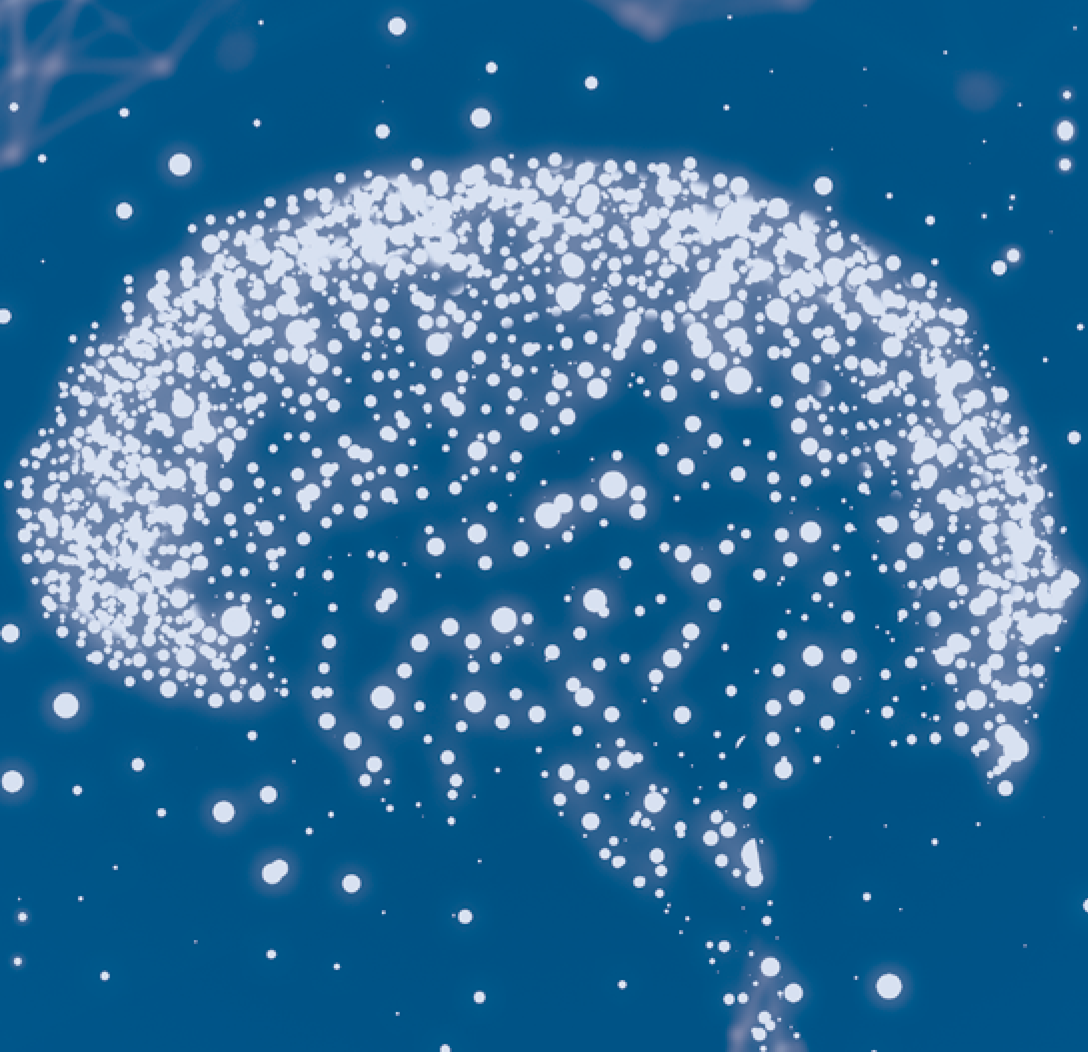
# Swarm intelligence

## Concept, vision and application



Thought Leadership

Atos

# Abstract


### Swarming as an evolutionary advantage

Using animal swarms as source of inspiration, we define swarm intelligence (SI) and investigate how SI can be applied in the human domain. Natural swarms demonstrate how the ability to apply the power of many through self-organization creates an evolutionary advantage, hence an enabler of survival of the species. We therefore position SI as an organizational paradigm.

### Swarm intelligence as a way to exploit human capital

Humans, being just a specific kind of animal, also have a tendency to swarm, but more from a social cultural than a survival perspective. Our capability for self-organization - the key feature of SI - is unprecedented. The majority of the artifacts that surround us are the result of how we mutually interact, i.e. how we manage to organize ourselves as humans.

Apart from a natural fit, today there is also a need to explore what we can do with SI. We are being challenged by an ever-growing complexity and accelerating speed of change, hence growing uncertainty and turmoil. Classical hierarchical organization models fail to deal with such an environment, while SI-based organization models provide a way out. SI brings the power of decision making to a local and distributed level, relying on the people at this level to resolve the issues they are confronted with. This, by optimally utilizing the capabilities and drivers of these individuals to organize themselves in response to the environment and to each other.

### Swarm intelligence as the basis for a global platform

If we want to explore how SI can help us at macroeconomic level, there are some challenges. Turning to the digital world, we see there how people adopt swarm behavior, e.g. in communities, often on a global scale. This creates tremendous opportunities to organize ourselves, regardless of place or time. However, we also see how SI-models do not really emerge as the conditions for SI to function are not met, quite often lack of trust being the major blocking factor. What is missing are the platforms for people to interact in a trusted way, relying on a next generation internet only accessible for people with e-identities issued by governmental authorities, an Internet of People. Blockchain is an example of a platform architecture that enables people to operate in a swarm manner.

### Swarm intelligence taking advantage of commoditized computational devices

In a similar way, as we explored for organizations, centralized expensive processing has become a bottleneck in many areas. As computing power nowadays is omnipresent, is interconnected and has become commoditized, a decentralized processing architecture can be realized at low cost. Such an architecture is also more natural than a central one, as needs for information processing and consumption reside locally. SI-principles can very well be applied to create groups of self-organizing relatively cheap devices, like drones, robots, smartphones, to implement the power of many in the automation domain at a high degree of resilience and robustness.

## Swarm intelligence in converging digital and physical worlds

To develop solutions relying on SI-principles, we need platforms, operating systems and architectures to enable a swarm-like self-organizing type of processing across a group of dispersed devices. Swarm-algorithms, as we explore, provide the layer of logic on top for devices to exhibit self-organization behavior in dealing with a particular target in a problem space. These local computational devices do not only mutually interconnect, but also provide the means for people to connect and to swarm in the digital world, regardless of place or time. As the physical human and the digital virtual world become more and more interwoven, we expect to see SI-based vertical solutions, e.g. aiming at specific groups of professionals like medical specialists, to support collaboration on common tasks, potentially at a global scale.

