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Transfer of synthesis, logistic and recycling processes in nature to industrial processes

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Abstract

In biological structures, where logistic, synthesis and recycling processes take place, one finds compartments for these different processes. These are arranged in a specific order so that there is optimal synthesis, transformation, logistics, freedom from interference and flexibility of action. Between the compartments run fast transport systems, microtubules or roads, along which information, molecules etc. are transported. Because production, transport and recycling processes run in every living cell, or numerous macroscopic logistical pathways between cells have been evolved and optimized, various biological functional and design structures can serve as models for industrial production processes. In the context of biointelligent production concepts, input and output of material, energy and information, resource-optimized biological production processes and recycling of materials are interesting aspects with transfer potential. In this paper, numerous examples from nature and approaches to transfer the principles to industrial production processes are presented. Some of them have already proven their effectiveness and efficiency, others have yet to do so. The hypothesis is that further optimization potential can be tapped if principles that have been successfully applied for millions of years are transferred to human processes that have only been developed over decades or centuries.

Keywords: Biointelligence; Biomimetics; Logistics; Ant Algorithm; Swarm Intelligence; Smart Dust; Compartmentalization; Factory Layout; Enzymatic 3D Printing

1. Introduction

"The biological transformation of industrial value creation describes the systematic application of knowledge about natural processes or nature for the purpose of optimizing value creation with regard to essential challenges of society by using all technological possibilities to connect the biosphere and the technosphere. It thus serves as a process on the way to sustainable industrial value creation." (“BiotrainStudy” [1, 2].

In biological transformation, it is the three sister disciplines of biomimetics, biotechnology and bioeconomics that bring biological knowledge into practical and technical application. The former in particular is suitable for learning from nature's processes, because principles are analyzed and transferred to the analogous technical context. In this context, biomimetics has regularly been able to bring a contribution of between 10% and 30% improvement to products that have already been optimized in engineering terms, e.g. in weight reduction through the application of tree topologies, friction resistance reduction after the application of evolutionary algorithms [3,4].

Biological transformation has so far been researched almost exclusively at the product level (development of hardware and software) or production level. But will the production processes including intralogistics, organization, training for biologically transformed products continue unchanged as before? Or can these processes not themselves be biologically transformed? Can't principles be copied from nature that make production more resilient, more flexible,

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more biocybernetic and increase information transparency for employees despite increased complexity?

The BIONOS project has shown that biomimetics is in principle also suitable for dealing with non-technical questions and problems in the economy, and has developed a process model for the sustainable design of value chains [5].

2. Parallelism of production processes in humans and ants

The history of production has always produced new cycles of innovation, some of which have been accompanied by industrial revolutions. Each time, these increased efficiency anew. The most recent industrial revolution, Industry 4.0, has opened up further potential thanks to the massive use of information technology (sensors and actuators and measurement data collection, real-time evaluation and automation) [6]. However, the increase in complexity also leads to greater effort in the planning of such production plants. Currently, hopes are pinned on artificial intelligence (AI) to be able to master the complexity.

When looking at production processes and value chains through the lens of biology, it is crucial to consider the dynamic overall system. Processes, technology and organization can be viewed as an orchestra. In addition, in the future, to ensure efficient and safe production processes, the focus will increasingly be on networking between production, buildings and building technology.

This example shows that the optimization in the 2nd half of the 20th century slipped into an economic maximization until the biology and ecology of the animals, soils and production areas were finally taken into account again.

Through an evolution of several thousand years, we are now at a point where the knowledge of the physiology and psychology of animals, the ecology and nutritional components and the performance and availability of modern technology and information technology can be brought together to achieve an overall optimum of economic performance, animal welfare and environmental protection.

Could not possible technical escarpments in many other production and logistics processes be avoided or reversed now by incorporating biological knowledge and ecosystem thinking?

