* (which is the only fundamental change in terms of the primary characters) or to form a cell (S/CS1-2/4) representing the *Scale Nagare*. For the *Scale Linked Batch*, the layout is predominantly process based, but certain machines in each area are dedicated fully to one particular product. The *Scale Nagare* also implements some Lean principles of multi-skilling workers whom take responsibility for all product family processes, and of removing in-process buffer (S/CS5-4).

The first Species of the *Product Line* Order, is the *Unpaced Asynchronous*, which belongs to one of two Genera under the Family of *Manual,* and distinguished by the implementation of single dedicated machine/ process types (P/CS3-4) arranged in a product layout (S/CS1-3). The *Unpaced Synchronous* is the second in the Genus and associated with assembly lines, where processes are done manually or using hand-tools (P/CS6-1), which creates the opportunity of balancing the line to minimise in-process buffers (S/CS5-3). The *Machine Paced* Genus introduces an automated primary material handling system (PMHS). Furthermore, the only differentiating factor within this Genus is the exhibition and exploration of different types of PMHS. The *Machine Paced Stop & Go* has an intermittent PMHS where the conveyor, in-line cart, etc., stops for every process/workstation (P/CS11-1); the product is usually of moderate size and typically includes over 30 workstations; processing time at each workstation is between say 30 seconds and several minutes (Takt timed). The *Machine Paced Continuous* features a continuous PMHS and the operator performs the processes whilst the product/part is being carried by the PMHS (P/CS11-2); operator process times are very quick, typically 1-10 seconds. The *Machine Paced Pick & Drop* also exhibits a continuous PMHS but the operator removes the part/product from the conveyor to perform process(es) then returns it (P/CS11-3); process times here are between, for example, 10-30 seconds. Specimens can be found, for example, in the final packaging line. The *Machine Paced Comb & Spine* differs slightly as operator removes part/product from the conveyor to perform process(es) but feeds it to another conveyor (P/CS11-4). This is typical of both the mixed model and postponement strategies. Both the *Machine Paced Moving* and the *Machine Paced Sliding Station* also have a continuous PMHS but whereas with the former the operators perform processes by 'walking' with the in-line cart (P/CS11-5), the latter has some workstations that 'slide' past others (P/CS11-6).

The *Automated* Family replaces human processing with machine processing. There are two Genera, the *Transfer* and the *Robot* with variations in process technology type and automated PMHS type explored. The *Transfer Intermittent*, like the *Machine Paced Stop & Go*, features an intermittent PMHS where the conveyor, in-line cart, etc., stops for every process (P/CS11-1), but also introduces non-CNC automated machines (P/CS6-4) and combines the secondary material handling with the PMHS (P/CS8-2). The role of the operator shifts to overseeing and monitoring processes (P/CS4-4). The other Species is the *Transfer Continuous* where the Automated PMHS type changes to a continuous cycle where parts/products are automatically processed whilst in motion. The *Robot Unidirectional*, as the name suggests, differs with the introduction of robots (P/CS6-6) as the primary process technology type. The *Robot Cyclic*, used with products where a simple sequence of fairly straightforward welding or machining processes take place. The PMHS stops for every process but cycles around; as one is removed from the pallet, another is added (P/CS11-8).

The third Order of *Group Technology* differs primarily with the introduction of a group technology layout (S/CS1-4) which all Species share. An additional character also appears, that of cell buffer. The *Lean* Family is composed of two Genera – the *Cell* and the *U-*

Line, both of which explore variations in operator task types and responsibilities, process technology types and cell buffer types. The *Cell Chase* introduces buffer at the level of the cell which decouples the cells creating independent cells (S/CS12-1); the operator task type/responsibility also changes from performing single or a very limited set of processes to performing all part family processes (P/CS4-6) and chases the part through the cell. The *Cell Agile* differs through the exploration of modular mechanised machine tools (P/CS6-3) which are typically on wheels/casters and can be quickly re-configured in response to changes in demand. The *Cell Zonal* introduces two or more operators whom share cell processes in zones (P/CS4-7). The *Cell Split* takes this further but introduces three or more operators processing a part each which are then brought together for final processing or assembly (P/CS4-8). The *U-Line* Genus comprises three Species, the first of which is the *U-Line Decoupled*. For this the buffer between cells (S/CS12-2) is eliminated creating a fully integrated set of cells in the shape of a large U-Line. With the introduction of modular mechanised machines (P/CS6-3), the *U-Line LeAgile* is created, which can be quickly re-configured. The *U-Line Multi* eliminates buffer at the line level (S/CS12-3) creating fully integrated U-Lines.

