Pollination - A Biologically Inspired Paradigm for Self-Managing Systems

Holger Kasinger  Bernhard Bauer

University of Augsburg, Institute of Computer Science
Universitaetsstr. 14, 86135 Augsburg, Germany
Phone: +49 821 598 4012, Fax: +49 821 598 2175
Email: {kasinger, bauer}@informatik.uni-augsburg.de
www.informatik.uni-augsburg.de/ds

Abstract: From the biology's point of view, pollination is an important step in the reproduction of seed plants. From the software engineer's view, pollination may evolve to a promising, biologically inspired paradigm for future, self-managing computing systems. This estimation is based on the self-* properties implied inherently by the pollination process between plants and insects. To exploit these characteristics for artificial, self-managing systems, this paper analyzes the components and sub-processes involved in the natural pollination process and identifies the emerging self-* properties. Based on that, the paper adapts this process by a formal specification for artificial pollination systems as well as a meta model of their system architecture. The paper illustrates the adaptation's benefits by a case study and evaluates its capabilities and limitations. Finally, it presents open issues and an outlook on future work.

Keywords: self-management, self-organization, natural paradigm, autonomic computing, formal specification, system architecture.

1. Introduction

Today, aircraft handling at an international airport is a complex process, by which dozens of time-critical ground services (baggage handling, catering, fueling, cleaning ...) have to be managed in parallel for every aircraft. Thereby, the services have to take place in such a manner, that the holding time of every present aircraft is minimized. Nowadays, almost all of these services are managed by human controllers of the ground control, a central facility most times located in the tower of an airport. In addition, ground control has to cope with any conceivable disturbances to these services, e.g. absent ground vehicles, accidents on the apron, delayed or different typed aircrafts, unavailable passenger bridges, occupied ramps (the places for embarking and disembarking) due to delay, or preceding services not finished properly.

However, in face of their valuable work, these centralized ground controls will become a bottleneck to airports in future regarding the worldwide passenger traffic. For example, in 2005, Munich Airport handled around 29 millions of passengers, while in 2015 this amount is almost doubled by estimated 56 millions of passengers. The result will be an increasing flight density at airports in future, which in turn will boost the management requirements of ground controls more and more. In order to counteract this evolution, ground controls are clearly in need of new management approaches to cope with the future challenges.

In some respects, this is an exponent of the tackled management problems by Autonomic Computing (AC) [5]. The vision of AC [6] is that due to the increasing complexity of IT systems future systems should become autonomous and self-managing, i.e. they are supposed to be self-configuring, self-optimizing, self-healing, and self-protecting (also referred to as self-* properties), and thus relieve humans from administrative efforts. Transferring this vision to the case study mentioned above, all aircrafts and ground vehicles would have to organize and manage the ground services themselves. However, expedient approaches for this kind of system-wide self-management are still missing (see [7]).

However, nature provides a feasible solution. The adaptation of natural and biological paradigms as well as the exploitation of their self-organizational behavior is a commonly used method for the solution of artificial problems. For example, Swarm Intelligence (SI) [2] uses the collective behavior of biological systems (e.g. ant colony foraging, bird flocking, or termite mound construction) as paradigm for solving optimization problems. However, as present, particularly SI-based paradigms are not applicable to the above problem, as they do not support interactions between two logically different types of agents, a novel biologically inspired paradigm for self-management is presented in this paper: pollination of plants. From the biology's point of view, pollination is an important step in the reproduction of seed plants. From the software engineer's view, pollination may evolve to a promising, biologically inspired paradigm for future, self-managing computing systems. This estimation is based on the self-* properties implied inherently by the pollination process between plants and insects.

The rest of the paper is organized at follows: Section 2 describes the natural pollination process with its involved components and sub-processes as well as the emerging self-* properties that make pollination useful for self-managing systems. Based on that, section 3 presents a formal specification for artificial pollination systems as well as a meta model of their system architecture. Section 4 illustrates the benefits of the paradigm exemplified by an autonomous aircraft handling system, while section 5 evaluates the capabilities and limitations of the adaptation. Section 6 concludes and presents open issues as well as an outlook on future work.
2. Pollination as an Autonomous System

Pollination is an important process in the reproduction of seed plants. Thereby pollen grains – the male gametes – are transferred from the anther of a flower to the carpel of a flower, i.e. the structure that contains the ovule – the female gamete. Note pollination is not to be confused with fertilization, which it may precede. The fertilization of a flower only occurs after a successful pollination and stands for the union of two unlike gametes from this fruit eventually grows.

2.1 Pollination Components

Normally two components are involved in the pollination process, plants – more precisely the flowers of a plant as pollen source and pollen sink – and pollination vectors – agents carrying pollen from the source’s anther to the sink’s stigma (the receptive part of the carpel). Admittedly, there are a few plants that can self-pollinate, but as this results in inbreeding, most species rely on cross-pollination by some kind of pollination vector to accomplish pollination. The pollination vector not essentially has to be an insect or an animal; also, wind and water come into operation. However, many plant species do not rely on random pollination by wind (statistically there is only an off-chance of a successful pollination and vast quantities of pollen are required) or downstream-only pollination pathways by water, thus insects and animals are the preferred pollinators of most species. In some cases, the evolutionary link between a species and its pollinator has become so tight that each is dependent on the other’s efforts for its continued survival.

