Evolutionary Theories in Manufacturing: Inspiration from Biology, Society, and Evolutionary Computing

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Abstract: Darwin's evolutionary theory of natural selection has had a strong impact on both science and culture, and has over the last decades become a popular inspiration in engineering sciences. Both the wide range of scientific areas where evolutionary theory is applied, and the simplistic metaphors used to explain evolution in schools and non-scientific situations have caused confusion of how key evolutionary concepts should be understood. In this paper, the cornerstones in biological and social evolutionary theory are identified and addressed from an engineering point of view. Previous efforts to apply evolutionary theories within engineering are then addressed and related to the needs and opportunities within manufacturing and assembly.

Keywords: Evolvable Assembly Systems, Bio-Inspired Automation, Multi-Agent Systems, Complex Systems, Evolutionary Theory.

1. INTRODUCTION

Biological and social evolution are extremely complex processes that are difficult to understand in detail; however, simplistic metaphors are commonly used to explain these processes in schools and non-scientific arenas. While, these metaphors are powerful, they may be misleading when applied to a scientific context. In addition, evolution approaches are currently used in a range of scientific fields, each with a different set of characteristics and issues to be addressed. Consequently, shared concepts are neither defined nor understood in the same way. In order to advance research on evolution in manufacturing it is of importance to define the essential characteristics of evolution. Only then is it possible to take advantage of the more complex processes in biological and social evolutionary theory.

Evolution is a dynamic process; the "focus of attention is on a variable or set of them that is changing over time and the theoretical quest is for an under- standing of the dynamic process behind the observed change" (Richard R. Nelson 1995). To evolve, the dynamic process requires some variation on which selection can be made. This selection should have a relation to the fitness of the variants with regards to their internal and external environment.

At this abstract level the engineering can definitely be considered an evolutionary process. Nevertheless, it has shown difficult, and possibly misdirected, to form a direct link between the building blocks of biological evolution and the evolution in non-biology disciplines, e.g. assembly or manufacturing system. A basic discussion of the evolution analogy does however increase our understanding of key evolution principles and hopefully helps to avoid misinterpretations. Consequently, the following sections within the introduction discuss the key aspects and interpretations of evolution within biology, social sciences, and engineering.

The introduction aims at providing a broad view of well established core concepts of evolution within biology, society, and engineering. The following introduction draws from several sources, mainly: (West et al. 2007), (Lehmann & Keller 2006), (Richard R. Nelson 1995), (Eiben & Smith 2003). The objective is then to discuss both how the characteristics of evolution can be mapped to the area of manufacturing, and how evolutionary concepts are currently used to aid manufacturing.

1.1 Evolution in Biology

In addition to the generic characteristics of evolution, i.e. dynamics, variation and selection; biological evolution has its own generic foundation. Evolutionary theory in biology is founded around two populations: *genotype*, defined as the genetic inheritance of species; and *phenotype*, defined as the physical appearance of an organism. For these populations to evolve three processes are imperative: (i) a mechanism that generates variation in the genotypes, (ii) a mechanism that links the genotype with the phenotypes, i.e. the entities that undergo the actual selection process (selection is commonly considered to take place both on the phenotype level and on a social group level, but not on the genotype level (Pigliucci 2008)), and (iii) a process for selection based on the fitness of the phenotypes, who's fitness is a reflection of the fitness of the genotype.

Biological species evolve through generations; phenotypes are born, live, reproduce, and finally die. This dynamic process enables the size and fitness of the species population to be linked to that of the preceding generation. While the concept of generations is natural in biology, it is problematic to apply as a generic property in other systems due to the lack of one or many of the stages in the life cycle of a biological phenotype.

The genotype variation is in biology achieved mainly through *reproduction*, i.e. combining the genes of two individuals; and *mutation*, i.e. a permanent and heritable change to a gene. The variation thereby carries over to the next generation, and enables the species to evolve. The mechanisms that link the nucleic acids of the DNA to specific phenotypic traits are too detailed for the purpose of this paper. However, it is important to understand that the phenotype is a combined result of the genotype, the environment and random variation. This means that two identical twins growing up in the same environment will be slightly different due to random variation; and if growing up separately they will be even more dissimilar due to the additional environmental effect. While this is apparent in a biological context, it is important to keep in mind when discussing evolution in other contexts.

