SWARM INTELLIGENCE AND ANT COLONY APPROACH - CAN THEY BE APPLIED IN OPTIMIZING CONSTRUCTION PROCESSES?

Fritz Gehbauer[1], Patricia Stock[2] and Peter Steffek[3]

ABSTRACT

A swarm can be described as a group of individuals using direct and indirect communication to act without central command with high efficiency in problem solving. For example, the insect society as a whole is extremely efficient due to a sophisticated form of self-organization is based on an indirect communication between its members. This communication is both between the members and their environment. For example the ant behaviour leads to repeatedly finding near optimum strategies in food supply, logistics and formicary construction. Studies of this behaviour have led to the first usable algorithms in the solution of logistical problems, in evolutionary programming and in manufacturing planning and control. A few examples will be presented.

This paper will further study the differences between construction intelligence and swarm intelligence and discuss the possibilities to adapt this evolution to systems and problems of construction processes. First considerations have shown that the principles of the existing ant algorithms and simulation tools of manufacturing can be used in construction as well. In case of disturbances fast reorganization of processes can be developed using the algorithm. Modifications have to be made in terms of a number of definitions and system parameters. Any self-organizing system relies on frequent measurement, rapid distribution of information and near optimum reactions. By improving the related abilities construction can be made more transparent and goal-oriented. The paper is concluded with considerations as to whether swarm intelligence and derived algorithms can make a contribution to a construction theory (understanding the processes).

KEY WORDS

Swarm Intelligence, ant colony approach, wasp colony approach, managing the process, optimizing construction processes, resource planning

[1] Professor, Institute for Technology and Management in Construction (TMB), University of Karlsruhe, Am Fasanengarten, D-76128 Karlsruhe, Germany, gehbauer@tmb.uni-karlsruhe.de

[2] Chief Engineer, ifab-Institute of Human and Industrial Engineering, University of Karlsruhe, Kaiserstraße 12, D-76131 Karlsruhe, Germany, patricia.stock@ifab.uni-karlsruhe.de

[3] Research Assistant, Institute for Technology and Management in Construction (TMB), University of Karlsruhe, Am Fasanengarten, D-76128 Karlsruhe, Germany, steffek@tmb.uni-karlsruhe.de

1. INTRODUCTION

Obviously, the title of this paper belongs to the wider context of bionics. Bionics deals with studying the techniques and technologies of nature and with learning from these. On the other hand technical biology uses technical knowledge to gain a better understanding of biological processes. A permanent interaction of feedback and learning takes place between the two fields. A considerable number of technical improvements from the field of bionics have been introduced into mechanical engineering, aeronautics and other fields in order to significantly increase performance. However, it should be noted that nature does not deliver blueprints and cannot be copied; but it can be understood and it can stimulate new ideas.

One well-known example is the development of the airplane by studying the birds. The result was the early airplane wing; however, the propulsion system of the airplane is completely different. The direct copy of the wingtips of eagles and other birds at the ends of most modern airplane wings for better aerodynamics came much later. Nature can deliver a lot of ideas for developing or modifying structural or mechanical elements. A considerable community of practitioners and researchers has been working in these fields for quite a while.

The application of bionics in processes is relatively new and underdeveloped. A number of fascinating books have been written by biologists describing how ants, bees, wasps, and termites are organized, how they build their complicated structures and how thousands or ten thousands of individuals survive, multiply, cooperate, and organize themselves. Compared to structural engineering little has been done so far from the engineering side to study natural organization and production processes to optimize human cooperation as well as to plan and control complex production processes. It is easy to understand why comparisons between animal states and human states and subsequent optimizations have not yet been attempted. Too large are the differences between the two. The animal state is absolutely necessary for the survival of its individuals. In the human world the individuals could survive without the state. Furthermore, the differences within the individuals are too big: Individuals in an animal state behave as a result of evolution, whereas in a human state the evolutionary heritage is there as well, but supplemented by individual wishes, aspirations, egoisms etc.

Nothing or not much has been done to studying natural organizations and co-operations in order to gain ideas for the organization of very large human groups with hundreds or thousands of individuals and their cooperation. The analogy, however, is obvious if we look at the large earthmoving jobs (railroad construction) of the 19th century when most of the earthworks was done by hand by thousands or more individuals. From the distance they must have looked like busy ants. Inarguably the humans working there were of incomparably higher intelligence than ants. Nevertheless, ants seem to be very efficient and effective in solving their logistical problems and in organizing their cooperation. Somehow the impression comes up that ants would organize a multi-thousand-agent hand excavation more efficiently than the humans. Even if one cannot agree with this perception, it seems worthwhile to study how completely unintelligent individuals can create something like termite hill with a ventilation or air conditioning system in a dynamically changing environment. A quick observation could be: It doesn't make sense to compare this with construction since the insects are controlled by genes developed by evolution. This is only partly true. There also exists a certain degree of self-organization that is worth studying in order to think about modifications in construction organization. The individuals communicate directly and indirectly between themselves and their environment. For example, the ant behaviour leads to repeatedly finding near optimum strategies in food supply, logistics and formicary construction. Consequently engineers, mathematicians, computer scientists dealing with logistical problems and processes engineering have studied the ant behaviour and developed algorithms based on the ants' heuristic approach to quickly reaching relatively fast near optimum solutions. The first algorithms are in use in solving logistical problems, in evolutionary programming and in manufacturing planning and control (see section 3).

Nothing of this sort has been done in construction thus far. The basic purpose of this paper is to initiate a discussion and to create a platform for further investigations as to whether and how further research would be feasible. This is done in three steps. In section 2 the behaviour of ants and other swarm insects are reviewed (by engineers!) to look at the difference between their organization, behaviour and construction organization. Have these highly efficient natural systems something to offer to construction planning and control? In section 3 some examples of algorithms derived from insect behaviour are presented in the application of logistical and production planning problems. They will also be reviewed in order to study their applicability in construction. In section 4 some possible applications in construction are presented and discussed. Section 5 presents conclusions and recommendations.