There are three Genera under the *FMS* Family – the *Semi-Flexible*, the *Flexible* and the *Robotic*. All Species share the following two features: an automated PMHS (P/CS7-2), and operators that solely programme, oversee and monitor processes (P/CS4-9). The *Semi-Flexible* Genus, most of which share the feature of the secondary material handling combined with the PMHS (P/CS8-2), begins with the *Semi-Flexible Bypass* which introduces CNC machine tools (P/CS6-5) and an intermittent unidirectional PMHS that can bypass processes as required (P/CS11-9). The *Semi-Flexible Desktop* and *Semi-Flexible Square Foot* further explore different process technology types in the form of micro machining units (MMUs) and modular MMUs, respectively. A common ancestor also leads to the *Semi-Flexible Rotary Indexer* and *Semi-Flexible Bidirectional Self Feed* through variants in automated bidirectional PMHS types with the former using a rotary indexing PMHS (P/CS11-10) and the latter using conveyors, or something similar, that move in two directions (P/CS11-11). The latter also moves to automated secondary material handling (P/CS8-3), a feature that is shared with the *Flexible* and *Robotic* Genera. For the *Flexible Ladder*, which is laid out in the shape of a ladder, the evolutionary distinguishing feature is the use of automated guided vehicles or AGVs (P/CS11-12). The *Flexible Open Field*, where there is no specific layout, self-guided vehicles (SGVs) are typically used (P/CS11-13). The *Flexible Reconfigurable* introduces artificially intelligent (AI) SGVs (P/CS11-14) in addition to modular CNC machine tools (P/CS6-7). The *Flexible Holonic* introduces autonomous CNC machine tools, i.e., with AI (P/CS6-8). The *Flexible Robot Centred* has a robot (P/CS11-15) as the PMHS, which is also a feature of the *Robotic* Genus. All Species have robots as the main process technology type (P/CS6-6). The *Robotic Plug & Produce* introduces modular robots (P/CS6-9) for reconfigurability. The final *Robotic Adaptive* exhibits autonomy through robots with AI (P/CS6-10).

4. Conclusions

The aim of this research was to unify the various discrete manufacturing system classifications, typologies and taxonomies in the literature. Two conceptual schemes were developed – hierarchical and cladistic classifications. Forty-six candidate manufacturing systems, using 'descriptors' drawn from a library of twelve characters and sixty-six states, are described and presented diagrammatically. The complementary classification organises this information hierarchically and groups Species under 'Genera', 'Families' and 'Orders' based on evolutionary proximity.

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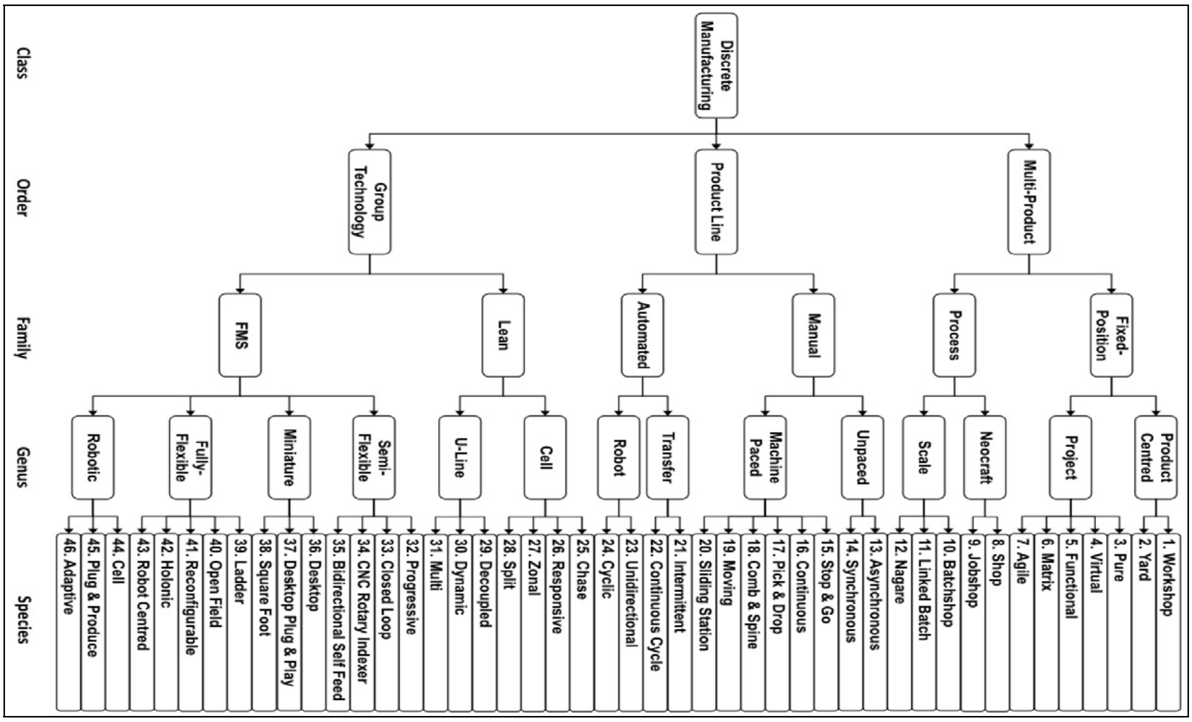