## What can we expect in the future from swarm intelligence?

Is swarm intelligence going to be a game changer? No doubt, in our view the answer is YES. In our complex world and fast-paced, constantly evolving environment, it is more than ever time to act as a person or a company smarter than others. Let's be swarm intelligence minded to better: answer questions, make predictions, optimize opinions, generate forecasts, reach decisions.

So, in a world in which almost all people and devices are connected, we argue in this paper that we should start to think about how to exploit this huge potential by developing SI-based digital and human solutions. It's striking to see how swarm intelligence is at stake in most of the influential technologies and associated business opportunities and challenges Atos put forward in its vision Journey 2022.

**Let's be ready to reap the rewards of the swarm intelligence promise:**

- **It's time to engage with nature**
- **Will your company be a disrupter or will it be disrupted?**
- **Take the right decisions faster than competition**
- **Create top class value from an ultra-connected world**

# Contents

# What is swarm intelligence about?

## 2.1 Defining the concept

### 2.1.1 Swarm behavior

Swarm intelligence is derived from swarm behavior as found in nature. **Swarm behavior**, or **swarming**, is defined here as "a collective behavior exhibited by agents, particularly animals, of similar kind which aggregate together, milling about the same spot or moving en masse in some direction" [1.].

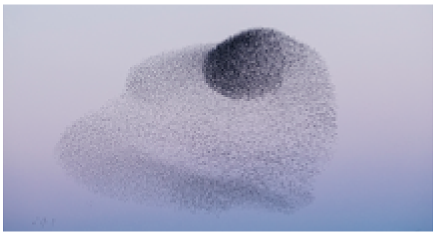
As human observers, swarm behavior intrigues us. Take for example of a flock of sparrows. While "being as free as a bird", when flocking, individual sparrows voluntarily give in their freedom entirely, but temporarily, to become part of something bigger, i.e. the swarm. Research has shown that this type of swarming is an effective strategy against predators, like falcons [3.]. So, by swarming there is an advantage for an individual sparrow to gain: survival. We can see how swarming is about animals organizing themselves to obtain the **power of many**. This property makes it interesting to see how we can apply principles of swarm behavior in the human domain.

### 2.1.2 Swarm intelligence

Swarm intelligence is derived from observing the swarming group behavior of animals and trying to mimic this behavior, by capturing this in rules, also called 'heuristics'. In that sense it can be seen as a specific product of biomimicry which is looking at nature for findings ways to solve human problems.

We define **Swarm intelligence** (SI) as "the collective behavior of decentralized, self-organizing systems", comprising of either humans or artificial artefacts [2.]. 'Swarm intelligence' was introduced by Gerardo Beni and Jing Wang in 1989, in the context of Cellular Robotic Systems (CEBOTs): a self-organizing system composed of a large number of autonomous robotic units.

SI systems consist typically of a population of agents, interacting locally with one another and with their environment. The agents each follow simple rules, and although there is no centralized control structure dictating how individual agents should behave, as a whole they develop goal-oriented behavior. Local, and to a certain degree random, interactions between such agents lead to the emergence of seemingly "intelligent" global behavior, which is more than the sum of the activities of the individual agents. This intelligent group behavior is what we call 'swarm intelligence' and is therefore considered as **emergent property** of swarm behavior.



## 2.2 What are the mechanics leading to swarm intelligence?

### 2.2.1 Elementary characteristics

SI does not result from just any kind of group behavior. For SI to emerge, the underlying group behavior needs to have the following elementary characteristics:

SI involves a **group** of similar or equivalent **agents** (natural or artificial) without a leader,

These agents have the capability of **being responsive** towards each other, i.e. they exchange data, either in direct contact or indirect, e.g. through repositioning in a shared environment,

The agents have an individual **task or goal**, each of them wants to accomplish, which is supportive to the goal of the group as a whole,

The **ability to act** (e.g. swim, walk, travel on the internet), to accomplish this goal or task and to conduct these actions in parallel from each other,

Each agent applies a set of (simple) **rules or heuristics** to accomplish the goal or task in an economic way (i.e. least energy consumed in as little time as possible),

To accomplish this goal or task, the agent has some form of **memory** (either internally of externally) to evaluate its proximity from its objective / task end-state and adapt its behavior accordingly,

The individual's goal or task accomplishment is to some extent **dependent** on some of the other agents and on their environment in a general sense,

The agents have certain **navigation** skills and **communication** patterns to accomplish the goal, which includes a certain degree of randomness.

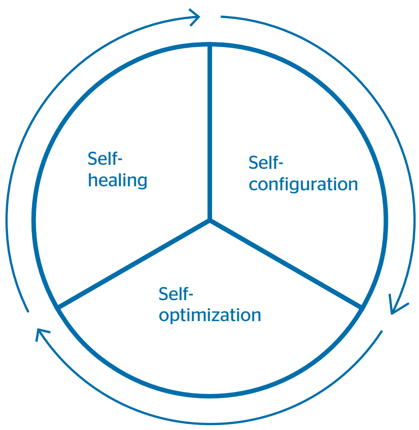
Each agent will apply its heuristics to reach its goal, while exchanging information with other agents in its immediate proximity. This results in the desired behavior of the group as a whole. SI is the resulting property of the group in relation to the group's objective attainment.

### 2.2.2 Self-organization as foundation of swarm intelligence

Within a swarm, the individual agents perpetually select their next course of action from a range of alternatives, in view of the actual state of affairs and the contribution of their best next action to the attainment of the group objective. The heuristics that the agents apply to determine their next action are based on control loop principles, like feedback and feedforward, to either correct or enforce an agent's actions, bringing it stepwise closer to the desired state. This is in essence what **self-organization** is about; the perpetual mutual alignment of the behavior of the agents from the perspective of each one's contribution to the group objective.

To demonstrate these principles of self-organization, we can look at ants foraging for food. This is a classic example that has inspired the development of algorithms to simulate this behavior as we address later on in this white paper. So, how do they do it? It starts with a common objective, being the search for food. To reach that goal, ants start to move around, leaving behind a pheromone trace to mark where they have been, serving as a memory. Initially they move randomly to cover the territory and change direction when this does not lead soon enough to the discovery of food, applying the control principles (in a feedback mode). Once an ant has discovered food, the ant will return and strengthen the pheromones trace left behind, which attracts the other ants to the food supply, again the control principles (in a feedforward mode).

For an outside observer, these swarm activities are seen as self-organization, which emerges as a property of the behavior of the swarm as a whole and as key element of swarm intelligence. In the man-made domain, we therefore consider how to apply swarm intelligence as a new organizational paradigm, creating the conditions for self-organization to take place.



# Obtaining swarm intelligence in man-made systems

## 3.1 From natural swarms to artificial swarm intelligence

We are interested in swarm behavior, not just because we study nature as such. From a biomimetic perspective we ask ourselves what we can learn from animal swarms to apply this in the human or man-made domain. Or, how to exploit the potential of the power of many and obtain the desired synergetic SI-effect?