2.2 Attracting Pollinators

During bloom the flowers of a plant need to attract pollinators that pick up and deliver pollen (grains) respectively to accomplish pollination. For the attraction, flowers provide visual and/or olfactory attraction cues. Showy petals or sepals with obvious shape, size, and color for the vectors’ vision are important visual cues. Of course, not every pollinator is attracted by the same colors, e.g. butterflies and birds are only attracted to red and yellow colors. Additionally, there may be color patterns (e.g. bull's eyes, splotches, or nectar guides) that form a high-contrast exhibit to make the flowers stand out against a background of green foliage. Such cues assist a pollinator to "see" the flowers and in beginning to concentrate its visits only on those with the same certain colors.

However, some vectors have limited visual capabilities but an extensive ability to find a flower by its fragrance. Thus, flowers produce volatile chemicals that diffuse and are carried by air movements through the environment. A vector that is able to recognize such a fragrance and fly up the concentration gradient, can easily find the next flower of a particular species. Flowers over time have evolved a wide array of fragrances, which results in efficient pollinator attraction too. Again, different pollinators have different sensitivities to certain fragrances, e.g. flowers specialized in attracting flies are famous for their fetid aroma.

Not until a successful fertilization succeeds the pollination, a flower ceases to attract pollinators, as there is no need of further pollen grains.

2.3 Rewarding Pollinators

Nevertheless, attracting pollinators is not fruitful on its own, as pollinators usually are intelligent enough to avoid the energy waste of behaviors that do not result in some kind of reward. Thus, a flower needs to reward an attracted pollination vector so that it will perceive the reward as a result of its visit. The vector's intelligence will then allow it to decide to visit similar flowers nearby to obtain additional rewards. This is the reason why vectors visit only one flower species on a trip.

While collecting its reward the vector unconsciously picks up and delivers pollen grains by its underside. Vectors collect rewards as long as they have had enough or they can not find anymore. This remarkable vector behavior ensures an effective pollination. The vector's reward can be either nectar, pollen, behavior, or some combination of these.

Nectar is a carbohydrate rich droplet that is used as an energy source for vectors. Hummingbirds, for example, must consume vast quantities of nectar to continue their high-energy method of flight. Bees collect nectar and evaporate it down to make honey for winter supplies. The pollen itself contains protein, starch, oil, and other nutrients. It is far richer than nectar in vitamins and minerals too. For bees, the collection and consumption of pollen is critical, as it is their basic protein supply. Fortunately, pollinators on this account are not very careful in cleaning off sticky pollen that cling to their bodies. Behavior (stimulation, hallucination …) can also be sensed as a reward that gets a repeat visit by a vector.

2.4 System Properties

Over the past millions of years, these components together with the two sub-processes have evolved a natural, self-managing system that exhibits various useful properties:

Self-configuration: The evolutionary link between a species and its pollinator is responsible for a seamless incorporation of new plants and pollination vectors. A plant is incorporated as soon as a linked vector scents its fragrance. Vice versa, as soon as a vector scents a linked fragrance, the vector is incorporated itself.

Self-optimization: Rewarding takes place by the "first come, first served" principle. Thus, vectors carrying pollen faster from flower to flower will collect more reward as other vectors. In addition, flowers providing higher reward will be visited more often as flowers with less reward. Both speeds up the pollination process by different strategies within the components.

Self-healing: The loss of pollination vectors yields (to a certain extent) to no significant disturbance of the pollination process, as other pollinators will pick up and deliver pollen grains instead of the lost vectors. This is the reason why flowers produce pollen as long as they get fertilized (for the time of their bloom).

Self-protection: Reward is only provided to vectors that pick up or deliver pollen during their visit. Flowers are structured in such a manner, that no intruders can receive any reward without picking up or delivering pollen as a trade-off. Furthermore, intruding vectors only being on a "journey through" have no effect to the pollination process.

Self-adaptation: A plant (species) not adapting its attracting and rewarding to the available pollination vectors will finally die out over the long run. Vice versa, a vector
(species) not adapting its behavior to the specific characteristics of the available plants will become extinct either.

Self-organization: Additionally, pollination exhibits all required aspects [15] for a self-organizing system: It exposes an ‘increase in order’ evoked by the attracting and rewarding, required aspects [15] for a self-organizing system: It exposes certain premises:

However, an efficient adaptation of this paradigm requires pollen, rewards, attraction cues, and pollination vectors.

3. Formal Specification of an Artificial Pollination System

The adaptation of pollination as paradigm and the exploitation of its identified self-* properties for self-managing systems requires an abstraction of the components and sub-processes presented in the last section. The relevant terms to be considered in this context are plants, flowers, pollen, rewards, attraction cues, and pollination vectors. However, an efficient adaptation of this paradigm requires certain premises:

(i) A single artificial pollination system represents a finite, natural pollination environment, e.g. a grassland or a piece of forest. The representation of the entire nature as a huge, single, and closed pollination system would be absurd. By this way, nearby environments can be considered as adjacent systems.

(ii) Sun, wind and rain come not into operation within the artificial pollination system, neither as pollination vectors nor as influencing quantities. Thus, pollination is based on “living” vectors only.

(iii) The attraction of artificial vectors is based on olfactory cues (fragrances) only, as volatile chemicals are representable, see pheromones [4] for example.

(iv) The rewarding of artificial vectors is based on nectar rewards only. It would be counterproductive if vectors were allowed to consume pollen.