2.1. Mushroom cultivation in leaf-cutting ants

It is amazing that complex production processes are not only reserved for humans. They are also found in much more primitive ones, the leafcutter ants. They are among the most amazing insects in terms of their ability to maintain complex social structures and perform complex tasks. The production processes in leafcutter ants are very specialized and require the cooperation of different castes within the ant colony. The main production processes in leafcutter ants involve the production of mushrooms, which serve as food for the ants, and the procurement and preparation of leaves as a mushroom-growing substrate. They crush leaves with their mouthparts and use them as substrate with which mushrooms from the species *Leucoagaricus gongylophorus* are cultivated in their burrow, on which the ants feed. They thus create veritable mushroom farms in their burrows. Their production process consists of twenty-nine individual steps, which are carried out by different ants [8][9]. A closer examination of these production steps provides clues for optimizing similar technical production processes. The following steps are typical of the production processes in leafcutter ants and have inspired scientists to develop and research various biomimetic transmissions:

- Material transport: The ability of leaf-cutting ants to transport large amounts of material over long distances has inspired researchers to develop autonomous robots capable of transporting heavy loads over uneven terrain.
- Self-organization: The complex division of work and organization within leafcutter ant colonies has inspired the development of new approaches to organizing robotic systems. Here, robots are coordinated in swarms and communicate with each other to perform complex tasks.
- Biodegradable materials: The ability of leafcutter ants to transform leaves into biodegradable substrate for mushroom cultivation has inspired the development of new biodegradable materials that can be used in various applications, e.g. as packaging material.

In terms of transfer potential to industrial processes, there is a direct analogous transfer to cultivated mushroom production. Necessary sterility of the brood and the substrate. Use of selective inhibition of foreign germs by specifically kept antibiotic-producing bacteria to keep the culture healthy. Maintaining optimal and constant climate control for the mushroom (temperature, humidity, ventilation for O2 supply and /CO2 removal) through structural arrangements in underground chambers, and keeping these mushroom gardens separate from other functional spaces such as brood chambers and waste heaps.

As can be seen from this, these processes that can be found make a great deal of sense, and humans, through empiricism and science, have independently adopted very similar processes for e.g. mushroom cultivation, but also for other agricultural productions, including cattle farming.

The question now is whether the transfer to human activities that are increasingly distant from the biological model, such as logistical processes and production in the technosphere, can be successful.

The hypothesis is that even further potential for optimization can be exploited if principles that have been successfully applied for millions of years are transferred to processes that have only been developed for a few decades or centuries.

3. Successful transfers from the biosphere to the technosphere and potential new inspirations.

3.1. Ant algorithms

Ant algorithms (AA), also known as ant optimization algorithms, are heuristic optimization algorithms inspired by the natural behaviour of ants. These algorithms are used in many fields of engineering to solve complex optimization problems. Here are some applications of ant algorithms in engineering [10].

- Network optimization: AA can also be used in the optimization of networks. This involves finding the most efficient way to transport data within a network. For example, the algorithm can help avoid bottlenecks in the network or minimize latency.
- Production optimization: In manufacturing, AAs can be used to optimize the planning of production processes and the allocation of resources. In doing so, the algorithm can help to increase the efficiency of production and reduce costs.
- Robotics: AAs can also be used in robotics to optimize the behaviour of robots. The algorithm can help robots move, navigate and complete tasks efficiently.
- Power management: they can also be used in optimizing energy consumption in power plants or other facilities. This involves minimizing energy consumption by having the algorithm calculate the optimal operating conditions.

3.2. Swarm intelligence

Swarm intelligence (SI) is a phenomenon in which groups of individuals, such as birds, fish or ants, are able to work together to solve complex tasks and make decisions that are beyond the intelligence of any single individual. In such swarms, emergent intelligence emerges from the interaction of the many individuals.

This phenomenon is increasingly used in engineering to solve complex problems where conventional approaches fail. Here are some examples of applications of swarm intelligence in technology:

- Robotics: SI is used in robotics to optimize the behaviour of robots and solve complex tasks. Algorithms based on the principles of SI are used to coordinate the robots in the group and control their movements.
- Traffic control: SI is also used in traffic control to improve the flow of traffic in cities.
- Financial analysis: SI is also used in financial analysis to make forecasts and predictions..
- Risk management: SI is also used in risk management to assess and minimize complex risks.