2. NATURAL ROLE MODELS FOR PROCESSES

At this point it should be mentioned that it is not intended to discuss the question: Can we put up a construction team on site and leave them to self-organizing, optimizing and creating their own structure as a result of the environmental parameters? In this paper we always comply with the paradigm that the original construction design and plan must be created at the end of the day. However, we discuss the possibilities of introducing some self-organizing features in our construction processes.

The natural reaction of cells to stress with the result of optimized structures can be biologically explained, but still holds a high degree of "wonder". It seems even more "wonderful" when we look at optimized structures that have been developed not by reactions to stress, but by completely unintelligent small insects. Are there some secrets of self-organization that could be used for construction execution and organization?

There are ants that construct vaulted nests of clay and that use existing straw and grass as living supports. How can ants be put into the position of constructing a millennium dome? Each little individual arrives with a little lump of clay. Where is the information for each one to put the piece of clay exactly into the curvature of the future dome? There is no construction manager. There is also no construction manager telling the compass termites to place each minuscule little lump of earth in such a way that the future huge structure has an exact north-south orientation. How do termites organize themselves when they restructure their ventilation system to adapt to changing conditions when there is no central command or measuring device? When and how do ants construct a facade and a winter covering for their formicary without central command? How do they organize their garbage disposal and cemeteries?

Various temperatures are maintained in various chambers of the formicary depending on whether eggs, larvae or pupae are found there. In various chambers of the formicary different degrees of humidity are necessary during various periods of the year depending on what should be produced there. This humidity is controlled by ventilation. Who measures and gives orders? How do ants rapidly find the fastest way around an obstacle even when this way cannot be seen? After severe disturbances defence brigades and repair brigades are built up immediately. How? Can we learn something for construction if we understand how the ants accomplish this?

The ant colony and construction

An easy answer would be: No, ants have their genes and act in a robot-like manner; those robots cannot be compared with construction workers. Many other arguments could be found to resist the idea of comparison. However, we would like to put forward the idea of studying similarities and of applying some principles of ant organization, which is not only genes, rather really self-organization. It should be noted that there are hierarchies and a considerable degree of specialization, as in construction. There are even sub-contractors (lice).

There is no blueprint of the nest in each ant as there is no blueprint of the complete building in the construction worker. The ants react to certain conditions. These conditions are not pre-determined or created by a leader or planner, rather each ant has the ability of rapidly measuring the environment, be it moisture, degree of sunshine, direction of sun, temperature, finest airstreams etc. Most of the individuals can measure these. This ability makes them reorganize the ventilation system, put the larvae in another chamber, relocate the nest according to weather conditions and execute many other organizational and structural activities. Generally, the most agile and sensitive ants will trigger the various processes. The measuring process is continuous and therefore the ability of the population to react is immense.

Here we have the major difference to the construction organization and intelligence that has to be discussed. Construction individuals do measure their own tasks in terms of dimensions, type of materials used, and other parameters of quality. That's about all. Sometimes the rate of progress is also measured by the individual or at least he or she has the sense of being fast or slow. The individuals neither know whether their rate of progress is correct at the moment in time in relation of the overall progress of the building, nor do they receive regular information as to the state of the other parts of the process. Measurement is carried out only by specialized people sometimes only by the project manager in his monthly status report. The frequency of measuring the determining parameters on site is much too low and the individual has no way of measuring the overall progress or receiving the information from other parts of the progress; there is no way of optimizing, fast reaction and quickly redistributing the resources. All this is different in the ant colony, where each individual can measure, reaction time is minimal and optimization of the processes is guaranteed. Doesn't that sound lean? The content of the latter phrase must be intriguing. Can we change construction in order to reach the same or similar results?

Can we create a system where management, information, knowledge and training can be designed for a more natural way of constructing? What is the "natural" behaviour of a construction worker? A modified construction must give the individual much more and quicker information about the construction process and must create an environment of motivation to use this knowledge for the overall improved progress of the project. This includes relocation of resources from places where time reserves exist to places that lag behind. It would also include the sub-contractors. The latter seems to be impossible. But what is the impossibility in this context? The actual state in construction is that every partner and stakeholder works according to his contract. He is prepared to fulfil the contract regardless of cost (to others). With this overdeveloped egoism sometimes an individual claim can be "achieved" mostly at the cost of the overall project result. A new construction system has to develop a system of overall benefits that would help to reach the project targets faster and more securely and distribute these benefits to all parties and individuals.

Without rewards no change. Incidentally, giving immediate rewards is another control instrument in the formicary. Caressing is rewarded by food transfer from one individual to the other. Larvae deliver drops of sweet resulting in the stimulus to care in the worker ant. Often work and performance are rewarded immediately. Can we devise similar systems of more rapid reward on construction sites? Many thousand times a day semi-products are passed from one worker to another or from one sub-contractor to another. The quality of this transfer determines the smoothness of the construction process. Unfortunately, a great deal of all working hours on site is spent with rework and the remedy of uncompleted or false products. The system of complaining should be replaced by a system of rewarding.

The individuals of one particular formicary population are identified by their smell. Individuals with this smell belong to each other, help each other and work for the common goal. In an improved construction system these common goals should be identified more clearly, shown more clearly and be part of the contracting system. Transparency and common knowledge would also contribute to better results.

How "lean" is formicary organization?