The following formal specification of an artificial autonomic system based on the pollination paradigm considers these premises.

3.1 Pollination System Environment

An artificial pollination system APS (see the meta model in Fig. 1) is defined as

\[ APS=(G,S,P,O,V) \]

where \( G \) is a set of genera, \( S \) is a set of species, \( P \) is a set of plants (see subsection 3.2), \( O \) is a set of orders (see subsection 3.1), and \( V \) is a set of pollination vectors (see subsection 3.7).

The scientific classification of natural plants into genera (e.g. roses or tulips) and species (e.g. Redleaf Rose, Gooseberry Rose …) goes back to Linnaeus [9] and is adapted here as well. According to Linnaeus, a genus consists of one or more species, whereas a species consists of a plenty of entities (plants). A species may be subdivided into subspecies, races, etc., but this refinement is not mandatory here. Linnaeus regarded genera and species as disjunctive sets, i.e. a plant belongs to a single species, and a species belongs to a single genus, what is reasonable for biology (a rose is a rose, not a rose and a tulip at the same time). However, for the APS this disjunction would hold some disadvantages that become clear in section 4. Thus, without loss of generality a plant \( p \in P \) is admitted to be a member of one or more species \( s \in S \), as well as a species \( s \in S \) to be a member of one or more genera \( g \in G \) at the same time – which represents evolution. Consequently, a natural pollination environment can be considered as a special case of the APS.

For zoology, Linnaeus specified a scientific classification too. For the APS only the hierarchical term of an order is adapted. Here, the natural disjunction remains, i.e. a vector \( v \in V \) belongs to exactly one order \( o \in O \) at the same time.

Because the system represents a finite pollination environment, the system boundaries are clearly defined and the number of plants and vectors is determinable at any time.

3.2 Plants

A plant \( p \in P \) is defined as

\[ p=(PG,PS,F) \]

where \( PG \subseteq G \) is the set of genera \( p \) is member of and \( PS \subseteq S \) is the set of species \( p \) is member of. \( F \) is the set of flowers attached to \( p \).

3.3 Flowers

A flower \( f \in F \) is defined as

\[ f=(g.s,Polprov,Poldes,R,A) \]

where \( g \in PG \) is the genus and \( s \in PS \) the species \( f \) is member of. In contrast to the entire plant, a flower is only allowed to be of a single genus and single species at the same time. From the fertilization’s point of view, the allocation of a flower to a species is not essential in either case. Sometimes it is sufficient, if the pollen grain a flower is pollinated with emanates from a flower of the same genus, independent of its species. As the opposite direction applies too, an asterisk as the second parameter represents these cases. \( Polprov \) (see subsection 3.4) represents the pollen set provided by \( f \), whereas \( Poldes \) (see subsection 3.4) represents the desired pollen set of \( f \). \( R \) (see subsection 3.5) represents the provided reward set of the flower and \( A \) (see subsection 3.6) its fragrance (aroma). The specification of the last four parameters follows in the next subsections.
3.4 Pollen

A pollen grain $\text{pol}$ is of the same species and genus as the flower it is produced by and hence defined as

$$\text{pol} = (g,s)$$ (4)

Note the specification includes no more information, in particular no hint on the flower serving as addressee or addressee for the pollen grain. For the following definitions, the term $\text{pol}^{g,s}$ will be used for the notation of a pollen grain, which is equivalent to the specification above. With this notation, the provided pollen set of a flower of the genus $g$ and species $s$ is defined as

$$\text{Pol}_{\text{prov}}^{g,s} = \{\text{pol}^{g,s}, \ldots, \text{pol}^{g,s}\}$$ (5)

where $i$ indicates the number of pollen grains the flower provides. Analog the desired pollen set of a flower of the genus $g$ and species $s$ is defined as

$$\text{Pol}_{\text{des}}^{g,s} = \{\text{pol}^{g,s}, \ldots, \text{pol}^{g,s}\}$$ (6)

where $j$ indicates the number of desired pollen grains.

The above specification of a flower together with the specification of pollen sets diverges from nature in one aspect: A natural flower does not know about the quantity of provided and desired pollen grains. The reason for this divergence is the representation of fertilization, as the moment of fertilization is responsible for the cessation of attracting and rewarding vectors. The specification represents this moment by the time a flower provides and desires no more pollen grains. On this account, the divergence has no effect on the overall process.

3.5 Rewards

The success of a natural flower in cooperation with the vectors depends on two variables: The quantity and the quality of the distributed nectar. Experiments (see [3], [10]) have pointed out, that honeybees do not determine a good food source by the quantity of the reward (as a bee is not able to determine the remaining reward resources of a flower) but by the quality, more precisely by the sugar concentration of the nectar. On the other hand, two quantitative aspects are important:

(i) A pollination vector solely will receive nectar, if it picks up or delivers pollen grains as a trade-off.
(ii) As more pollen grains a vector picks up or delivers as more nectar it will receive.

To cover these quantitative aspects, the constraint ‘per picked up or delivered pollen grain a vector will receive one reward unit’ is defined. Thereby a reward unit $r$ corresponds to an appropriate nectar drop. Principally, the weighting of picked up or delivered pollen and the received reward units is arbitrary, it is merely important that there exists a direct proportionality between them and that the weighting is unique to the entire pollination system.