Particularly for production, swarm intelligence is found in the:

- Production planning: SI is used in production planning to determine the optimal time and sequence for the production of goods. Algorithms based on the principles of SI are used to coordinate and optimize the decisions of the individual machines and robots in the production line.
- Quality control: SI is also used in quality control to detect and eliminate patterns and errors in production. Many data of different sensors and cameras are combined to evaluate the decisions and observations.
- Maintenance and servicing: SI is also used in the maintenance and servicing of machines and plants to detect and eliminate potential problems and errors at an early stage.
- Material flow control: SI is also used in the control of material flow in production to determine the optimal path and sequence for transporting raw materials, semifinished products and finished products.

3.3. Morphological-functional transfers

Some approaches are based on the morphology of natural models. These include, for example, the Tree-Based Hierarchical System (TBHS), a concept that is based on the canopy structure of trees and has been transferred to logistics. The aim is to improve the efficiency and flexibility of transport and storage processes by orienting them to the natural hierarchy of trees [11,12]. The TBHS concept divides the transport process into different levels, similar to the branches and twigs of a tree. The highest level involves the storage and transport of raw materials or semifinished products in larger units, such as pallets or containers. At the next level, these units are divided into smaller parts, which are then transported to the individual production lines.

The further down the hierarchy you go, the smaller the transport units become. Finally, at the lowest level, individual parts or products are transported and stored. The structure of the TBHS allows each element of the transport system to be tailored to its specific tasks. Larger vehicles and storage facilities can be used in the higher levels, while smaller robots and machines can be used in the lower levels to optimize transport routes.

Another important aspect of the TBHS concept is flexibility. The hierarchical structure allows the system to react quickly to changes in production or transport. For example, if a production line breaks down, the transport routes can be automatically adjusted to deliver materials to another line.

The TBHS concept is already in use in some applications, such as warehouse logistics or automotive production. The advantages are obvious: by optimizing transport routes and using automated systems, efficiency and productivity can be increased. At the same time, the environmental impact can also be reduced by lowering energy consumption and CO2 emissions.

3.4 Sensor networks

There are other aspects of plant and animal transport systems that have received little attention so far. It is striking that in trees substances are successfully transported and exchanged over astonishing heights from the roots to the last leaves. As a rule, this does not happen in large packets, but they are transported on evenly and fluently. The same can be seen in the animal counterpart, the transport medium blood. Inspired by the abilities of cells and platelets that circulate in the body, collect data and communicate with each other is the concept of "smart dust". It uses tiny, networked autonomous sensors that are able to collect information and communicate with each other via radio, infrared, optical [13]:

The idea behind Smart Dust (SD) is to produce numerous tiny sensors that are so small that they can fit on a sheet of paper. An important aspect of Smart Dust is the ability of the sensors to operate autonomously. Each sensor is able to make its own decisions based on the data it collects. For example, a sensor that measures temperature can decide whether it needs to increase or decrease its readings to be more accurate.

These sensors can be used in various applications where a variety of parameters need to be measured and monitored.

3.4. Intracellular functional rooms

In biological structures, where combined logistic and synthesis processes take place, one finds compartmentalizations (CM) of the different processes. These are arranged in a sequence accordingly, so that an optimal synthesis, transformation, logistics, freedom from disturbances, flexibility of action is given. Interesting aspects of the transfer are input and output of material, energy and information as well as certain distribution principles. In addition, the recycling of materials that are not (no longer) needed.

Compartmentalization in cells has various functions and advantages. It enables efficient organization and regulation of biochemical reactions and ensures that the various functions of the cell can be coordinated and optimized. Here are some important reasons why cells are divided into different compartments:

- Separation of reactions: CM can be used to separate and optimize various biochemical reactions. For example, enzymes and proteins can be concentrated in a particular compartment to increase their efficiency and reduce the likelihood of unwanted side reactions.
- Regulation of concentrations: CM allows cells to concentrate certain substances and ions inside or outside a compartment to regulate electrochemical balance. For example, by separating ions in different compartments, cells can create an electrochemical gradient that can be used to generate energy in the cell.
- Protection of DNA and RNA: DNA and RNA are contained in the cell in special compartments such as the nucleus and mitochondria to protect them from the effects of chemical reactions and enzymes. This ensures that genetic information remains intact and can be retrieved effectively.
- Isolation of waste products: CM also helps to collect and isolate waste products from biochemical reactions in a particular area to minimize the impact on other cellular areas. For example, the waste products of metabolism are collected and disposed of in lysosomes.