Production and organization of a formicary are controlled by the natural rhythms: seasons, day and night, multiplication, breeding, foraging. Individuals react to these controlling factors in an optimal way. It is the perfect pull system. Steady flow of food and information is the basic factor in producing something like workflow reliability. Pheromones (see section 3) guide systems to optimize logistics and also to contribute to workflow reliability. The fact that this was so, long before Lean Construction came up, should facilitate the thought of applying one or the other concept of ant organization to construction sites as well. It should be noted that there is a certain degree of push in the ant colony system as well. If a pheromone path is artificially interrupted by humans, there will be a hold up on the ants' logistic road; no individual knows what to do at this point of missing information. Suddenly, one individual runs across (being pushed by social or physical pressure?), thus closing the gap and all are on their way again. This pushing into new situations can be observed in other situations as well.

Pull is also generated when the number and size of larvae (and their appetite) are increasing. During these periods the worker ants develop their greatest activity and aggression in terms of foraging. They work until exhaustion. Overloading and overproduction is obviously a natural reaction in some situations. How can this be introduced as a "natural" factor to construction?

Another construction feature, the strong specialization and division of work, is more natural than we assume. Some ant populations have more than 10 specialist worker types in their work force. An extreme example of specialization is the body of the higher developed animals. The specialization of the various organs is even more developed and complicated than the construction system. The difference is that, in nature, the more specialized cells or organs are the faster and better the communication must be. Hormones and other means of communication function in seconds or milliseconds in order to guarantee the harmonized and organized cooperation of the specialist organs. Far away are we on construction sites from such a system of communication. Of course we cannot put up such a system, functioning in a frequency of seconds or minutes, but we have to increase the frequency of measuring to the frequency of disturbances. As in construction, nature is inclined to specialize. In order to handle this, it is decisive to establish an intensive communication between the specialized groups. Some principles of Lean Construction and software support are designed to improve this communication. Further improvement and systematic approaches are necessary.

Table 1: Traditional construction and swarm organization

Prevailing situation in construction	Swarm organization
Reward frequency: weeks or years	Immediate rewarding
Measurement frequency: weeks	Immediate and frequent measurement
Cooperation between stakeholders: week, sometimes „anti-operation“	Individuals measurement
Specialization high, but no or slow direct communication	Fast communication for optimal solutions
Central command from position of limited information	No central command, only framework by genes
Individual has practically no information of the overall process; Triggering action: directive (what, when, as fast as possible)	“What to do” is in the genes and “When to do it and how” are triggered by measuring and sensing the environment (light, sun, small, sizes (larvae), moisture, temperature, etc.)

Many of these are already part of lean thinking and are discussed in numerous IGLC papers (e.g. Alarcón, Serpell 1996; Barlow 1996; Lantelme, Formoso 2000; Bertelsen 2003).

3. THE STATE OF THE ART OF ANT AND OTHER ALGORITHMS

The Idea of Swarm Intelligence

First of all, Beni and Wang (1989) proposed the idea of Swarm Intelligence in the context of cellular robotic systems composed of autonomous robotic units accomplishing tasks in cooperation. Today, the concept of self-organizing robots is still going strong. For example, for the cleaning of public places (e.g. train stations, airports, supermarkets) Siemens have developed cooperating cleaning robots. The robots clean not only a predefined section, but rather operate dynamically: E.g., if an airport robot is forced to pause, because the waiting queue at the check-in counter is to long and passengers are blocking its path, the machine attempts to contact its colleagues in order to request help to clean the area as soon as it is clear (for details see Zechbauer 2002).

However, the concept of Swarm Intelligence has gone beyond the scope of robotic systems. It’s now also a technique of artificial intelligence. Bonabeau, Dorigo and Theraulaz (1999, p. 7) define Swarm Intelligence as “any attempt to design algorithms or distributed problem-solving devices inspired by the collective behaviour of social insect colonies or other animal societies is defined as swarm intelligence”.

A swarm can be described as a group of individuals using direct and indirect communication to act without central command with high efficiency in problem solving. This communication can be both between the members and their environment. Grassé (1959) introduced the term stigmergy to explain the behaviour of termite societies building their nest. More recently the same term has been used to indicate communication mediated by modifications to the environment that can also be observed in other social insect societies. Therefore, an insect society as a whole is extremely efficient due to its sophisticated form of self-organization

Some typical examples for social animal societies are listed in Tab. 2. Many of these examples have been applied successfully to practical problems.

Table 2: Examples for Swarm Intelligence and their practical application

The Ant Colony Approach

Example for Swarm Intelligence (Source: Bonabeau, Dorigo, Théraulaz 1999)	**Practical application** (Source: Bonabeau, Théraulaz 2000, pp. 77)
Termite nest building	-
Division of labour and task allocation	Distribution of work in the paint shop of an automotive company
Wasp nest building	Control of autonomous satellites in the orbit
Cooperative transport	Cooperative transport of robots
Foraging of ants	Routing of telephone networks as well as internet traffic
Foraging of bees	-
Self-organization on the combs of honeybee colonies	-
Cemetery organization or brood sorting by ants	Analysis of financial data
Thermoregulation in clusters of bees	-

One of the most successful swarm intelligence techniques currently in existence is the Ant Colony Approach which is derived from the foraging of ants: In the beginning, the foraging is totally unsystematic and the ants spread out uniformly in all directions. The ants deposit a diffusing chemical substance called pheromone on the paths taken, both on the way to the feed as well as on the way back to the formicary. Later on, the ants probably prefer trails with a high pheromone concentration. Gradually, short paths to the feed have a stronger pheromone concentration than long paths. Therefore, the shortest path to the feed in the best time can be identified by the ants. Also, new barriers can be detected and bypassed (see Fig. 1; acc. Goss et al. 1989, p. 579): After the direct path to the feed (a) is blocked, the ants initially have no preference for one of the by-passes, since the pheromone concentration on both paths is zero (b). Therefore, they use both paths uniformly. After a little while, the pheromone concentration on the shorter path becomes stronger than the pheromone concentration on the longer path (c). Finally, almost every ant uses the shortest path (d). In the same way, a path can be abolished, when no feed is left. Goss et al. (1989), Deneubourg et al. (1990) and Boneaubeau et al. (1997) investigated the behaviour of biological ants.