To cover the qualitative aspect, additionally the concentration is incorporated into a reward unit. Thus, a reward unit is defined as

$$r = (g,s,c)$$ (7)

where $g$ is the genus and $s$ the species of the flower providing the reward unit and $c$ represents the concentration. For the following definition, the term $r^{g,s}$ will be used for the notation of a reward unit, which is equivalent to the specification above. With this notation, the provided pollen set of a flower of the genus $g$ and species $s$ is defined as

$$\text{R}_{\text{prov}}^{g,s} = \{r^{g,s}, \ldots, r^{g,s}\}$$ (8)

The size of the reward set $(i+j)$ is a result of the constraint defined above. Because a flower provides $i$ pollen grains and desires $j$ pollen grains, it has to keep ready a reward unit for each of these pollen grains. Additionally, it is assumed that the concentration of all provided reward units of a flower is the same and a change of concentration affects all reward units in the same way.

Note, one can consider the concentration of a reward unit as the price per pollen grain a flower is willing to pay. Once a flower increases the concentration of its reward units, a picking or delivering vector will receive a better price (reward of higher quality) per pollen grain. Similar to the price formation by supply and demand in economics, this better price will attract more vectors as before. The opposite direction is analog. By this mechanism, a flower has the ability to manage the velocity of pollen pickup and delivery.

3.6 Fragrances

A fragrance has to propagate the current reward conditions of a flower and therefore has to include all the information vectors need to decide to visit the flower. Thus, the fragrance $A$ of a flower of genus $g$ and species $s$ is defined as

$$A = (g,s,c,i,j,l)$$ (9)

Thereby $I$ represents the (decreasing) intensity of the fragrance and ensures two natural aspects:

(i) The temporal volatility of a fragrance
(ii) The route guide for a vector

By the evaluation of the intensity, a vector has the ability to determine the topicality of the conditions as well as the ability to follow the fragrance’s concentration gradient to the emitting flower. The concentration parameter indicates the ‘price relationship’ on a flower at the time of emitting the fragrance. The quantities of reward units left at this time are included by the values $i$ and $j$. For example, if the fourth parameter ($i$) of a fragrance is zero, this indicates, that the flower provides no more reward units for the pickup of pollen grains of this type.

Note that like in nature the specification of a fragrance consciously includes no information on the identity of the emitting flower. A vector follows a fragrance because it wants to receive an adequate reward, no matter from which flower of a certain species or genus. If the vector scents on its way to this flower another fragrance with better conditions, the vector may follow the new fragrance.

3.7 Vectors

The last term to be specified is a vector. A vector $v \in V$ is defined as

$$v = (o, VG, cap, VR, VP)$$ (10)

where $o \in O$ is the order the vector belongs to, $VG \subseteq G$ is the set of genera $v$ is a pollinator for, $cap$ is the reward unit capacity of $v$, $VR$ is the set of reward units currently collected by $v$, and $VP$ is the set pollen grains of currently picked up by the vector $v$.

This specification represents the natural fact that not all vectors serve as a pollinator for every genus, but only for elected ones – flies will not pollinate roses for example. Thus, a vector $v$ can only pick up or deliver pollen from or to flowers of genera $g \in VG$. Due to the constraint defined in subsection 3.5, visiting other flowers would have no effect to both vector and flowers. In particular, a vector in this case
will not receive any reward units and thus even not follow fragrances of flowers of genera $g \notin VG$.

Furthermore, a natural pollination vector is not able to collect unlimited quantities of nectar, as its stomach is limited. This limitation is represented by the vector’s reward unit capacity $cap$. Thus, a vector can only collect reward units up to its capacity before it is full. The currently collected reward units are stored in $VR$.

In nature, a bee, for example, that is full of nectar, will fly back to its hive, and deliver the collected nectar as honey. As hives are not directly part of the APS, another way for a vector is defined, in order to get rid of collected reward units. Otherwise it would not be able to collect further reward units (and hence not pick up or deliver further pollen grains), as its capacity always remains utilized. Therefore, constraint ‘per deliveder pollen grain a vector may consume two reward units’ is defined. The consumption of reward units corresponds to the delivery of honey. Thus, a vector with no more free capacity may only visit flowers in order to deliver pollen grains and to free its capacity again by the consumption of reward units – the ones collected for pickup and the ones collected for delivery. In addition to the constraint defined in subsection 3.5, this constraint guarantees the invariant, that a vector with no picked up pollen grain possesses the maximal reward unit capacity.

However, by the constraint another natural fact is ensured. As natural vectors only visit flowers of a certain species and genus on a trip, the constraint represents – more precisely results in – the end of a trip. As the genus and species of the first collected reward unit of a vector predefine the only species to be visited on the trip, the end of the trip is represented by the moment a vector has collected no more reward units ($VR=\emptyset$). This is the time when all picked up pollen grains are delivered.

Additionally a vector keeps an account of its currently collected pollen grains in $VP$. Similar to nature, no order ($FIFO$, $LIFO$ ...) is defined on the set $VP$. An order may result out of the application domain an APS is applied to, but is not a necessary condition.

4. Case Study: An Autonomous Aircraft Handling System

In order to demonstrate the utility of the adapted pollination paradigm, its application is illustrated by a potential, simplified autonomous aircraft handling system as a new management approach for the case study in section 1. This will exemplify the possible decision making processes of the system components and the interaction patterns between aircrafts and ground vehicles.