The direct analogy is obvious for the chemical industry: to point 1. separation of reaction rooms, to point 2. concentration in the sense of storage in one place, from where the substances and materials are brought to the locations of consumption. To point 3. technology and software worthy of protection in control cabinets securely locked, access of energy and data via the incoming cable connections. which corresponds to the microtubules in the cells (see below). To point 4. collection of waste either for direct reuse in production (e.g. by remelting metal residues) or for disposal by a waste management company or the wastewater treatment plant.

3.5. Intracellular transporting systems

At a finer granularity, Helbig et al. [14] studied the transport processes between compartments at the molecular level and presented interesting aspects whose transfer to industrial contexts is worth discussing. A few of them are:

Motor proteins and microtubules are components of cells and play an important role in intracellular transport of proteins and other molecules. Microtubules are long, cylindrical structures composed of tubulin proteins and are found in many cell types. They form the scaffold of the cytoskeleton and serve as highways for transporting nutrients, signals, and organelles to specific locations within the cell. They glide along microtubules using energy from ATP (adenosine triphosphate) to perform transport tasks. There are different types of motor proteins that have different tasks. Of interest is the prevention of congestion and the control of transport dynamics. For this, nature has implemented some control mechanisms to regulate the speeds of motor proteins. However, in general, the transport of molecules into and out of the nucleus occurs very rapidly. Some studies estimate that several thousand transports can occur per minute, with some transport proteins reaching speeds of up to 10 micrometers per second. In this context, the size of proteins is in the lower nanometre range, and the length of microtubules is 25 µm, which shows the enormous transport speed [15,16].

Analogous industrial in-house transport systems can be found - (pneumatic tube, cable robotics, conveyor belts, driverless transport systems), but except for driverless transport systems, material packages cannot overtake each other and the relative speeds and traffic density is far from the performance of biological microtubule motor protein systems.

Recycling is an important feature of cellular logistics. Material transport between the periphery and the cell centre occurs simultaneously with sorting of ingested cargo and information exchange (signal transmission to the nucleus). This parallelism enables cells to perform transport and sorting of goods and sorting on enormously compressed temporal and spatial scales, and to avoid overcrowding in transport processes to the nucleus. In human transport systems, only sequential functional processes are found. However, starting in the 1920s, the German national postal service introduced postal wagons on which letters were sorted during transport, resulting in a significant acceleration of delivery and increased efficiency. With the introduction of mail centres and full automation, sorting by human hand during the journey was terminated again.

The high logistic performance in the cell is achieved by a combination of several processes, which could be of interest for an analogous implementation in the technosphere. First successful resulting control principles may be self-organized and decentralized (bottom-up approach) traffic control systems. These react flexibly to the actual local situation and not to an average situation.

3.6. Optimization of factory layouts

Tinello and Winkler [17] tested the arrangement of functional areas in three real-world factory layout approaches, where biological design structures such as of nautilus shell, wheel spider webs, honeycomb bees, and Fibonacci double spirals were transferred to factory layouts for their optimization and compared with classical ideal layout planning. Four objective categories were evaluated by means of multi-criteria evaluation 1. material flow; transport performance ratio, 2. the area requirement 3. the planning effort, calculation effort, area shape changes as well as the complexity of the method and 4. the changeability; flexibility and mutability of a layout.

The biological system design patterns found were able to improve an existing layout situation. Moreover, three of the four biological approaches gave a better overall score than the studied classical layout design procedures. The rearranged layout using the Fibonacci double-spiral method was able to reduce the transport performance ratio of the original layout by 43.5%. Applying the theorems of Tompkins and White [18] that between 20% and 50% of the total operating expenses within production can be allocated to material handling costs, the bioinspired factory layout planning could reduce the production costs at least between 10% and 30% and also increase the productivity. Bio-inspired approaches show their strengths especially in more complex nonlinear material flows and in the target category changeability compared to classical methods. However, in the planning effort category, bio-inspired methods underperformed due to the more complex approach and the additional effort involved.