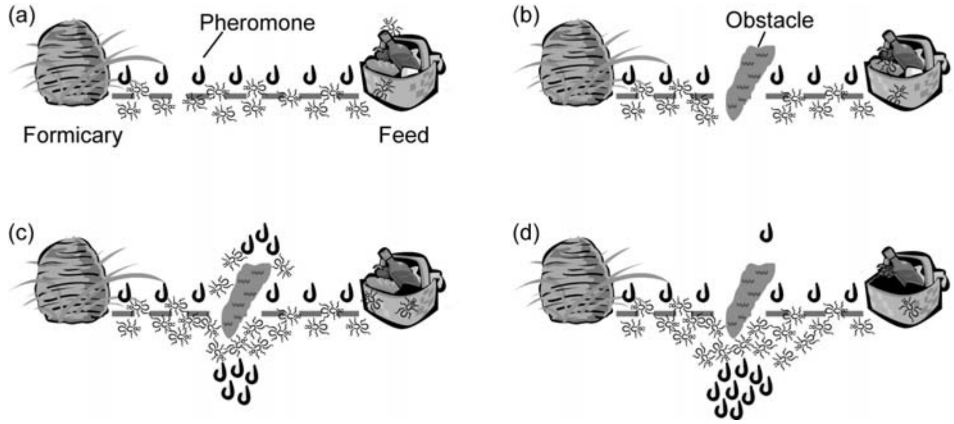

Figure 1: A colony of Iridomyrmex humilis selecting the shortest by-pass of the obstacle (acc. to Goss et al. 1989, p. 579)

Dorigo (1992) transferred the results from biological to artificial ants and the first ant algorithms, the so-called "ant system", in order to solve the Travelling Salesman Problem. The Travelling Salesman Problem is a problem in combinatorial optimization (for details see e.g. Lawler et al. 1985): The travelling salesman has to visit a number of cities exactly once and then to return to his starting point. In doing so, his goal is to minimize his total expenses. Although the problem is simple to describe, the solution of the problem is rather complex. The Travelling Salesman Problem is a prominent example for a class of problems in computational complexity theory which are hard to solve (so called NP-hard).

The Ant System is using the behaviour and pheromone tracking of biological ants though it also differs in several characteristics, namely (Dorigo, Di Caro, Gambardella 1999, p. 142):

- Artificial ants live in a discrete world and time,
- Artificial ants have a memory of their past actions,
- Artificial ants may have special capabilities (e.g. foresight, local optimization) and may have access to further information particular to the problem (so-called heuristic information),
- Artificial ants update pheromone trails only after having generated a solution and the amount of pheromone deposited may be a function of the quality of the solution found, and
- Pheromone evaporation is required.

The ants of the Ant Systems undergo the following phases repeatedly (Dorigo, Stützle 2004, pp. 65):

- In the first phase, a colony of ants moves concurrently and asynchronously through the solution space. They move by applying a stochastic local decision policy that makes use of pheromone trails and heuristic information (1). A strong pheromone trail on a path indicates that preceding ants have found good solutions when choosing that path (a posteriori measure; so-called t), while the heuristic information forecasts the (actual) quality of a path (e.g. the costs of a path; a priori measure; so-called h).

- After all the ants have established their tours, the pheromone update is done. The pheromone trail's value can either increase, as ants deposit pheromone on the used solution, or decrease, due to the perpetual pheromone evaporation (2).

Probabilistic determination:

$$p_{ij}^k = \frac{[\tau_{ij}]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{l \in N_i^k} [\tau_{il}]^\alpha \cdot [\eta_{il}]^\beta} \text{ if } j \in N_i^k, \text{else } 0 \quad (1)$$

Update of pheromone trails:

$$\tau_{ij} \leftarrow (1-\rho) \cdot \tau_{ij} + \sum_{k=1}^{m} \Delta\tau_{ij}^k \quad (2)$$

with k ant
i, j nodes
τ_{ij} pheromone trail
η_{ij} heuristic information value
α, β adjustable parameters for the influence of τ_{ij} and η_{ij}
N_i^k feasible neighborhood of ant k when being in city i
ρ pheromone evaporation rate

Initally, three different versions of the Ant System differing in the kind of the pheromone management were proposed. Two of these variants were abandoned because of their inferior performance. In the third variant "ant-cycle" the amount of pheromone deposited by each ant is set to be a function of the tour quality performance (Dorigo, Stützle 2004, p. 70). Experiments have shown that Ant System provides results comparable or even better than those achieved with general heuristic methods (e.g. Simulated Annealing) if the problem instance is small (approx. 30 to 70 cities). For larger problem instances, the optimal solution is found only after a great number of iterations (BONABEAU, DORIGO, THERAULAZ 1999, p. 46).

Nowadays, the importance of the original Ant System remains mainly in being the prototype of a number of ant algorithms (Maniezzo et al. 2004, p. 103). Those ant algorithms have been changed in many ways to improve their efficiency and overview can be found e.g. in Dorigo, Stützle (2004, pp. 65). In some areas, ACO algorithms have obtained world-class performance, which is the case, for example for vehicle routing, scheduling or packet-switched network routing (Dorigo, Stützle 2003, pp. 269).