In the man-made domain, we can adopt an engineering approach to purposefully design systems in a way that they are going to exhibit SI-features. In doing so, we are inspired by swarm behavior in nature, but we need to take into account some key differences between natural and man-made systems.

First of all, the **agents** of a man-made swarm can be entirely artificial (like robots), people (in case of a group) or a combination of people and artificial devices (like mobile phones). The types of interactions can therefore vary from exchange between robots, between people and between people and devices.

Another essential difference is in the **proximity** feature of a swarm. Physical proximity is a condition for animals to swarm. For humans or devices, just the ability to mutually communicate (e.g. through the internet), is sufficient to enable self-organization, hence to obtain collective behavior. An agent's interactions are therefore not limited to its immediate neighbors only. Principally, any agent can interact with any other connected agent. Specific for human agents, proximity also takes the shape of being like-minded, or having a common interest as a condition to swarm.

Man-made systems consisting of artificial devices are **programmable**. So, algorithms can be used to make these systems behave in a way that they exhibit SI. Human behavior is not programmable in this way. Instead, we need to provide the right sort of **incentives** that will stimulate people to behave in a swarm-like manner. This is what we will call 'social contract'.

Man-made systems are usually part of something bigger, often being an organization like a company. This creates the possibilities for man-made swarms to operate within a **hierarchical** structure, where the higher level takes care of setting the objective and constraints (like budget and plan) for the group as a whole. The group then organizes itself to attain this objective, within the given constraints.

In the next section we explore how SI principles can be applied in the human context and how SI-based systems can be used to resolve problems in a different way than through a traditional approach.

## 3.2 Schools of thought

In exploring how man-made systems can be designed to exhibit SI-features, three schools of thought are found in literature and practice, focusing each on SI from a specific angle:

1. **Algorithmic school:** Research in this domain addresses the development and application of mathematical algorithms to resolve computational problems, inspired by natural swarms.
2. **Organizational school:** The subject of this school is to investigate how SI-principles can be applied in the design of processes and structures in which people are the swarm's agents, to overcome problems encountered in classical organization models.
3. **Automation school:** This school studies how automated devices in the IT domain, like robots, computers, or programs can apply SI-principles to improve execution of specific tasks, often making use of the algorithms studied by the first school.

## 3.3 Algorithmic school

### 3.3.1 Algorithms and their application

The approach followed here is to develop algorithms, mimicking natural swarm behavior. These algorithms are commonly used in resolving certain optimization or simulation problems through an iterative approach, executed by the agents of the swarm (or in this context often called "particles"). An SI-approach is applied either because the only way to resolve the problem is iteratively, or the problem's resolution time is shortened by making use of the processing capabilities of the agents (instead of a by single central processor).

The algorithm specifies a few elementary rules, to be applied by every agent, which: (1) enables a decomposition and delegation of the overall problem resolution task to the agents, and (2) results in self-organization amongst the agents. In turn, this lead to a collective behavior that produces the desired outcome in conjunction to the formulated problem. The elementary rules cover both feed-back and feed-forward mechanisms. SI-algorithms are selective in a sense that successful behavior is amplified, and that randomness is applied to obtain the variety of inputs necessary for being successful.

Over the last decades, a large variety of algorithms has been developed (see for instance [5.]). In the next section we explore one of the most popular algorithms (i.e. PSO) as an example of the approach followed by the algorithmic school.

### 3.3.2 Particle Swarm Optimization (PSO) algorithm as example

#### 3.3.2.1 Application

PSO is applied to solve optimization problems, i.e. find out the most appropriate solution in a set of candidate solutions. It is widely applied to resolve a wide diversity of simulation, analytical and design problems (see [4.] and [5.] for application examples). The goal of the algorithm is to have all he particles locate the optimum in a multi-dimensional space of potential solutions. This is achieved by assigning initially random positions to all particles in the space and small initial random velocities. The algorithm is executed like a simulation, advancing the position of each particle in turn based on its velocity, the best known global position in the problem space and the best position known to a particle.

The PSO algorithm is applied for instance in bioinformatics for which problems lay in the huge amount of data, and thereby computational complexity. As a result, a satisfying approximation to the solution is often used instead of an unaffordable exact one.

#### 3.3.2.2 Principle

How does PSO work? A subset of candidate solutions to an optimization problem is defined as a swarm of particles which may flow through the possible solutions space defining trajectories which are driven by their own and neighbor's best performances evaluations. Over a number of iterations, the particles of the swarm have their values adjusted closer to the member whose value is closest to the target at any given moment.

A particular's behavior is determined by a combination of two types of actions: (1) exploration, which is the behavioral component that takes care of covering the search space and (2) exploitation, which takes care of utilizing the particles current position in terms of its target proximity. Exploration is the random part of an element's behavior. In implementations of the algorithm usually a variable is used so set the ratio between both factors. The bigger the role of exploration is, the longer the process may take, but the less likely it gets that not the best available solution in the solution space is reached.

## 3.4 Organizational school

### 3.4.1 How do human beings swarm?

People swarm as well under certain circumstances, but not driven by an algorithm as explored in the previous section. As addressed earlier, a key aspect of SI is the capability of self-organization, we therefore consider two basic forms of human organization encountered in practice,

- **Formally designed organizations**, which have been structured explicitly to reach a certain objective, like private companies, governmental institutions, or sports teams,
- **Informally evolving organizations**, where objective and structure are not predefined, but emerge as an outcome of the collective behavior of the participants, who share a common interest.

### 3.4.2 How formal organizations can benefit from SI

#### 3.4.2.1 Limitations to the formal organization model

In the age of industrialization and expanding markets, formal organizations with rigorously divided tasks were a prerequisite to manage growth, while making efficient use of scarce goods, like machinery. Today, the environment of these companies has changed dramatically in terms of its dynamics and complexity and many markets have shifted from being manufacturer- to buyer-driven.

While Organizational structures in the past focused on stability, internal control and obtaining economies of scale, organizational structures today should accommodate for a state of permanent flux and focus at first and foremost on serving their environment. In this situation size and structure have become an obstacle as they created inertia in dealing with change. So, how have organizations responded to this?.

#### 3.4.2.2 Semi-autonomous groups for agility where needed

Initial response of western industrial organizations to the changing environment, starting in the '70's, was to handle the size and complexity issues. This was dealt with by concentrating on core-business and strengths, while outsourcing or divesting non-core parts. However, the fundamental structure was often not touched upon and for instance rigid vertical chains of command remained sources of tardiness, conflicting interests and miscommunication.