3.7. Transition Towards Circular Economy

Bockholt et al. [19] investigated processes of continuous foraging and digestion of organisms, and transfer to industrial product recovery systems. A parallel was found between digestion and recovery processes. By transferring the biological methodology of digestion curves for different food types, a mathematical model was developed, which can be used to calculate an optimal recycling process for products can be calculated. This allows well-founded strategic decisions to be made about product types and their end-of-life recovery strategies: is a recycling process worthwhile, or is reprocessing or reuse after refreshing preferable?

3.8. Tools and materials of sustainable production

In the search for ecologically sustainable production strategies, one comes across the following four requirements that characterize them:

- Resource efficiency: The optimization of production processes to minimize the use of raw materials, energy and water. This also includes measures such as the use of renewable resources, the reduction of waste and emissions, and the use of recycling and upcycling methods.
- Circular economy: the promotion of production processes that aim to return waste to the production cycle in order to use it as a resource. This includes measures such as designing products that are easy to repair or recycle, and using waste products to make new products.
- Environmentally friendly materials: using materials that are more environmentally friendly than conventional materials. This includes bioplastics, which are made from biodegradable materials, and materials derived from renewable sources such as wood, bamboo or chitin.
- Energy efficiency: The optimization of production processes to minimize energy consumption.

Since nature has now obviously found optimal production strategies for all the points mentioned, the question arises as to how nature does this exactly, which are the tools of nature that are able to build structures at ambient temperature.

Nature's tools - whether they are animals or plants or fungi or bacteria - are enzymes. Enzymes are proteins that serve as catalysts in biological systems. They accelerate chemical reactions necessary for metabolism and other vital processes in organisms. Enzymes are specific to a particular reaction and interact with the molecules they transform to speed up the reaction. This builds up, transforms and breaks down structures. Enzymes seek out their reaction sites and reactants, found among hundreds of others.

How can a biomimetic transfer for technical production processes look like?

Partial transfer of properties from biological production systems has in principle been achieved using additive processes. What all current processes have in common is that material particles are fused by the action of heat. The particles must be made of pure material. And if they are of biological origin, these have been heavily processed (e.g. polyamides (PA), polylactide (PLA)), which in turn has a negative impact on degradability. The truly sustainable biopolymer must be both biogenic and biodegradable; all other types of bioplastics must be labelled as fraudulent. It must be possible to reintroduce unreacted biopolymer substrate into the cycle, which is often limited due to the necessary purity of previous powders.

Another strategy is to use the same natural tool to create the strongest chemical bonds, the covalent, in biogenic substrates. For example, Protte and Schwarz [20] use the second most abundant biopolymer, chitin powder, generated in crustaceans, insects, and fungi, to additively process it into artefacts using enzymes and other biogenic additives. A number of other biological resources such as wood and wood components (lignin and cellulose) and other agricultural side streams are currently being investigated as potential plastic substitutes to be molecularly linked via enzymes [21,22]. All four of the above sustainable production strategies are addressed by enzymatic 3D printing (so-called ENCAM processes [21]):

- Use of renewable resources and waste materials, production processes at mild temperature (< 70 C),
- no molecular changes in the starting materials that would hinder biodegradability.
- Reusability of raw materials not consumed in additive processes, as well as the
- possibility to reuse the components of the artefacts after the end of their life.
- Potential for self-healing through reactivation of added enzymes.

4. Conclusion

It could be shown on the basis of the leaf cutting ants that there are striking analogies between biological production processes and man-made ones, which shows that the human logic follows the same idea of effectiveness and efficiency as that of evolution.

Some algorithms belonging to model-based biomimetics have been successfully applied in the technosphere. They have been able to optimize best practice examples at various levels.

Others presented biological logistic, production and recycling processes on different scaling levels differ at first sight from industrial ones. However, they are each incredibly powerful in their own context. It is worth reflecting on the relevance to industrial processes, understanding the principles and thinking about the possible analogous transfer.

Whether companies are optimization-driven or innovation-driven, they both find inspiration in macroscopic and microscopic biological processes - because everywhere there is transport, production, selection, recycling, just on smaller scales. The hypothesis remains that even further potential for optimization can be exploited if principles that have been successfully applied for millions of years are transferred to human processes that have only been developed for decades or centuries.

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