Ant algorithms can be applied to all problems which can be described by flows in networks. Currently, the great majority of problems solved by ant algorithms are only static problems, for which all the necessary information is available and does not change during the problem solution, e.g. the classic Travelling Salesman Problem (Dorigo, Stützle 2003, p. 278). Therefore, the ant algorithms must compete with very well-established algorithms, often specialized for the given problem (e.g. see Bersini et al. 1996, p. 615). However, Dorigo and Stützle (2003, p. 278) appraise "that ACO algorithms will really show their greatest advantage when they are systematically applied to 'ill-structured' problems for which it is not clear how to apply local search, or to highly dynamic domains with only local information available".

4. APPLICATION OF THE ANT COLONY APPROACH IN CONSTRUCTION

Process-oriented Planning, Calculation and Work Preparation

Process-oriented planning includes the identification of all process needed during the creation of a structure and the consideration of the interdependencies of the individual processes (predecessors, successors). The processes act as containers for additional information (resources, location), as illustrated in Fig 2.

Standardized process databanks facilitate the calculation and allow for a targeted management of knowledge through feedback of lessons learned.

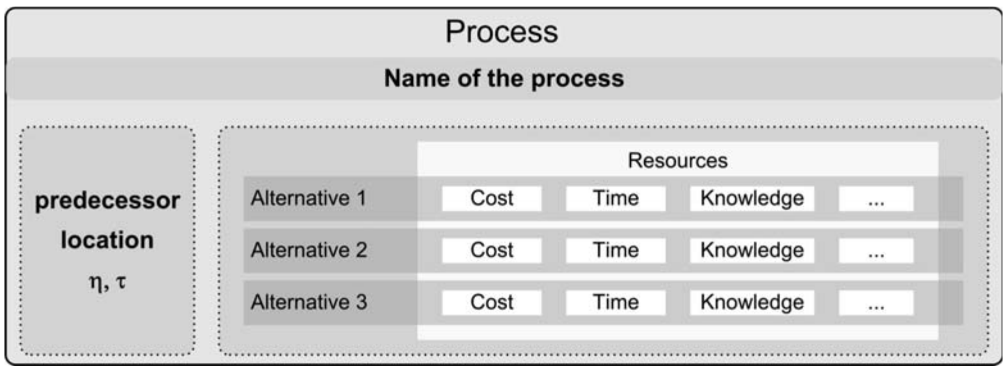

Figure 2: Process as container

The Construction Site as a Process chain

In practice this means that the entire construction process must be subdivided into individual processes. An individual process should thus be understood as a completed activity. In a next step these individual processes are linked with each other in such a way that existing dependencies are taken into account. This means that each process is assigned to its predecessors, which must be fully completed in order for the process to be executed (only beginning – ending relationships). A process web is thus created in which all necessary dependencies for the creation of a structure are considered. The duration of a process and the needed resources are not yet known at this point.

In a last step the individual processes are assigned differing approaches along with various resource requirements. The desired variations for executing the processes should be taken into consideration at this time. The transversely linked process web results in a transversely linked process chain in which each process has several possible sequences with various resource requirements (see Fig. 3).

This creates the possibility of achieving the best possible results for the given conditions (e.g. "observe the due date in three month and minimize the costs") using the ant algorithm. The combinations of various resources in various processes, including the temporal alignment of the individual processes in the complete organization is also considered.

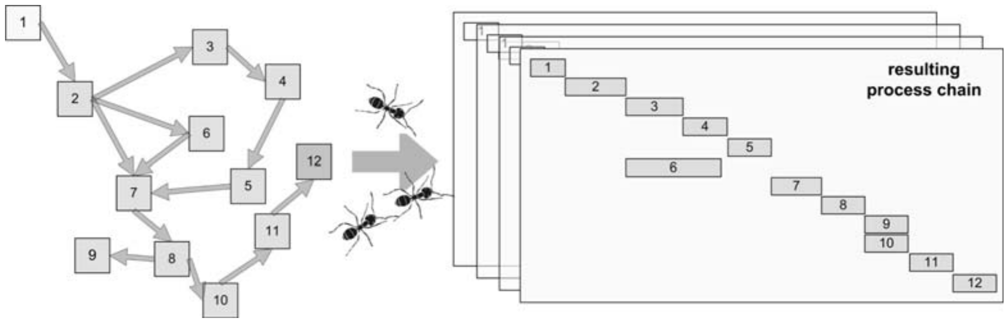

Figure 3: Process web with alternative process chains for execution

Areas of Application in Construction

Combined process scheduling and resource planning with the Ant Colony Approach

The classic application example for ant algorithms is the Travelling Salesman Problem: For example, a travelling salesman should visit 14 cities in Germany, starting and ending in Frankfurt on the Main (see Fig. 4, top). This results in 3,113,510,400 possible travel routes. The task is to find the shortest possible route in which each city is only visited once. At the start of the trip the travelling salesman can choose to travel to any city, whereas after each stage of this trip his options are reduced by the cities already visited. In a first stage the routes between all cities must be initialized with the pheromone value $t_{0,}$ in this case a value of 0.0059. For the first generation of ants $t = t_0$, whereas h is calculated from the reciprocal of the distance to the next city. This results in, for example, a selection probability for Cologne of 13.8 %. Each ant stochastically selects the next city to visit. In this manner each ant successively constructs a route. Once all ants have found a solution the pheromone trails are refreshed. The succeeding generation of ants hence takes the changed t, representing the knowledge of its predecessors, into account during their decision. Since this is a static problem (the distance between the cities remains constant) h is the same for all generation of ants.

Combined process scheduling and resource planning in construction can also been seen as such a routing problem which can thus likewise be solved with ant algorithms. This will be elucidated using the example of the foundation of a structure: In our case this is accomplished with bore piles, which can in turn be manufactured using various equipment (resources) (see Fig. 4, bottom). After the pile foundation has been put in place, a lean concrete layer is placed and the heads of the bore piles are prepared. This leaves us with three separate operations, each of which is carried out in a different manner and with different resources, thus resulting in various execution times and costs.