The selection of species is commonly described as "survival of the fittest" or "natural selection", terms which are often misinterpreted to mean that only the physically strongest or most intelligent species and individuals will prevail, and that this leads to optimal individuals. This crude understanding of selection is valid in an environment where species or agents passively compete for the same resource or niche, similar to a 100 meter dash, where everyone's time is independent of the other runners'. However, in most environments there is a negative feedback loop that creates an equilibrium state. For example, an increased fitness of a predatory species leads to a decrease of its pray, which may lead to that the predators are less likely to survive and generate offspring, which in turn may lead to an increase of pray. This state of equilibrium is path dependent, i.e. the current state cannot be derived from the current environmental conditions since they have evolved based on previous environmental conditions. Consequently, the current species have evolved in an environment that possibly did not require the same abilities as the current conditions do. In addition, the elements of luck, breeding capability, and the geographical locality of environmental conditions leads to that current species are unlikely to be optimal with regards to their environment.

1.2 Evolution in Society

While biological evolution is focused on fitness of one individual, social evolution is focused on the effect of interactions between agents. This means that from an evolutionary perspective, social behavior effects both the fitness of the individual carrying out the action and one or more other individuals. Consequently, behavior that either does not affect the actor's or recipient's fitness is not considered social behavior. Social behaviors can either have a positive or negative effect on the fitness of the actor and the recipient (Hamilton 1964), resulting in the matrix in Table 1.

For evolution to occur there must be a tension between conflict and cooperation (Frank 1998), it is therefore important to stress that social behavior is not synonymous to cooperation. While the former disregards whether the actor's and recipient's fitness increase or decrease, the latter is a term that should only be used for behavior that increases the recipient's fitness. Cooperation is defined as "a behaviour which provides a benefit to another individual (recipient), and which is selected for because of its beneficial effect on the recipient" (West et al. 2007). This means that there must be an intended increase in the fitness of the recipient for it to be classified as cooperation, not only that a recipient is using the actor's waste. Social evolution consequently requires that an actor is intentionally behaving to increase the fitness of the recipient.

The fitness in social evolution is in general related to the individual's production of offspring, or more specifically to the offspring's ability to generate and provide for offspring. Consequently, a behavior's effect on fitness should always be considered over the individual's lifetime, e.g. altruistic behavior must have a long-term negative effect on the fitness of the actor, not only temporary.

Fitness is divided into *direct fitness*, i.e. "the component of fitness gained through the impact of an individual's behaviour on the production of offspring", and *indirect fitness*, i.e. "the component of fitness gained from aiding the reproduction of related individuals" (West et al. 2007). Direct fitness can either be attained if the cost of a behavior is lower than the benefit, or through some form of enforcement. The main categories of enforcement mechanisms to attain direct fitness through cooperation are: reward, punishment, policing, sanctions, and reciprocity, i.e. the probability of future mutually beneficiary cooperation.

Fitness is usually calculated with economic methods, e.g. time value money, or by the relatedness in kin selection (Frank 1998). The former is analogous to including the interest rate when calculating the value of next year's money; to evaluate the fitness of today's population with the next generation, the value of the offspring is reduced by the growth rate of the population.

In kin selection, it is assumed that an individual favors the reproduction of their own relatives. The cost of a specific behavior should therefore be related to the extent to which the behavior transfers the individual's genes to the next generation, directly of indirectly. This means that there is no difference between using a certain amount of recourses to generate one offspring of your own, or to give those resources to a full sibling to generate two offspring.

Table 1: Fitness consequences

		Recipient	
		Fitness +	*Fitness –*
Actor	*Fitness +*	***Mutual Benefit***	***Selfishness***
	Fitness –	***Altruism***	***Spite***

1.3 Evolution in Computing

Since the early nineties, *evolutionary computing* has been used as a comprehensive term for several closely related approaches, e.g. evolutionary programming, evolution strategies, genetic algorithms, genetic programming (Eiben & Smith 2003). There are two main areas within evolutionary computing: first, to generate something that resembles intelligence within the artificial computer through evolution of the computer program, and second, to increase the understanding evolution and intelligence in nature (Fogel 2006). The latter is enabled through the ability to in a very short time simulate something that in nature requires millions of years. Even though this aspect is of great importance, it is of less importance for our understanding of the characteristics of evolutionary theory, and of less importance for evolution in manufacturing.

The purpose of intelligence in computing is derived from the Darwinian concept *survival of the fittest*, and the ambition to become increasingly fit by generating and evaluating generations of a computer program. The path towards higher fitness can metaphorically be described as an *adaptive landscape* (Figure 1), a concept introduced to intuitively relate the fitness of all possible genotypes, i.e. the genotype space (Wright 1932).