Figure 1. Hierarchical Classification

PRIMARY CHARACTER STATES		
1	**General Layout Approach**	
1-1	Fixed position layout	
1-2	Process layout	
1-3	Product layout	
1-4	Group technology layout	
2	**Location of Production**	
2-1	On-site (dedicated facility)	
2-2	Remote location	
3	**General Machine/Process Type and Number**	
3-1	Single universal-machine/process types	
3-2	Limited universal-machine/process duplication	
3-3	Extensive universal-machine/process duplication	
3-4	Single dedicated-machine/process types	
4	**Operator Task Type / Responsibility**	
4-1	Performs all processes; produces full product	
4-2	Performs significant processes; produces part of product	
4-3	Performs single or a very limited set of processes	
4-4	Oversees/monitors processes	
4-5	Performs all product family processes	
4-6	One operator performing all cell processes	
4-7	Two or more operators sharing cell processes in zones	
4-8	Three or more operators processing a part each which are then brought together for final processing or assembly	
4-9	Programmes and oversees/monitors processes	
5	**In-Process Buffer**	
5-1	No buffer between processes	
5-2	WIP between processes	
5-3	Line balanced to minimise in-process buffers	
5-4	In-process buffer seen as waste and removed	
6	**Process Technology Type**	
6-1	Manual / hand-tool	
6-2	Mechanised machines (manually operated machines)	
6-3	Modular mechanised machines	
6-4	Automated machines (non CNC)	
6-5	CNC machine tool	
6-6	Robot	
6-7	Modular CNC machine tool	
6-8	Autonomous CNC machine tool (i.e., with artificial intelligence)	
6-9	Modular robot	
6-10	Autonomous robot (i.e., with artificial intelligence)	
6-11	Precision micro machining unit	
6-12	Modular precision micro machining unit	
6-13	Modular universal (versatile) micro machining unit	
7	**Primary Material Handling System (PMHS)**	
7-1	Manual / mechanised PMHS	
7-2	Automated PMHS	
8	**Secondary Material Handling**	
8-1	Manual / mechanised	
8-2	Combined with PMHS	
8-3	Automated	
9	**Management Style**	
9-1	Entrepreneurial	
9-2	Project managed	
9-3	Agile project managed	
9-4	Centralised	
10	**PM Resource Power**	
10-1	*Intra*-organisational project resource pool	
10-2	Functional manager is project manager	
10-3	PM has power over specific functional resource secondment	
10-4	*Inter*-organisational project resource pool	
11	**Automated PMHS Type**	
11-1	Intermittent: The conveyor, in-line cart, etc., stops for every process/workstation	
11-2	Continuous: The operator performs process(es) whilst in motion	
11-3	Continuous: The operator removes part/product from the conveyor to perform process(es) then returns it	
11-4	Continuous: The operator removes part/product from the conveyor to perform process(es) then feeds it to another conveyor	
11-5	Continuous: The operators perform process(es) by 'walking/moving' with the in-line cart	
11-6	Continuous: The operators perform process(es) by 'walking/moving' with the in-line cart; some workstations 'slide' past other workstations to perform processes	
11-7	Continuous cycle: Parts/products are automatically processed whilst in motion	
11-8	Intermittent cycle: The PMHS cycles	
11-9	Intermittent progressive bypass: The PMHS can bypass processes	
11-10	Intermittent closed loop bypass: The PMHS is cyclical and can bypass processes	
11-11	Bidirectional: CNC Rotary Indexing	
11-12	Bidirectional: The PMHS can move in two directions	
11-13	Multidirectional: The PMHS can deliver parts to any machine in any sequence	
11-14	Mobile: Automated Guided Vehicle (AGV)	
11-15	Mobile: Self Guided Vehicle (SGV)	
11-16	Robot	
12	**Cell Buffer**	
12-1	Decoupling cell buffer (i.e. creating independent cells)	
12-2	No buffer between cells (i.e., cells are fully integrated)	
12-3	No buffer between lines (i.e., lines are fully integrated)	