In the easiest case, the sequence of processes is already defined and merely the resources have to be selected. In the example (Fig. 4, bottom) the case results in 36 alternative process chains. The artificial ants only ever see the direct successor to the process just completed. In other words, upon completion of the process “pile foundation” they may only choose between {L1, L2, L3}. The selection of the appropriate process chain is in part dependent upon the planner's target system: in other words questions like "What does 'best' solution mean? What is the ratio between costs and time? How does the planned finishing date affect these considerations?" On the other hand, in addition to the parameters such as execution time or process costs, which are known ahead of time, other dynamic factors such as e.g. availability of resources must also be taken into account.

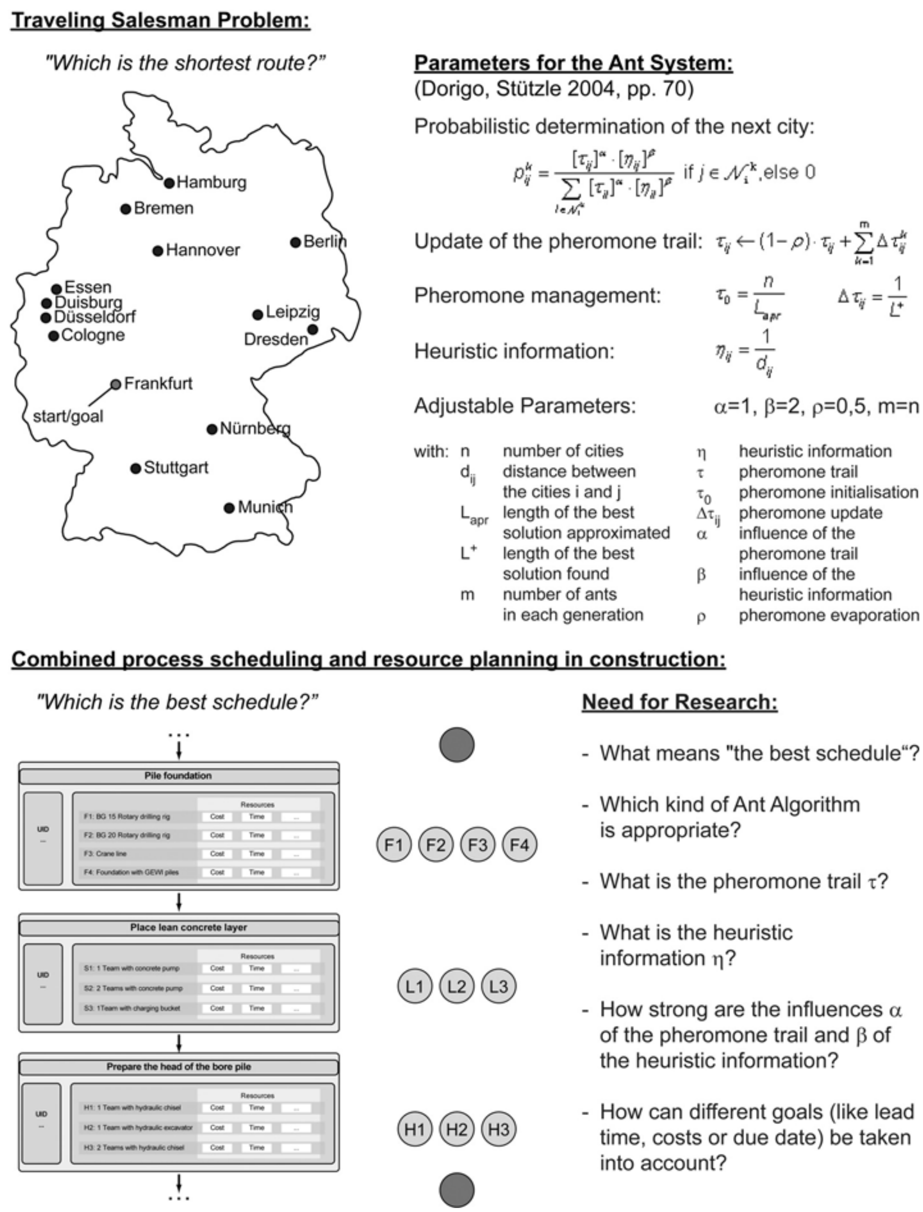

Figure 4: Process and resource planning as a Travelling Salesman Problem

The problem becomes even more complex when the sequence of the processes is no longer defined, rather can also be varied. In the example above, this could mean that "pile foundation" must be completed first and that "place lean concrete layer" must be executed before "prepare heads". If necessary (e.g. in the case of material shortage) the two latter processes could however also be switched. As a result, after completion of the process "pile foundation" the ants have more alternatives to chose from than if the process sequence is fixed, namely {L1, L2, L3, H1, H2, H3}. This results in 72 alternative process chains. In addition to the questions already considered, the prioritization of the process must also be taken into account appropriately.

Scheduling of processes on several machines

A further common application area for ant algorithms is machine scheduling: The simplest application is the One-Machine-Problem in which the order sequence has to be optimized so that the resulting schedule has the lowest costs possible. Thus, each job has a processing duration and a due date. The costs result from deviations from the due date, calculated from storage costs for early completion as well as penalties for delayed deliveries. The cost of a schedule is as such the sum of all incurred costs. Process costs or similar are not taken into account. In accordance with the Ant System, t_{ij} is then marked with the quality of the solution found, while the heuristic value is generally calculated with $h_{ij}=(c_{ij}+1)^{-1}$. In contrast to the static Travelling Salesman Problem, in which the distances between the cities are unchanging, this represents a dynamic problem since the costs are dependent upon the previously made decisions. The complexity of the problem increases when not only one but several parallel machines are available for the processing of the order programme. Detailed summaries can be found in e.g. in Dorigo and Stützle (2004, pp. 39 and pp. 153).