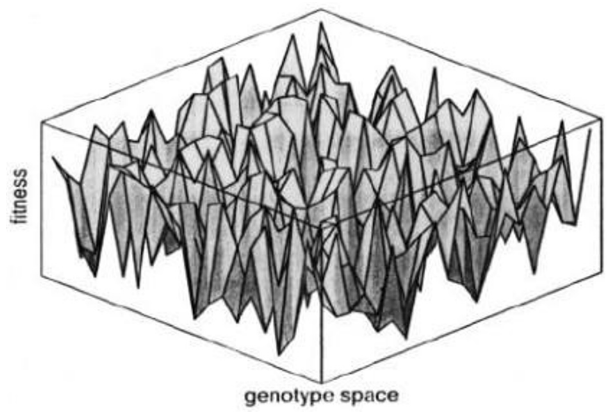

Figure 1: Illustration of Wright's adaptive landscape (Kauffman & Levin 1987).

Depending on scale, a species or individual evolves as it climbs a peak towards increased fitness; an adaptive peak can then be understood as representing one species and the valley surrounding it are unfit hybrids of different species. The metaphor of rugged adaptive landscapes is often considered too simplistic to capture the complexity of evolution, due to the difficulty of illustrating multiple dimensions at once. For example, in three dimensions it appears as if a new species is always of lower fitness than an established species; and it seems possible to compare the fitness of different species, e.g. mammals, birds, and fish.

Instead of a low-dimensional genotype space, which is usually depicted, there are generally hundreds or thousands of dimensions in the genotype space. In high-dimensional landscapes there are large areas where specific traits can evolve without affecting the mean fitness of the species, (Pigliucci 2008), initially presented in (Gavrilets 1999). This means that a species can evolve into a new species without having to go through a valley of lower fitness.