Table 1. Characters and States

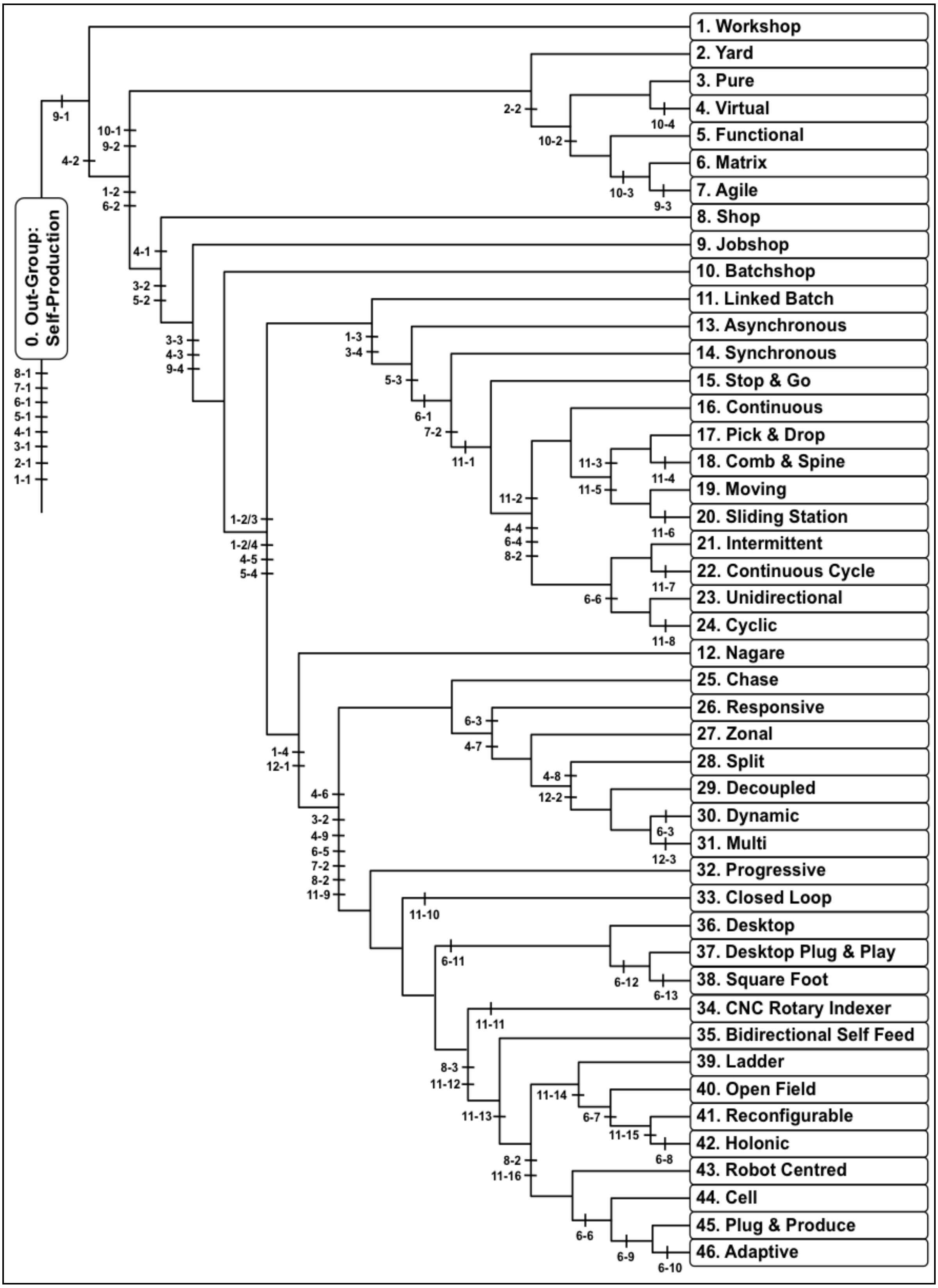

Figure 2. Cladistic Classification