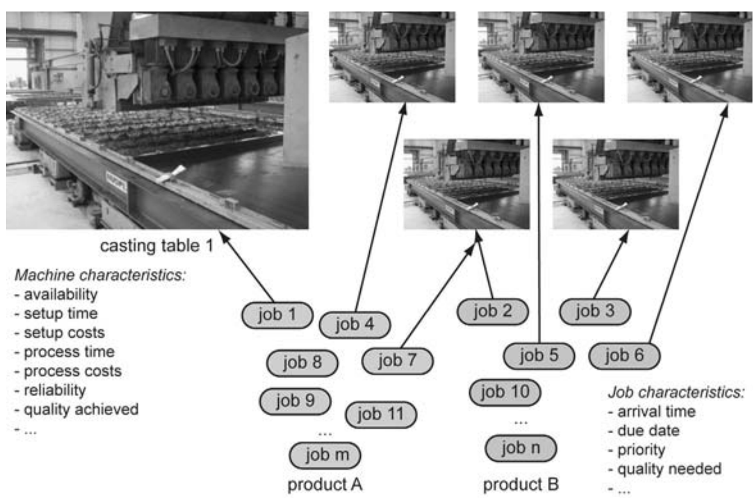

Figure 5: Scheduling of several processes on six machines

This machine scheduling problem can also be found in construction: In a pre-fabricated segment plant, for example, several orders for 2 product types are currently being produced (see Fig. 5). These can be described by job characteristics such as arrival time, due date or priority. Six casting tables are available for processing the orders and differ in their machine characteristics. These include e.g. the machine availability, which can change depending on the time of request, or even the execution time for an order, which can be calculated from the order-specific data. The best possible job schedule must then be found. Ant algorithms can be used to find a solution to such problems, whereas it will be the task of research to develop new algorithms and to find specifications of h and t.

Task scheduling with wasps

Wasps present a further approach to solving task scheduling problems: Wasps' interactions occur in a probabilistic manner and through a dominance hierarchy (see Theraulaz, Bonabeau and Deneubourg 1995). This means that those wasps with a higher social status have a higher probability of being able to assert their interests. Since this interaction takes place in a probabilistic manner (as in the Ant Colony Approach) the dominance of the higher ranked wasps is not inevitable. Cicirello and Smith (2002) presented a concept for a self-organizing job scheduling in a dynamic factory scheduling environment based on the dominance hierarchies of wasps (see Fig. 6, left): High priority jobs correspond to high ranking wasps in the social hierarchy of the nest. Therefore, the probability increases, that a machine will choose one of the high priority jobs after the current job is finished. The force variable F_w of the job w is computed as a function of the processing time T_w^p and setup time T_w^s, the average processing time $\overline{T^p}$, the due date D_w, the weight W_w, and the current time T_{now}.

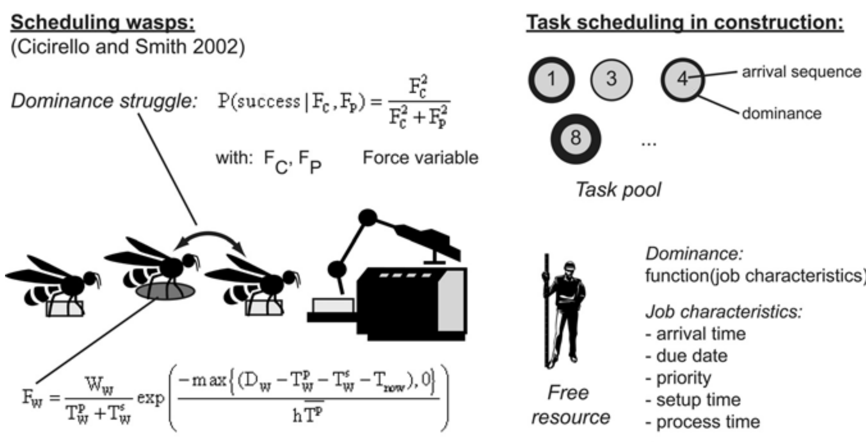

Figure 6: Task scheduling in construction with wasps

This concept can also be applied to the task of scheduling in construction, whereby the wasps are represented by the tasks (in other words individual elements in the process chain): All currently released orders are summarized in a task pool. Orders whose predecessors have not yet been executed completely are not yet contained in the task pool. For example, the processes "place lean concrete layer" and "prepare heads" are only then dispatched into the task pool once "pile foundation" has been completed. All orders in the task pool compete for completion by the freed resources. If one resource becomes free all tasks bid for it. Each task possesses a force variable F which is made up of various general factors, such as e.g. due date, process costs or processing time. In order for a task is allowed to attract the attention of the resource it must be established whether the resource is qualified to execute this task. Depending on the thus determined force variable, the resource then decides, in a probabilistic manner, which task it will process next. In other words, it is highly likely the one with largest force variable (so to say the one yelling the loudest) will be awarded the next processing slot. In Fig. 6 (right) four tasks are competing for processing by the construction worker. Task 8 has the greatest dominance and will thus likely be executed next.

SUMMARY AND OUTLOOK

In this paper three distinctive areas of the overall topic have been discussed. The first one deals with the biological background (interpreted by engineers) with some comparisons to construction. In order to reach the efficiency of the ants construction would have to change in the following contexts: process information has to be collected in more detail and be spread to the stakeholders more rapidly; the frequency of measuring has to be increased to the frequency of disturbances; the optimum between directive and self-organization has to be found; common goals should be identified more clearly, shown more clearly and be part of the contracting system; the system of complaining and claiming should be replaced by system of rewarding.