Organizations which recognized this begun to explore other models, in which the human factor in terms of capabilities and motivational factors were more explicitly taken into account. In turn, this led to the concept of **semi-autonomous groups**. We call these groups 'semi-autonomous' because their autonomy is limited to the way in which they produce certain deliverables, which are used by the larger organization of which they are part. So, they operate freely and regulate mutually their activities within the boundaries of a given assignment (see also [6.]).

The self-organizational capabilities of the group - as we have seen an essential property of SI - assure its perpetual orientation towards the common goal. Without central management, the members of the team divide the work amongst themselves, depending on progress and availability of team members. The obtained result is a form of memory (also called "stigmergy") that is directly visible to everyone and thereby supports the team members in deciding on and coordinating next steps. By applying SI principles, the team becomes more resilient and efficient in attaining the group's required result than is the case in a classical management structure. This applies in particular when dealing with a high degree of uncertainty or turbulent environment that may affect the goal attainment.

For semi-autonomous groups to be successful, a number of conditions is to be satisfied (see also [7.] and [8.]). Autonomy, congruence of objectives, open communication, multi-skilled participants, team cohesion, shared accountability and short-cycled feedback loops are ingredients of a successful team.

A good example of such a semi-autonomous group in the IT domain is a DevOps team. In essence, a DevOps team is a self-organizing group in which everyone manages his/her own activities in a way that they are aligned to the activities of the others in the team and that they contribute to producing the required deliverable.

Semi-autonomous groups take on different shapes in organizations, like task forces or incubators, but in general provide a degree of autonomy that enables and stimulates people to deliver a high-quality performance in a volatile, unpredictable or unstructured environment. They are not a silver bullet for just any organizational issue. Semi-autonomous groups provide another organizational paradigm, that can be implemented in conjunction to the classical model, there where this makes sense. E.g. in those parts of an organization that are directly exposed to the organization's environment, like R&D, Marketing and Sales.

### 3.4.3 How informal organizations can benefit from applying SI

#### 3.4.3.1 Communities as a form of human swarming

People join formal organizations on the basis of a negotiated contract (i.e. a committed performance versus a salary). However, there is still another type of contract for human beings to organize themselves. This other type is based on people joining each other voluntary on an equal basis, because they have similar personal objectives that cannot be achieved individually. A **community** is about people joining in this way on the basis of what we call here a 'social contract', which contains regulations on for instance code of conduct or confidentiality, to protect the interests of the participants.

As with animal swarms, the very first human communities may have originated because of survival arguments (think about tribes). Nowadays we participate in a community because we want to share emotions or knowledge with others, or we want to achieve something together.

An audience in a soccer stadium forming together a wave is an example of sharing emotions through which an individual person feels to be part of something bigger. Being with like-minded people creates feelings of safety, belonging and recognition.

Communities differ from the semi-autonomous groups we encountered in the previous section. A community can be fully autonomous in a sense that it can define its own objective, whereas this is a given for a semi-autonomous group being part of a larger formal organization to which it needs to contribute. Consequently, the social contract for a community can be a rather lose one and individuals can freely leave or join a community as they please.

[1]The concept of semi-autonomous groups is not new. Experiments with this concept began in the 1960's, done by the British Tavistock Institute, building upon earlier research at the Hawthorne Works (in Chicago) between 1924-1932 into the relationship between productivity and motivational factors.

#### 3.4.3.2 Swarming in the digital world

As in animal swarms, the early human communities required individuals to gather physically to obtain the required level of self-organization. Individuals being in direct proximity of each other was a prerequisite for having swam-type of direct interaction. The coming of the personal computer, the internet and smartphones have changed this dramatically. Being together physically is no longer necessary to connect.

As long as someone in the "digital world" is reachable via a digital address, anyone can participate in any community, regardless of location.

But what kind of communities in this Digital world could be qualified truly as 'SI-communities'?

What is called a 'community' in the digital world can in many cases hardly be called a community in the sense as we just described. Often internet communities, facilitated by the familiar social media companies, are places where people connect to, just to ventilate opinions and given some proof of their existence. Mechanisms of self-organization and clear objectives leading to convergent behavior are often absent.

However, there are examples of successful digital communities in which we can recognize SI-principles:

- **Buying groups**, consumers connecting with the objective to obtain best possible prices and conditions for certain products or services. These groups may exist only temporary, initiated by someone who has a direct need to acquire a product or service. By joining the group, one can get a better price than operating individually.
- **Knowledge groups**, the best example is Wikipedia that provides the platform for authors to group around a specific topic and contribute to its documentation. Jointly the authors take care of expanding and improving the quality of the documentation, relying on a stigmergy kind of memory.
- **Shared economy**, people living in the same neighborhood make their property (e.g. power tools, cars) available for lending amongst the participants without any charge. People can only borrow when they make some of their properties available for lending to the others.
- **Meeting groups**, people sharing an interest and living in the same village or region use the internet to group around topics for which they want to organize face-to-face gatherings. This can be social meetings or working groups for instance to share views. However, this type of swarming may also take a more destructive shape, e.g. hooligans gathering for a riot.

In the last two examples a digital community is used to establish connections in the physical world. This is done by creating a virtual proximity first, which can then be followed by the physical proximity. The digital community is used in this way as a low threshold facility enabling individuals to judge whether they want to make the additional and more substantial effort of joining physically. All mentioned examples have very clear objectives and attaining these objectives depends on sufficient participation of like-minded individuals.

#### 3.4.3.3 What are prerequisites for successful communities in the digital world?

For digital communities to exhibit self-organization properties, the same key principles apply as for semi-autonomous groups: clear overall objective, close alignment with personal objectives of participants and a homogenous composition of the group. In particular in digital communities, when people are remote, trust is an important condition for these communities to be successful. Trust takes time to develop and traditionally requires people to meet face-to-face. Trust stimulates someone to invest in a relationship and to take risks in exploring new avenues. The higher the trust amongst individuals, the higher the ambition level can be set for the community as a whole. Prerequisite is that people equally contribute to this and trust each other to do so.

When people work physically together and in a formal organization, measures are available to obtain the desired behavior, e.g. through the formal contract and social control. However, when people are remote only connecting through the internet without knowing each other face-to-face, misbehavior is more likely to occur and trust much more difficult to develop. We see in the digital world how communities often have a temporary nature and fail to reach their objectives, as participating individuals fail to develop sufficient trust in the other participants, and then decide not to contribute as needed.

Individuals and companies can use today's digital world to create organizational settings, for joining forces to reach individual objectives through a group performance. Apart from the factors mentioned in this section, what is needed to make this happen, is a digital platform for people and companies to exchange transactions in a safe and trusted way. These transactions embody new types of social contracts for working together and support self-organization as described earlier.