In evolutionary computing adaptive landscapes, are used to illustrate optimization of multi-dimension problems where both the model and the desired output is know. In the evolutionary algorithms used for optimization, several possible solutions are initially tested with regard to their fitness, they are then randomly mutated and recombined, i.e. two or more solutions are merged to generate offspring. This process goes on until an optimal or satisfactory solution is found, Figure 2.

```
BEGIN
  INITIALISE population with random candidate solutions;
  EVALUATE each candidate;
  REPEAT UNTIL ( TERMINATION CONDITION is satisfied ) DO
    1 SELECT parents;
    2 RECOMBINE pairs of parents;
    3 MUTATE the resulting offspring;
    4 EVALUATE new candidates;
    5 SELECT individuals for the next generation;
  OD
END
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Figure 2: The general scheme of an evolutionary algorithm (Eiben & Smith 2003).

The similarities between biological evolution and evolutionary algorithms become apparent when the fundamental components of the latter are matched to those of the former. The quality of an evolutionary algorithm is dependent on the quality of the following characteristics (Eiben & Smith 2003):

- representation (definition of individuals)
- evaluation function (or fitness function)
- population
- parent selection mechanism
- variation operators, recombination and mutation
- survivor selection mechanism (replacement)
- initialization procedure and a termination condition

Evolutionary computing shares several characteristics of evolution in biology and to some extent social evolution. Engineering tasks that are too complex for traditional methods can successfully be addressed with evolutionary computing.

2. EVOLUTION WITHIN MANUFACTURING

Evolutionary concepts established for biology, society, and computing are becoming increasingly popular as metaphors and methods within manufacturing. The popularity stems in the ability to use already established concepts to explain difficult manufacturing concepts; and to utilize scientific progress within other domains to advance manufacturing.

In manufacturing system literature there are mainly three different approaches that can be derived from evolutionary theory: (i) cladistics, a classification of similarities and differences of manufacturing systems used to predict future traits of a system; (ii) the increasing complexity of systems to be designed and operated requires efficient methods that are able to find a satisfactory solution in a vast solution space; and (iii) evolutionary manufacturing system concepts are designed to handle highly dynamic variations of products and volume variation, and to evolve in accordance with its dynamic environment.

To facilitate a correlation between the characteristics of biological and social evolution, and evolutionary computing, these characteristics are related to the manufacturing domain in the following section.

2.1 Evolutionary Concepts in Manufacturing

In biology the fundamental units of selection are the genes. Even though the selection is not directed directly on the genes, they are the carriers of hereditary information, and are thereby the key to selection and evolution. Possible equivalents to *genes* outside of biology are technologies, policies, behavioral patterns, and cultural traits, which clearly influence what agents do (Dosi & R. R Nelson 1994). Equivalents to the genotype in manufacturing are the ontology, taxonomy, standards and manufacturing technologies. In these, the information that shapes all aspects of a manufacturing system is stored and transferred between system generations. Similar to genes, the manufacturing system genotype is dynamic yet stable over time when compared to the actual manufacturing systems. The ontology, taxonomy, standards and technologies all vary, which is necessary for natural selection to function, and for the most fit varieties to prevail and evolve over time in accordance with changes in the environment

The transformation from the genotype to the phenotype is in nature affected by both the environment and some variance. The same process is also relevant in generating the phenotypic traits of the manufacturing system (Table 2). Following the biological analogy, the environment here constitutes the requirements that the stakeholders of a specific manufacturing system put on a system These are related to all aspects of a manufacturing company, its supply network, customers, competitors, and the product(s) that are to be manufactured. There is always variance in a complex environment, leading to that two independently developed systems sharing the same genotype and environment will not have exactly the same phenotypic characteristics. Variance can be understood as indirect variables and emergent behavior that is impossible or impractical to determine. The phenotype is the physical and quasi-physical result of this process; it should be understood as the actual manufacturing system and its enabling systems. For a highly granular, modular, multi-agent system, as Evolvable Production System (Onori 2002), (Onori et al. 2006), the phenotype is equivalent to both the modules and the agents. These are the entities upon which natural selection is made, and which thereby enables genotypic evolution. The specific agents and modules are unable to evolve by themselves; however, they can adapt to new environmental conditions.

Adaptability should here be understood as a module's or agent's ability to adapt its process functionality to a limited range of changing external and internal conditions (related to process and module feed rates, axis performance, et cetera). This ability is exercised within a limited parameter range, i.e. solution space, and is intended to affect only local parameters.

2.2 Classification through Cladistics

Cladistics a one form of classification used in biology to generate a hierarchical tree, called cladogram; which illustrates the recency of common ancestry. In Figure 3 a cladogram of automotive production paradigms illustrates how different paradigms are related and their shared parameters (McCarthy & Tsinopoulos 2003).

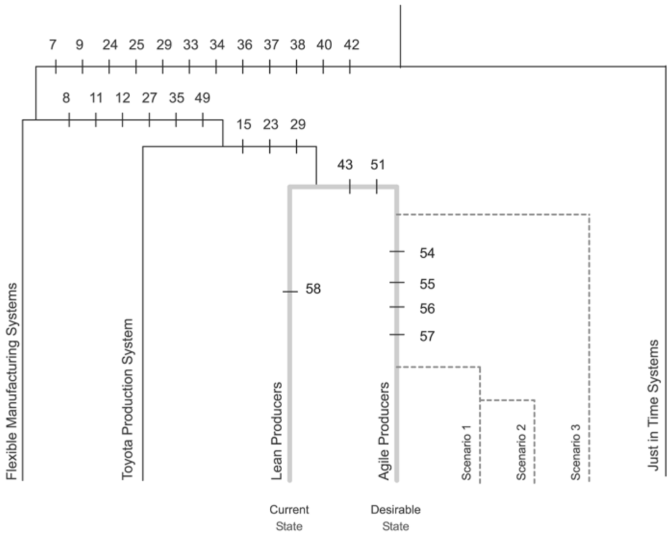

Figure 3: Cladogram of automotive manufacturing system paradigms, numbers indicate characteristics of that branch (McCarthy & Tsinopoulos 2003)

In manufacturing, cladistics is (a) used for understanding an organization's or system's configuration relative to other competing solutions; (b) identifying characteristics of competing solutions; (c) mapping configurations for new scenarios; (d) finding the easiest path to a preferred configuration (McCarthy & Tsinopoulos 2003); and link the cladistic relationships of a product into the strategic issues of the manufacturing system (ElMaraghy et al. 2008).