4.1 Initial Scenario Setting

Consider an arbitrary international airport, e.g. Frankfurt Airport (FRA), as aircraft handling scenario setting. To simplify matters only three aircrafts are involved in this scenario: An Airbus A340-600 from Los Angeles (flight number LH 457), a Boeing 747-400 from Singapore (flight number SQ 026), and an Airbus A330-300 from Montreal (flight number AC 874). In addition, to simplify matters only three ground services are necessary for an aircraft handling in this scenario: Baggage handling, catering and fueling. On this account, only the data relevant for these services will be mentioned below.

Flight LH 457 arrives from L.A. with 860 pieces of baggage on board and requires 830 pieces of baggage, 1330 meals, and 204,000 liters of kerosene for its return to L.A..

Flight SQ 026 arrives from Singapore with 940 pieces of baggage and requires 990 pieces of baggage, 1460 meals, and 216,000 liters of kerosene for its return. Flight AC 874 from Montreal arrives with 620 pieces of baggage and requires 590 pieces of baggage, 950 meals, and 97,000 liters of kerosene for its return. The aircrafts arrive in turn.

To handle the ground services the airport runs a baggage center. In addition, a fixed base operator (FBO) – a service center at an airport that may be a private enterprise or may be a department of the municipality that the airport serves – runs a catering center as well as a tank farm at the airport. For the baggage handling service, the airport provides five baggage trains with a capacity of 300 pieces of baggage each. The FBO provides two catering trucks with a capacity of 150 meals each and two fueling vehicles with a capacity of 250,000 liters of kerosene each.

4.2 Application of the Pollination System

The model depicted in Fig. 2 represents an instance of the meta model in Fig. 1, and visualizes the mapping between APS elements and aircraft handling entities at the airport.

The ground services baggage (handling), catering and fueling each are mapped on a genus and the flight numbers of the arriving aircrafts, LH 457, SQ 026, and AC 874, each are mapped on a species, while every species is a member of all genera in this scenario.

Each aircraft is mapped on a plant, whereas the first aircraft (plant $p_1$) from L.A. is member of species LH 457, the second one (plant $p_2$) from Singapore is member of species SQ 026 and the third one (plant $p_3$) from Montreal is member of species AC 874. Aircraft facilities are mapped on plants too, whereas the baggage center (plant $p_3$) is member of the genus baggage, the catering center (plant $p_3$) is member of the genus catering and the tank farm (plant $p_3$) is member of the genus fueling. Every airport facility is member of all species in this scenario.

Every relevant device of these plants (the hatches of the aircrafts, the conveyor belts of the baggage center, the docks of the catering center, and the dispensing heads of the tank farm) is mapped on a flower and emits radio signals – mapped on fragrances –, that attract ground vehicles – mapped on vectors – of a certain vehicle type – mapped on orders. The system consists of the three orders bag_train, cat_truck and fue_vehicle. Imagine all vectors as vehicles driving autonomously and having a human operator on board that handles manually the transported goods but has no influence on the vectors’ decisions. In future, these human tasks may be taken over by the vectors too. The baggage trains (vectors $v_1,...,v_5$) belong to the order bag_train and are the pollinator for the genus baggage; the catering trucks (vectors $v_6,v_7$) belong to the order cut_truck and are the pollinator for the genus catering; the fueling vehicles (vectors $v_8,v_9$) belong to the order fue_vehicle and are the pollinator for the genus fueling.

Analog to nature, an attracted ground vehicle carries the pieces of baggage, meals or liters of kerosene – each mapped on pollen grains – from the provided pollen sets of
flowers – here the freight by arrival ArrFreight, the ProvBaggageSet, the MealSet and the FuelSet – to the desired pollen sets of other flowers – here the DesBaggageSet, the freight by departure DepFreight, the meal set by departure DepMealSet, and the fuel by departure DepFuel. Due to these activities, the ground vehicles are rewarded with money – mapped on reward units – of the supply of money – mapped on the provided reward sets – of every flower.

By means of the aircraft handling, the following subsections each present different characteristics of the pollination system.

4.3 Ground Service Baggage Handling

Provided that $p_2$ has landed first, its freight hatch (flower $f_1 = \text{(baggage, LH 457, 860, 830, 1690, A1)}$) sends the message $A_1 = \text{(baggage, LH 457, 10, 860, 830, 100)}$ as fragrance per radio signal as soon as the aircraft arrived at its designated ramp. Note the concentrations of reward units in this scenario are well chosen but have no specified measurement, although monetary units are imaginable. Let the initial intensity of every fragrance be 100 (percent). $A_1$ possibly is received by the baggage trains $v_1, v_2,$ and $v_3$ while $v_4$ and $v_5$ are out of reach. As the baggage trains are a pollinator for the genus included in $A_1$, they start heading for its source $f_1$ by following the signal strength of the fragrance (see Fig. 3). All other vectors also receiving $A_1$ are not attracted by it, as they are no pollinator for this genus. Once arrived at the hatch, $v_1$ begins collecting reward units up to its capacity (300) and thereby picks up the same quantity of pieces of baggage (pollen grains). As soon as $v_1$ is sated, it leaves the hatch with its pollen grains and $v_2$ starts the same action for another 300 reward units. Arriving at last, $v_3$ only collects the remaining 260 reward units. Generally, it draws no distinction if vectors arrive at a flower in sequence or in parallel – provided that a flower is able to serve more than one vector in parallel. A vector will always collect reward units either as long as reward units are provided by the flower or the vector is sated before.