**Blockchain** can provide the concept for such a platform. The way blockchain transactions are processed amongst participants provides a basis for trust. We expect blockchain platforms to provide the additional support layer for using the internet in a trusted way. This enables people, being remote and strangers to each other, to cooperate and conduct transactions amongst themselves as they would do when being physically together. Neither is there the need for a trusted middleman or central regulating agent, as found in the traditional models, to compensate for some of the weaknesses inherent to the digital world at present. Blockchain will enable a community to develop the closeness (or virtual proximity) that is needed for people to swarm and bundle their power.

### 3.4.4 What future organizations will look like

As the digital world matures, we can expect that communities professionalize as well, for instance through adopting SI-principles. They will institutionalize, become more successful and will more clearly differentiate from non-SI type of social gatherings on the internet. These new communities will also develop their own economic models and incentivization mechanisms, leading to new types of social contracts. This to provide the necessary stability and trust base for participants to work together on more ambitious objectives, than merely chatting and exchanging pictures. As the integration of the digital world into the physical world progresses, these communities could become the foundation for the companies of the future. We might see next how some of these communities are going to swarm themselves, that is grouping with other communities, when synergetic advantages can be obtained.

Organizations adopting (selectively) SI principles, will be better fit for the future than organizations that stick to more conventional models solely. The need for an organization to be more responsiveness to an increasingly uncertain and volatile environment, the shift towards knowledge-based economies, almost everyone and everything being connected in the digital world, growing flexibility and commoditization of technology, are just a few trends that put classical organization models under pressure. Combining these trends, we can expect to see increasingly less large-scale companies in the future (see also [9.1]). Specialized companies will shape up by bringing workers virtually together to work for a certain period together on particular objectives or tasks in a swarm-like manner. Companies like these will need to liaise with other companies, each covering a particular part of a business chain. Like with the workers, these liaisons may be of temporary nature, thereby forming swarms (or "ecosystems") of companies.

## 3.5 Automation school

An autonomous system is defined here as a man-made system that can independently compose and select among alternative courses of actions to accomplish goals based on its knowledge and understanding of the world, itself, and the dynamic local context. It must be able to respond to situations that are not pre-programmed or anticipated prior to its deployment.

There are numerous advantages to using swarm principles in designing autonomous systems, including:

- **Parallelism:** tasks can be decomposed and performed in parallel rather than sequentially,
- **Efficiency:** tasks can be decomposed in such a way, that different agents of the system can cooperate together to obtain a better end-result than individuals might achieve,
- **Fault tolerance:** the failure of a single agent within a group does not necessarily imply that a given task cannot be accomplished.

Potential applications for swarm automation are many and some are described in the next sections. They include tasks that demand miniaturization like distributed sensing tasks in micromachinery or the human body, and activities that demand cheap designs, for instance mining or agricultural foraging. It is also considered that one of the most promising uses of swarm automation is in disaster rescue missions (see [11.]). Another large set of applications is autonomous surveillance and reconnaissance. U.S. Naval forces have also tested a swarm of autonomous boats that can steer and take offensive actions by themselves (see [11.] and [13.]).

### 3.5.1 Value of swarm robotics systems

A robot is usually inspired by human behavior. As it is hard to simulate the human interactions, such robots are often sophisticated, complex to design and consequently expensive. Comparatively, **Swarm Robotics** is inspired by social animals for which the mimicking of animal groups is simpler to simulate than human behaviors. As the individuals in a swarm are reasonably simple, small and low cost, it gives swarm robotics a bright future in dealing with large scale operations or environments, offering novel approaches:

- **Goal seeking:** a swarm robotics system's behavior is driven by the objectives of the tasks they are assigned to.
- **Control loops:** a swarm robotics system as a whole has to stay focused to achieve the task it has been assigned to, whatever the conditions and the events encountered by any individual of the swarm.
- **Memory:** a swarm robotics system relies on communication between adjacent individuals that maintains local knowledge shared between neighbors.
- **Multiple inputs:** collecting data about the working environment or surrounding environment of a swarm robotics system is an everlasting job.
- **Resilience:** a swarm robotics system needs to work continuously towards the objective of the system's task without significantly degrading performance, in case of individuals fail for some reason, to deliver the right outputs.
- **Scalability:** individuals are substitutable and can therefore join or quit a task at any time without interrupting the whole swarm robotics system that can self-adapt to the change in population through implicit task re-allocating schemes without any external operation involvement.

### 3.5.2 Usage of swarm robotics systems

Various types of applications of swarm robotics systems have been found valuable by academics, industry and military over de recent years, as demonstrated in real-life, like:

- **Underwater habitats:** The EU-funded Collective Cognitive Robotics 2011 project [12.] aimed at developing a swarm of autonomous underwater vehicles that are able to interact with each other and which can balance tasks such as ecological monitoring, searching, maintaining, exploring and harvesting resources in underwater habitats.
- **Space exploration:** NASA has investigated swarms for future space exploration missions [14.]. Given that many of the spacecraft could collide with one another or with asteroids and become lost, multiple-spacecraft missions offer greater likelihood of survival and flexibility than single-spacecraft missions. Additionally, the self-directed swarm will exhibit intelligence, which is critical since round-trip delays in communication from Earth can stretch to tens of minutes.
- **Pollutant absorbing:** researchers of Massachusetts Institute of Technology have developed a fleet of low-cost oil absorbing robots called 'Seaswarm' for ocean-skimming and oil removal [15.]. The system provides an autonomous and low-cost solution for ocean environment protection.

### 3.5.3 Improve trust and traceability with blockchain

The properties of swarm robotics systems can be greatly leveraged by the blockchain technology [10.], [18.]:

- **Security:** individuals of a swarm robotics system need to safely detect and trust their counterparts. A blockchain technology can fulfill these objectives, proving the identity, guarantying reliable peer-to-peer communications, making transactions using unsafe and shared channels, overcoming potential threats, vulnerabilities, and attacks.
- **Distributed decision making:** blockchain technology allows for the possibility of creating distributed voting systems for swarm robotics systems that need to reach an agreement making sure that all individuals continuously share an identical view of the world.
- **Knowledge acquisition and transfer:** any individual joining a swarm robotics system will be promptly get trained and synchronized with the rest of the swarm by downloading the history of all agreements and all related transactions, and knowledge already discovered and stored in the blockchain.
- **Behavior differentiation:** swarm robotics systems deployed to achieve different tasks will need to handle different behaviors according to these tasks purposes. It can be handled by the capability of blockchain technology to link together several blockchains that will allow a swarm robotics system to act differently as per the particular blockchain being used.
- **New business models:** one of the most common usages of blockchain technology is cryptocurrencies. It is an ideal Application Programming Interface for economic applications that will allow swarm robotics systems to directly take part in an economy.