Table 2: Relation between genotype and phenotype in manufacturing.

Genotype	+	Environment	+	Variance	=	Phenotype
Ontology		Product Features		Indirect variables		Agents
Taxonomy		Volume		Emergence		Modules
Standards		Variants				System
Manufacturing Technologies		Strategies				

Cladistics is a powerful tool that provides manufacturing engineers with a better understanding of the current state of their system and possible future paths. It is important to stress cladistics does not affect the ability of the system to evolve; it merely provides a better understanding of the system's current state and the current state of the environment, based on the current state of the competing systems.

2.3 Evolutionary Optimization in Manufacturing

Evolutionary computing is in manufacturing normally used for job-shop and flow-shop scheduling, dynamic scheduling and comparisons between different scheduling algorithms (Dimopoulos & Zalzala 2000), and in control system engineering (Fleming & Purshouse 2002).

Similar to the generic evolutionary algorithm in Figure 2, evolutionary scheduling follows an iterative spiral where an initial set of heuristic scheduling rules (genotype) generate schedules (phenotype); the performance of the schedules are measured, and selected based on natural selection, which tunes the scheduling rules Figure 4.

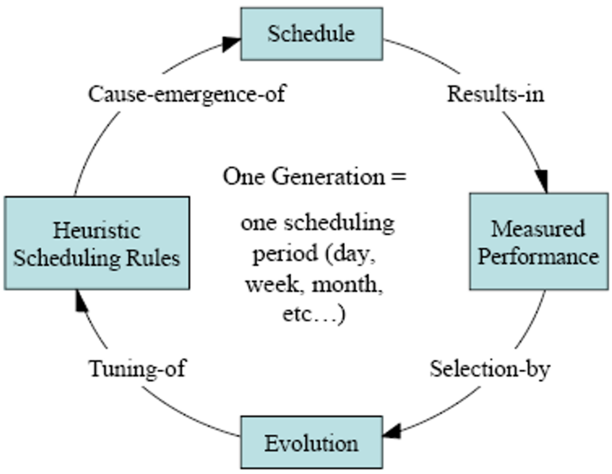

Figure 4: Intelligent Scheduling Using Evolved Heuristic Rules (Ulieru et al. n.d.).

2.4 Evolvable manufacturing systems

Several manufacturing roadmaps state that one of the most important objectives for addressing the new manufacturing challenges is sustainability (EUPASS 2004), (Jovane et al. 2008). Sustainability is a multi dimensional concept that addresses the relationship between a system and its dynamical environment. To achieve sustainability, the manufacturing system must in an energy and cost efficient way align itself with regards to the dynamical environmental requirements; the manufacturing system must become adaptive and possess the ability to evolve over time.

In accordance with Table 2, evolution of the ontology, standards, technologies, etc. lead to an evolution at the shop floor of the modules, agents and systems. The rate of change for the biological evolution is generally too slow for the process to have much effect on the sustainability of the whole manufacturing system. In other words, the rate of change in the biologically inspired evolution is lower than the rate of change for the manufacturing system's environment, c.f. discussion on evolution and technological change (Richard R. Nelson 1995).

Evolution on the societal level requires some form of interaction between the actors that can result in a change of their fitness. Neither a biological and social definition of fitness related to the ability to produce offspring, nor an economical one related to cost or profit seems reasonable in the case of multi agent systems. A feasible alternative to these one-dimensional definitions would be an integrated, multi-variant measure of fitness, e.g. (Naman & Slevin 1993). This type of measure would be directly related to the behavior of the agents, and consequently the modules.

The rate at which the system is able to evolve is strongly dependent on the granularity of the modules. With a higher granularity, the number of possible module combinations increases, and thereby the system's possible solution space within which the system is able to evolve increases. However, high granularity requires that modules can be connected to each other in an efficient way. A modular system approach with clear module interfaces, an ability to communicate at the module level, and a transparency of the modules' abilities and goals facilitates the whole manufacturing system to evolve et the rate of its environment.

3. CONCLUSIONS

Biological evolution is directly related to the genotype and phenotype; in this paper these have been paralleled to manufacturing entities. The main conclusion from this analogy is that while the selection is carried out on manufacturing modules, agents and systems; it is actually the ontology, taxonomy, standards, technologies, etc. that evolve. This means that a specific manufacturing system cannot evolve at nearly the same rate as its environment when only biology inspired evolution is at play.

In a system, social behavior of subsystems and modules is enabled through agents that are capable to communicate and cooperate with each other. This cooperation is should be intended to increase both their individual and collective fitness. To increase the rate of social evolution the granularity needs to be high and the modules must have transparent goals and well defined interfaces, processes and abilities. Theoretically, these are the requirements that need to be fulfilled for a manufacturing system to be able to evolve at the rate of its environment. However, further validation is needed through simulation and real life tests to prove the concept.

The ideas developed within evolutionary computing are in manufacturing mainly used to find solutions to complex multivariable problems, e.g. scheduling. In this approach it is the system concepts that evolve; the final system is however not necessarily evolvable or sustainable.

Cladistics and classification of evolution is an aid to establish a system's current state with regards to its competitors, thereby determining the future evolution of the system. This approach is not generating an evolvable system; rather it is a method for determine a system's environment and possible future states.

The approaches discussed in the introducing sections in this paper all have bearing on manufacturing; however, for the purpose of developing an evolving manufacturing system it is mainly useful to study evolution within social networks. This must be further researched through modeling, simulation and a test bed of a collaborative manufacturing system.

Biological evolution is slow in comparison to social evolution, which makes it less suitable for application to manufacturing. However, the evolution could possibly speed up if the evolution of the manufacturing genotype can affect not only future manufacturing phenotypes, but also current manufacturing systems, modules, and agents. Further research is needed to see the full implications and possibilities of such a process.

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