Meanwhile the conveyor belt (flower $f_{10}$) of the baggage center $p_4$ emits the fragrance $A_2 = \text{(baggage, LH 457, 1, 830, 860, 100)}$. As $v_i \ldots v_j$ are fixed to the species LH 457 for their trip and do not receive any other fragrance of the same species and genus, $v_i$ and $v_j$ may only follow $A_2$, as they have no more available capacity. $v_j$ possibly could pick up 40 more pollen grains, however only of the same genus and species. However, as $v_j$ also receives no such message, it follows $A_1$ too.

This time, $v_4$ and $v_5$ also receive $A_1$ and as they might be close to $f_{10}$, they arrive first and pick up 300 pieces of baggage each in turn. At next $v_j$ arrives, delivers its pieces of baggage, and collects another 300 reward units as trade-off while consuming all 600 collected reward units. Now the trip of $v_j$ is ended and the vector has its maximum reward capacity again. Thus, it starts immediately picking up the remaining 230 pieces of baggage provided by $f_{10}$ and follows $v_4$ and $v_5$ in the direction of $f_1$.

By the delivery of their pollen grains, the trips of $v_2$ and $v_3$ end at the conveyor belt $f_{10}$ too. As they are now free to decide which species to visit and the conveyor belt ceases to emit any fragrance, they possibly head for the second aircraft $p_2$, already landed and sending messages in the meantime. The cessation of sending further messages by the conveyor belt $f_{10}$ is the result of its successful fertilization, as it neither provides nor desires any more pieces of baggage.

4.4 Ground Service Catering

The pollen grains (meals) of the genus catering only have to be transported unidirectional, from the catering center docks (flowers $f_{11}, f_{12}$ and $f_{13}$) to the corresponding hatches of the aircrafts. In this case (see Fig. 4), $f_{11}$, member of species LH
457, sends the message $A_3 = (catering, LH 457, 1, 0, 1330, 100)$, $f_{13}$, member of species $SQ 026$, sends $A_4 = (catering, SQ 026, 1, 0, 1460, 100)$, and $f_{15}$, member of species $AC 874$, sends $A_5 = (catering, AC 874, 1, 0, 950, 100)$. The reason for the matching of the respective desired pollen sets by the aircrafts and the provided pollen sets by the catering center are the corresponding messages of the airlines in front of the aircraft arrivals.

![Catering trucks scenting fragrances.](Image)

Fig. 4. Catering trucks scenting fragrances.

Catering truck $v_6$, near by dock $f_{14}$, receives all these messages, but with different intensities. The intensity of $A_3$ possibly is 90 by reception, as the truck is in the near of dock $f_{14}$, whereas the intensities of $A_4 (80)$ and $A_5 (70)$ possibly are lesser. $V_6$ starts to evaluate the fragrances by comparing their concentrations, but as these are all the same, the truck decides to follow the fragrance with the highest provided reward set, in this case $A_3$ with 1460. Even the intensity of $A_3$ is not the highest (which indicates that its source is more far-off and the conditions may have changed with higher probability), the truck estimates the chance of collecting a plenty of reward units as the best.

Catering truck $v_8$, near by dock $f_{15}$, receives the same messages, again with different intensities. From its point, the intensity of $A_5$ is the highest and as the concentrations are all the same, $V_8$ decides to head for it, although its provided reward set (950) is the lowest. Nevertheless, as the intensity indicates the topicality of the reward conditions, the truck estimates the chance of collecting these reward units as surer. Once loaded, $v_6$ and $v_8$ follow the corresponding fragrances of the hatches $f_5$ of $p_2$ and $f_3$ of $p_3$, respectively, as these hatches are sending the only fragrances matching to the species and genus of the picked up reward units, and deliver the meals.

The omission of dock $f_{14}$ by $v_6$ and $v_8$ may result in a delay of flight $LH 457$. Hence, $f_{14}$ increases its reward unit concentration continuously to improve its attraction to potential vectors. Provided that new flowers assigned to further docks start with a reward unit concentration of 1 again, this ensures the supply of $f_{14}$ the next time the trucks return.

4.5 Ground Service Fueling

The tank farm $p_6$ at the airport possesses two dispensing heads (flowers $f_{14}$ and $f_{15}$) both providing 500.000 liters of kerosene. In this scenario, fueling is that kind of genus, where pollen grains (liters of kerosene) serve for the pollination of flowers independent of their species. Thus $f_{14}$ and $f_{15}$ emit the fragrances $A_6 = A_7 = (fueling, *, 1, 500.000, 0, 100)$ with an unspecified species. The two fueling vehicles $v_8$ and $v_9$ receiving these messages start heading for $f_{15}$, as they are possibly both nearby. When $v_8$ arrives, $f_{15}$ possibly is already occupied by $v_9$ and hence not accessible. However, due to the similar fragrance $A_7$ still scented, $v_9$ proceeds to $f_{15}$ and taps kerosene up to its capacity too.