### 3.5.4 Which future for automation school?

Swarm intelligent autonomous systems are one of the most fascinating research and application areas of recent decades. It perfectly fit the emergence of the networked connection of people, process, data and things that is exploding, pushed by either Business-to-Consumer (B2C) or Business-to-Business (B2B) business models, for which current vertical architectures will not work anymore. As computing capabilities in the cloud and at the edge become increasingly intertwined, we will see the emergence of large computing continuums. Much as we see swarms in nature acting as intelligent collectives, the individual computing capacity of the devices at the edge will be complemented and supplemented by their dynamic cooperation with other objects in swarm communities acting as an intelligent whole.

This key trend of swarm of connected computing devices will only get successful is the Artificial Intelligence capabilities of distributed systems are evolving accordingly. We will need by example to evaluate learnings from individual participants and enforce and spread out the ones that are considered as the most promising.

The future of swarm intelligent autonomous systems is definitely paving the future of the B2C and B2B business models.

# Is swarm intelligence going to be a game changer?

## 4.1 It's time to engage with nature

Did you know the Eiffel tower, 324 meters tall with a ground square of 125 meters' width, was inspired by your femur, the lightest and strongest bone of the human body? In addition, if you imagine a cylinder that completely wraps around the Eiffel tower, the air in this tube outweighs all the iron in the tower.

Biomimicry: **turn to nature for innovative design solutions**

It surrounds us, the secret to survival: there is no better designer than nature. Through billions of years of evolution, life's products, so to speak, have been extensively prototyped, market tested, upgraded and refined.

Back to the Eiffel tower, you don't have to go to Paris to see it. Just look down at your feet. In 2017, scientists at Georgia Tech investigated how ants built themselves into towers to escape confinement or danger [19.]. They discovered that the ants climb upwards, on top of each other, until they find an empty spot. Then they stop. The next one does the same, and so on. As the tower grew, the ants in the middle start sinking and climbing out from the bottom. They then restart their journey to the top as they continuously rebuilt the tower. It inspired the researchers who believe that this construction method could be useful in programming swarm intelligent robots for building purposes.

Since the beginning of the humanity, our story has been driven to gain our independence against nature. **Biomimicry** becomes more than just a new way of looking at nature. This sustainable design approach becomes a race and a rescue.

Are you ready to create man-made swarm intelligence based on the biomimicry revolution that introduces an era based not on what we can extract from nature, but on what we can learn from her?

## 4.2 Will your company be a disruptor or will it be disrupted?

While many companies are struggling to attract, and retain top millennials (Gen Y), they are starting to see another tsunami, potentially just as disruptive: **Gen Z**.

But what's Gen Z? Gen Z, people born from the mid-1990s to the early 2000s is the first generation to be raised in the era of smartphones. They have been exposed to an unprecedented amount of technology in their upbringing and do not remember a time before social media. Gen Z valuable characteristics are their acceptance of new ideas and a different conception of freedom from the previous generations [16.].

Gen Z is also driven by YOLO: "You Only Live Once". In other words: be spontaneous and transparent, always communicate openly and honestly, and live life to the fullest. They don't want to waste time with things they don't enjoy. Corporates need to understand how to embrace the YOLO entrepreneurial spirit, developing new models of lifelong learning, a combination of hands-on experience, training and mentoring.

Lastly, Gen Z is as the heart of the digital revolution and feels definitely comfortable with the digital world. Waves of disruptions based on digital revolution they are born with are increasingly revolutionizing traditional industries. Any company has now to manage fundamental changes in the way its deals with customers, the way it builds its brands, the way it processes, distributes, markets, analyzes information, and the way customers access its products and services. It becomes more about dynamics and agility to keep ahead of the competition rafter than efficiency and stability which are the essence of traditionally hierarchical organizations. This hyper-competition is driven by multi-dimensional innovation capabilities, at least two different types of innovations being interlaced and promoted simultaneously: products and services on one hand and business models one the other hand.

This new multi-dimensional competition for innovation as well the Gen Z expectations are strong organizational challenges for companies. It is not only definitely required to build interdisciplinary teams beyond the traditional departments and already established hierarchies, but also teams that are capable of quickly acting and reacting to unforeseen changes. Efficiency of such teams relies on peer-to-peer connections and self-organization and they have to perform as swarm-organizations: team individuals are appointed to a higher occupational competency and have freedom of action. It requires greater flexibility and self-motivation, working as internal entrepreneurs within their own company, which is a key driver for Gen Z motivation, involvement and satisfaction.

Although the **gig economy** is not yet widespread, it is gaining traction of the workforce, specially to gen Z with their main differentiator of attitudes and behavior and for which flexibility is a key driver for seeking a new employment experience [16.], [17.]. Working in multiple roles such as part-time, freelancing or in temporary assignments rather than a traditional full-time position will become increasingly common. Rather than investing in expensive, inflexible long-term employee contracts, companies might temporally bring in individuals with specific skillsets as needed, or grow and shrink their workforce as demand, resources, profitability etc. The gig economy could appear to yield benefit for both workers and companies.

Blockchain's decentralized model enables secure peer-to-peer transactions without the need for intermediaries or centralized authority. It also makes it possible to execute self-executing contracts that are called. If and when the pre-defined rules are met, the agreement is automatically enforced. It is the simplest form of decentralized automation [18.]. For the gig economy, this combination of blockchain transactions and smart contracts makes it possible to create freelancing and resource-sharing platforms where employers can find and hire employees and compensate them without the need for a broker. Payments are made immediately in cryptocurrency without any delays.

We could even consider smart contracts associating freelancers and investment funds competing against classical companies on a deal-per-deal basis. In such environments, corporates would not face anymore a situation where the gig economy brings them advantages, but competitors with the best experts, great flexibility and agility, and backed on credible financial capabilities. It could even shake the long-term future of corporates.

It's time to ask you: will your company be a disrupter or will it be disrupted?

## 4.3 Take the right decisions faster than competition

Gen Z has grown up in the middle of an era of developed information technology, constantly engaging in online exchanging of information and conversation among its peers. They value career growth and development above anything else when it comes to employability. They are in a world where environments are complex, changing all the time where the global optimum possibilities and value may change with time. They want systems that help them to take a decision on the fly.

In the same way, with digitalization and disruptive technologies, businesses are challenged all the time and they need systems which can help them decide on the direction to take in these complex systems.

The expectations from the systems are that they should enable them to derive insights and help the business identify directions in a highly non-linear, correlated parameters environment. With traditional mathematical modeling, finding an accurate estimate for all the parameters is very time consuming and almost impossible for such complex models.

SI algorithm's, like PSO we discussed earlier, can be deployed to track this dynamic shifting optimum. It will help to work together in synchrony, forging a unified dynamic system that can help them make decisions by exploring a decision-space and converging on a preferred solution.

These systems will allow the user to perceive and react to the changing system in real-time integrate noisy evidence, weigh competing alternatives and converge on a reasonable optimum quite faster than any other approach and at a competitive computing cost.