The second part describes existing algorithmic approaches developed from ant behavior. Production planning and sequence planning can be optimized by these algorithms. Direct applications in construction can be seen in pre-cast element production, structural steel jobs and concrete steel jobs.

The third part gives first indications of how these approaches could be used in other construction areas. The distinctive research field is opening up here. Not only do the parameters of existing algorithms have to be modified or redefined but also algorithms for dynamic systems have to be found. Within the group of the authors one dissertation is under way in the area of dynamic problems in manufacturing another one is being initiated in typical construction applications. In conjunction with modified organizational, behavioral, contractual, and procedural modifications these algorithmic approaches can contribute to progress in Lean Construction and to a better understanding of our construction processes.

REFERENCES

Alarcón, Luis F. and Serpell, Alfredo (1996). „Performance Measuring, Benchmarking, and Modelling of Construction Projects.“ *Fourth Annual Conference of the International Group for Lean Construction*, Birmingham, U.K., August, 1996.

Barlow, James (1996). “Partnering, lean production and the high performance workplace.” *Fourth Annual Conference of the International Group for Lean Construction*, Birmingham, U.K., August, 1996.

Beni, G. and Wang, U. (1989). “Swarm intelligence in cellular robotic systems” *NATO Advanced Workshop on Robots and Biological Systems*, Il Ciocco, Tuscany, Italy.

Bersini, Hugues, Dorigo, Marco, Langerman, Stefan, Seront, Gregory, and Gambardella, Luca Maria (1996). “Results of the first international contest on evolutionary optimization (1st ICEO).” *Proceeding of IEEE International conference on evolutionary optimisation*, IEEE, Nagoya, Japan, pp. 611-615.

Bertelsen, Sven (2003). “Complexity – Construction in a New Perspective.” *Eleventh Annual Conference of the International Group for Lean Construction*, Blackburg, VA, USA, July, 2003.

Boneabeau, Eric and Théraulaz, Guy (2000). “Virtuelle Ameisen als Software-Agenten.” *Spektrum der Wissenschaft*, May Issue, 72-78.

Bonabeau, E., Dorigo, M., and Théraulaz, G. (1999). *Swarm Intelligence: From Natural to Artificial Ants*. Oxford University Press, New York.

Bonabeau, Eric, Theraulaz, Guy, Deneubourg, Jean-Louis, Aron, Serge, and Camazine, Scott (1997). “Self-organization in social insects.” *Trends in Ecology and Evolution*, 12(5) 88-192.

Cicirello, V. and Smith, S. (2002). “Distributed Coordination of Resources via Wasp-like Agents.” *First NASA GSFC/JPL Workshop on Radical Agent Concepts (WRAC)*, January, 2002.

Deneubourg, J. L., Aron, S., Goss, S., and Pasteels, J. M. (1990). “The self-organizing exploratory pattern of the Argentine ant.” *Journal of Insect Behavior*, 3(2) 159-168.

Dorigo, Marco (1992). “Ottimizzazione, apprendimento automatico, ed algoritmi basati su metafora naturale (Optimization, Learning and natural algorithms)” PhD Thesis, Dipartimento di Elettronoica e Informatica, Politecnico di Milano, Italy.

Dorigo, Marco, Di Caro, Gianni, and Gambardella, Luca M. (1999). “Ant Algorithms for Discrete Optimization”. *Artificial Life* 5(2) 137-172.

Dorigo, Marco and Stützle, Thomas (2003). “The Ant Colony Optimization Metaheuristic: Algorithms, Applications, and Advances.” *Handbook of Metaheuristics*, Glover, Fred and Kochenberg, Gary A. (eds.), Kluwer Academic Publishers, London, pp. 251-285. (International Series in Operations Research & Management Science, 57)

Dorigo, Marco and Stützle, Thomas (2004). *Ant Colony Optimization*, MIT Press, Cambridge, MA.

Goss, S., Aron, S., Deneubourg, J.-L., and Pasteels, J. (1989). “Self-organized shortcuts in the argentine ant.” *Naturwissenschaften*, 76(12) 579-581.

Grassé, P. P. (1959). «La reconstruction du nid et les coordinations interindividuelles chez Bellicositermes natalensis et Cubitermes sp. La théorie de la stigmergie: Essai d’interprétation du comportment des termites constructeurs.» *Insectes Sociaux,* 6(1) 41-81.

Lantelme, Elvira and Formoso, Carlos T. (2000). «Improving performance through measurement: The application of lean production and organisational learning principles.» *Eighth Annual Conference of the International Group for Lean Construction*, Brighton, U.K., July, 1996.

Lawler, E. L., Lenstra, J. K., Rinnooy, A. H. G., and Shmoys, D. B. (1985). *The Traveling Salesman Problem: A Guided Tour of Combinatorial Optimization.* John Wiley & Sons, Chichester et al.

Maniezzo, Vittorio, Gambardella, Luca Maria, and Luigi, Fabio de (2004). “Ant Colony Optimization.” *Studies in Fuzziness and Soft Computering: New Optimization Techniques in Engineering*, Onwubolu, Godfrey C. and Babu, B. V. (eds.), Springer, Berlin et al., pp. 101-121.

Theraulaz, G., Bonabeau, E., and Deneubourg, J. L. (1995). “Self-organization of hierarchies in animal societies: The case of the primitively eusocial wasp polistes dominulus christ.” *Journal of Theoretical Biology*, 174(3) 313-323.

Zechbauer, Ulrike (2002). “Mr. Clean – Reports for Service” Siemens, *Pictures of the Future*, Fall 2002, 58-61.