Provided that all aircrafts are at their ramp now, $v_8$ possibly receives the messages $A_8 = (fueling, *, 10, 0, 204.000, 50), A_9 = (fueling, *, 9, 0, 216.000, 60)$, and $A_{10} = (fueling, *, 22, 0, 97.000, 70)$ (see Fig. 5). Although $v_8$ may only collect 97.000 reward units by the delivery of its kerosene to $p_3$, it evaluates $A_{10}$ as the best fragrance to follow, as the latter provides the highest concentration. While the catering trucks $v_6$ and $v_7$ in subsection 4.4 additionally had to evaluate the intensity of the fragrances, here all concentrations are different what makes the decision easier.

![Fueling vehicles scenting fragrances.](Image)

Fig. 5. Fueling vehicles scenting fragrances.

Shortly after $v_8$, $v_9$ possibly also evaluates $A_{10}$ as best and starts following it too. In the meantime, $v_8$ arrives at $p_3$ and starts fueling, which causes the fueling valve $f_9$ of $p_3$ to adjust its fragrance due to the new conditions. Thus, $v_9$ still on its way to $p_3$ may scent the fragrances $A_8 = (fueling, *, 10, 0, 204.000, 80), A_9 = (fueling, *, 9, 0, 216.000, 70)$, and $A_{10} = (fueling, *, 22, 0, 97.000, 60)$. Another evaluation makes $v_9$ now to change its original direction and to proceed in the direction of $A_{10}$, as this is the fragrance with the highest provided concentration.

Once every flower of an aircraft is fertilized, i.e. the aircraft provides and desires any more pieces of baggage, desires any more meals as well as desires any more kerosene, the aircraft is ready for departure and may leave the ramp for a runway.

The Boeing from Singapore, plant $p_2$, not in the know of these processes, remains unserved regarding fueling. Hence, its hatch $f_3$ by and by will increase continuously the concentration of its reward units to improve its attraction to potential vectors due to the same reasons as the catering center dock $f_{14}$ in subsection 4.4.

5. Evaluation

The initial objective of the pollination adaptation was to exploit the self-* properties for self-managing systems implied inherently by the biological paradigm. On this account this section evaluates the theoretical capabilities and limitations of the adapted self-* properties extracted from the adaptation. A practical evaluation will follow as soon as a simulation of the APS is available.
5.1 Self-configuration

The pollination system configures itself automatically in accordance with high-level policies. High-level policies for a plant or a vector specify desires, e.g. the maximum fertilization time of a plant's flowers or the minimum reward collection by a vector within a certain period. When a new component (plant or vector) is going to join the system, the component incorporates seamlessly by sending and receiving messages as fragrances respectively. The rest of the system adapts to the presence of the newly joined component without any (re-)configuration. More precisely, a plant is incorporated as soon as a vector receives a message from it. Vice versa, as soon as a vector receives a message, the vector is incorporated in the system itself.

However, due to the biological paradigm the system is based on, the artificial system's self-configuration is limited to some extent. In nature, a recently grown plant, member of a species nonexistent in the environment so far, may not be pollinated by pollen grains from the same species, as long as no more specimens of this species are present in the environment too. Although the plant may attract pollination vectors that pick up its provided pollen grains – if its species is member of a genus already available in the environment – it may not become fertilized (except by self-pollination). The problem intensifies, if the plant's species is member of a genus nonexistent in the environment too. In this case, the plant may even not attract any pollination vector for pickup, as long as at least one adequate vector enters the environment or becomes a pollinator for this genus too. In nature, these limitations are compensated for by evolution, as time plays not such a significant role and vectors can evolve to pollinators for new genera in the course of time.

5.2 Self-optimization

All components of the APS continually seek ways to improve their operation and identify opportunities to make themselves more efficient. Plants and their attached flowers respectively optimize the pollen pickup and delivery by adjusting the concentration of reward units. To keep the concentration optimized, one can consider the concentration as the result of a utility function [13] flowers incorporate. Learning strategies for attracting and rewarding vectors will change this function and optimize the result further.

The evaluation of fragrances by vectors also can be considered as the result of a utility function vectors incorporate. The reward unit crop of every trip will change this function permanently and yield to a different but optimized future behavior of vectors.

However, just like in nature, locally optimized behaviors of components will not yield consequentially to a globally optimized system, e.g. an optimized running flower may remain unserved by optimized running vectors due to better conditions on other flowers. In particular, this is the result of fairness not guaranteed in nature. There, this limitation is compensated for by huge quantities of plants of the same species, which ensures the continued survival.

5.3 Self-healing

The system compensates for failures or losses of components without effects on the stability or efficiency of the system up to a certain degree. Buggy or broken flowers are scuffed by their plants and replaced by new ones of the same type according to the natural paradigm. The loss of a vector is compensated for by other vectors of the same order that take on the lost vector's job.

However, the natural paradigm also entails limitations here. The loss of vectors carrying desired pollen grains for rare flower species slows down the pollination process. The loss of a vector being the last of its order actually may disrupt the process. Even nature cannot compensate completely for these limitations, which sometimes leads to the extinction of a species or genus.

5.4 Self-protection

The pollination system defends as a whole against large-scale, correlated problems arising from malicious attacks or cascading failures that remain uncorrected by self-healing. For example, malicious flowers cannot increase the concentration of reward units arbitrarily, but only up to a certain limit, as nectar is saturated at a certain point. Thus, such flowers not scuffed yet will not destabilize the entire system completely. Malicious vectors, being regular parts of the system or just intruding the system, only trying to collect reward units are barred from pollination by the constraint defined in subsection 3.5. Furthermore, vectors only picking up pollen grains, but not willingly to deliver them, are barred too, as they cannot consume their collected reward units by the constraint defined in subsection 3.7 and hence not pick up any more pollen grains.