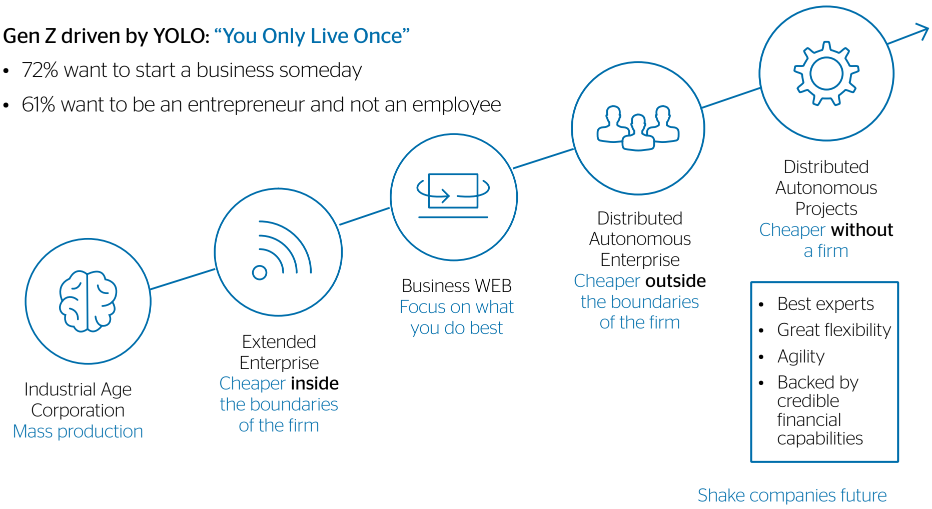
Our world is moving extremely fast and decisions to conduct businesses are more and more difficult to take in such an environment in which we have to weight tons of considerations. We would wish some time to make sure we take the right ones. However, both staying ahead of the competition and making the Gen Z who is paving our future feeling comfortable with our company, require from us agility and instantaneous appropriate actions and reactions.

Collective Humans coming together as a swarm will even form a hive mind – a 'brain of brains'. With machines augmenting the 'brains of brains' governed by above trends, like AI, these combine the knowledge, wisdom, insights, and intuitions of real people and in real time, enabling large swarms of networked humans to quickly converge upon optimized decisions, predictions, solutions, and evaluations that are driven by algorithmic capabilities (like PSO). Organizational decision making in this way becomes a perpetual rather than a periodic process, enabling an organization to continuously adapt its direction and actual state of affairs in response to a highly volatile and uncertain environment. Adopting this capability can become a matter of survival for an organization, as we have seen flocking is for a swarm of sparrows.

Let swarm intelligence and PSO like algorithm promises to make our life and business easier.

**Gen Z driven by YOLO:** "You Only Live Once"

- 72% want to start a business someday
- 61% want to be an entrepreneur and not an employee




**V**olatility **U**ncertainty **C**omplexity **A**mbiguity

Being a large organization is no longer an advantage

**Speed** is essential to survive

Knowledge, wisdom, insights, and intuitions combined in real time

Large swarms of networked humans quickly converge upon optimized predictions and decisions driven by swarm algorithms (like PSO)

- On time decisions
- Continuous adoption
- Multi alternatives - simplified heuristics

**Not the best, but fastest good enough ones stay ahead of competition**

## 4.4 Create top class value from an ultra-connected world

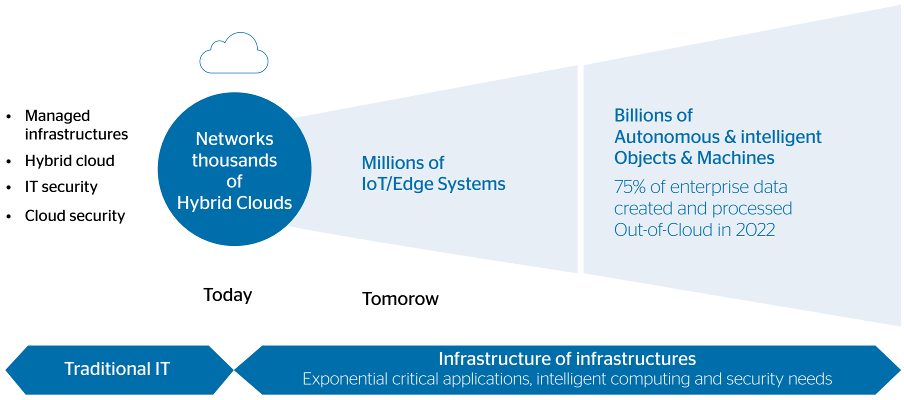
Waves of disruptions based on digital revolution have increasingly revolutionized traditional industries in the B2C sector, starting in the media industry and trade. The industrial revolution in the B2B world didn't however take-off so early and has only recently started with the emergence of intelligent machines essentially defining **'Industry 4.0'**. It is estimated that smart machines and robots will perform 45% of all manufacturing tasks by 2025, compared to about 10% in 2016 [20.].

This is also driven by the terrific growth of data. By 2020, there will be more than 16 zettabytes of useful data (16 trillion GB), reflecting a growth of 236% per year from 2013 to 2020. The **Internet of Things** (IoT), meaning the things that are networked together and produce data, is driving this data explosion. IoT applications will yield a vast quantity of data that has to be analyzed, and can be analyzed with recent advances in computing power and connectivity [21.].

Nevertheless, a complete and efficient industrial product or process in its whole life cycle has be accompanied by a virtual representation, often called "**digital twin**" that allows design optimization, process control, lifecycle management, predictive maintenance, risk analysis and many other features [22.]. This digital twin bridges the gap between the physical and digital worlds, relying on the connections at the interface between fields of expertise, domains and businesses, and across the complete lifecycle of products and systems, improving speed to market and efficiency.

It takes place in the digital revolution under way for which the agents are proliferating, e.g. Edge Computing, Big Data, Industrial Data Platforms [23.], High Performance Computing, Blockchain [24.]. These agents are enabling the transformation of services and manufacturing and reshaping entire sectors of the economy.

This shift is starting from the current vertical architecture promoting the cloud as owning all the intelligence, collecting data from sensors and sending commands to the actuators, creating a cognitive loop. Then, we are moving to the world of the edge computing with smart machines autonomously running on the field functions that delegated from the cloud, leveraging decisions that are taken as close as possible to the point of action. Last, the **fog computing era** is coming with the intelligence spread everywhere. Transversal cooperation is definitely supplanting vertical hierarchy with systems running altogether full processes as a swarm intelligence, having the ability to operate out of the control of the cloud.