However, just like in nature, the system is not immune against manipulated pollen grains. In the same way natural vectors can pass diseases on flowers by the delivery of afflicted pollen grains, artificial vectors may deliver manipulated pollen grains. As artificial as well as natural flowers are not able to reject manipulated and afflicted pollen grains respectively, the latter can have fatal effects to the flower's continuity.

5.5 Self-organization

On the one side, the self-organizational behavior of plants and insects builds the basis for the self-management in the artificial pollination system. Thereby, the absence of an external control ensures full autonomy at system-level.

On the other side, this self-organization entails a couple of challenges with regard to efficiency. For example, pollination provides no guarantee that plants will become fertilized within a certain amount of time. This has no impact on the natural paradigm, as time again plays not a significant role, but in terms of aircrafts, waiting for departure this uncertainty is critical. Indeed the APS integrates mechanisms to work against this drawback, e.g. the ability of plants to increase their reward concentration in the case of lack of time, but these mechanisms still do not completely guarantee fertilization and thus the satisfaction of a plant up to a certain time.

6. Conclusion, Open Issues and Outlook

This paper presented a biologically inspired paradigm for future self-managing systems, which is based on the pollination process between plants and insects. By the adaptation of the natural system architecture as well as the
common behavior of the involved components the naturally emerging self-* properties were exploited for the solution of an artificial management problem. The evaluation of the paradigm identified, that the limitations to these promising self-* properties mainly have natural causes so far.

Despite these promising capabilities, the pollination paradigm provides no blueprint for all kinds of future self-managing systems. A domain-specific application requires a possible mapping of plants, flowers, fragrances, pollen grains and vectors on appropriate entities that are desired to run autonomously. Beneath autonomous aircraft handling, one can think of autonomous manufacturing control, where robots (vectors) carry workpiece (pollen grains) to product machines (plants), or high bay warehouses with a similar behavior, for example. Of course, these application scenarios already today run automatically, but inevitably not autonomously.

Admittedly, the pollination paradigm is not the first approach to utilize natural paradigms for the solution of management problems. One of the most familiar natural paradigms for self-managing systems obviously is the human body's autonomic nervous system (ANS), which provided the inspiration for the AC initiative. Further paradigms also adapted from the human body are the reflex and healing system, e.g. used in high energy physics experiments requiring stability [1], the heartbeat, e.g. used for a fault tolerant mechanism of an artificial heartbeat monitor (HBM) [11], the pulse frequency, e.g. used for a telecommunications fault management architecture [12], or the immune system, e.g. used for the development of an antivirus system [14], just to name a few of them. A drawback of these solutions is the usage of a centralized manager (according to the natural paradigm) that prevents good scalability and thus limits their applicability in particular to the case study mentioned.

In contrast, biological systems achieve self-management through entirely different, often fully distributed, and emergent ways of processing information. There is often no subsystem responsible for global self-* properties, these properties follow from some simple local behavior of the components typically in a highly non-trivial way and hence no centralized managers are involved. However, as mentioned in section 1, these paradigms rely on SI and thus are not suited for the case study too. Despite its use of pollination vectors like bees, the pollination paradigm is not SI-based, as the self-* properties emerge from the interaction between to logically different types of agents, plants, and insects.

However, several open issues and challenges remain that have connections among different areas. As the behavior of flowers and vectors and hence the behavior of the entire system is guided by utility functions, it is not clear yet, how to represent these functions as high-level policies understandable to human administrators. In addition, to manage the global, emergent behavior of the entire system by high-level policies, the correlations between policies for the global behavior and the local behavior of the system components have to be clarified. Otherwise, the formulation of a high-level policy possibly may yield in an unintended system behavior. Additionally, for the identified limitations to each of the self-* properties evaluated in section 5, solutions have to be found that eliminate these limitations at least up to a certain degree.

To meet these challenges, the next step will be the simulation of an artificial pollination system. In addition, the simulation may shed light on further alterable system parameters, as the optimal relationship between the number of plants, flowers, and vectors, a flower's fragrance emitting frequency, the intensity (decrease) of a fragrance as well as the reward unit concentration adjustment by utility functions, for instance. This enables a functional evaluation of scalability, efficiency, robustness and low-latency of the artificial pollination system as well as possible improvements of the self-* properties. In a next step, the unintended emergent behavior of the system has to be bared, for example by methods of agent technology as accomplished in [8].

References


Author Bios

Holger Kasinger graduated in 2005 as a computer scientist from the University of Augsburg in Germany. There he is currently working as a scientific assistant to Prof. Bauer and preparing his Ph.D. thesis. His research interests include self-managing and self-organizing computing systems, in particular architectures, engineering methodologies, and policies for autonomic and organic computing systems.

Bernhard Bauer graduated in 1992 as a computer scientist from the University of Passau in Germany. He received his Ph.D. from the Technical University of Munich in 1996 and joined Siemens Corporate Technology as a principal research scientist for the following six years. Since 2003, he is a professor for distributed systems at the University of Augsburg. Prof. Bauer was involved in the agent standardization FIPA and contributed to the UML 2.0 standard. Among other things, he is a reviewer for the European Commission as well as for various conferences and workshops.