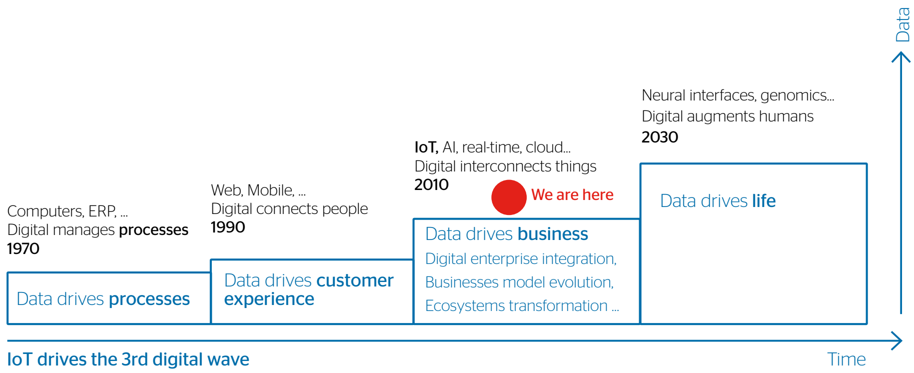

It requires us to consider the perspective of self- and swarm-operating machines with capabilities of data analysis and context-specific decision-making that are beyond the level of human performance. The consequences are manifolds and we have to carefully anticipate benefits and risks, including ethic and societal impacts.

This hyper-connected and distributed world is resulting into data and more importantly information and next knowledge becoming new gold mines. These mines are exploited using new avenues of digital platforms. A digital platform can be thought of as a set of technical building blocks that act as a foundation upon which an array of firms (a business ecosystem), can develop complementary products, technologies or services. Data is used there to bring context and insight, identifying potential business moments that are subsequently exploited. Now, applying this to swarm intelligence, these platforms will become more intelligent and will adopt creating differentiation through improving understanding and situational awareness when preparing the next generation of its products and services.

These data platforms with disruptive digital technologies will enable **new business models**. SI characteristics of resiliency, decentralized, self-repairing and scalability without experiencing complexity problems, present immense opportunities to resolve problems or complete tasks. This is done through cooperation between local elements all working on the same overall objective, rather than having tasks distributed in a compartmentalized way as we see in conventional parallel processing. With IoT providing information about assets and with objects becoming increasingly self-aware, the sharing platform of the future could have capabilities of permanent availability for use in real-time and efficient decision making. Enhanced tagging and tracking capabilities with swarm intelligence, present enormous economic opportunities to prolong the life of goods, plug leaks and make use of materials previously considered to be waste that contribute to promote a circular economy.

Most of the 16 zettabytes of useful data we mentioned will be generated and kept at the edge, moving away from centralized data storage concepts. Challenges will be around the control of these data, like sensitivity to intellectual property, access to and privacy of data. Digital giants are attempting to monopolize its monetization through controlling ownership rights of even personal data assets by various means, including some of dubious legality, morality or legitimacy. This is creating new agenda items for the public and political debate. Enforcing open API access to certain data types (e.g. PSD2 in Europe and UPI in India), and EU laws relating to personal data privacy (GDPR) are all moves to avoid such anti-competitive behavior and protect citizens. Consequently, there will be some organizations who take a nervous approach to this and secure all their data, treating them as personal data, and inevitably blocking new opportunities.

Is your company on track to create top value from your information assets and rush ahead of the competition?



# Conclusion

## Is swarm intelligence going to be a game changer? No doubt, the answer is YES.

## Swarm intelligence involves a different way of looking at things, whatever it is exercised by human or machines leveraging the capability of a group to be smarter when thinking and acting together than individuals would be on their own.

In our complex world and fast-paced, constantly evolving environment, it is more than ever time to act as a person or a company smarter than others. Let's be swarm intelligence minded to better: answer questions, make predictions, optimize opinions, generate forecasts, reach decisions, and so on.

So, no matter which way you look at this, in a world in which almost all people and devices are connected, we demonstrated we should start to think about how to exploit this huge potential and develop the SI-based digital solutions and human being. We now have the basic technology to make it happen and there is a natural fit between SI and the zeitgeist. It is this coincidence of trends in society, business, economy and technology that we belief is likely to set the scene for SI to break-through in organizations and in digital solutions and services, of which we mentioned some in this document, and to become mainstream.

Swarm intelligence is already at stake in most of the influential technologies and associated business opportunities and challenges Atos put forward in its vision **Journey 2022** in which we expect to see a post-digital world that has a greater focus on understanding and responding to the more human, real-world implications of digital and business technologies. All these challenges deeply discussed in Journey 2022 are fully connected to our statement: swarm intelligence is going to be a game changer. Each of them perfectly fit one or several of our SI predictions:

It's time to engage with nature

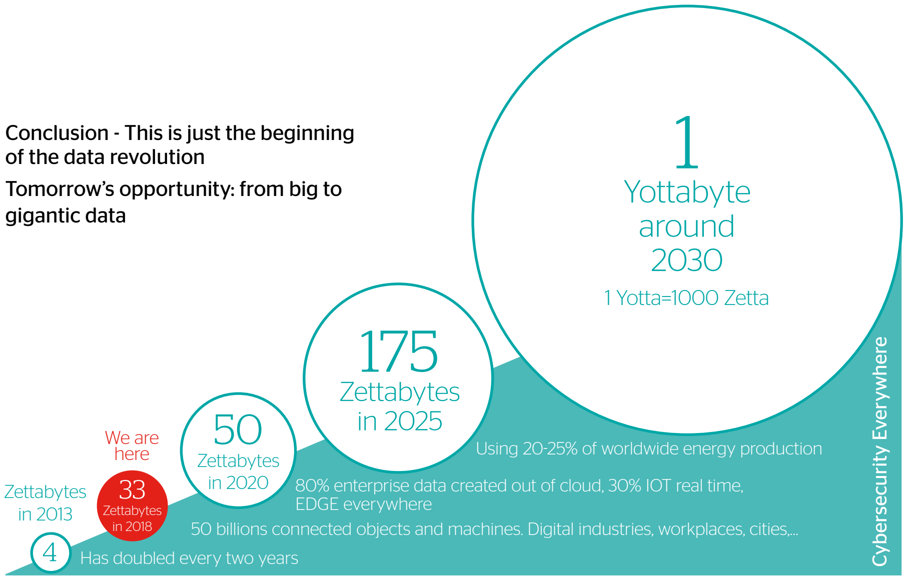
Will your company be a disruptor or will it be disrupted?

Take the right decisions faster than competition

Create top class value from an ultra-connected world

**Conclusion - This is just the beginning of the data revolution**

**Tomorrow's opportunity: from big to gigantic data**




Sources Gartner, IDC, Statista, Atos

1 ZETTABYTE = 1,000,000,000,000,000,000,000 bytes

## Ready to reap the rewards of swarm intelligence promises?

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# About Atos

Atos is a global leader in digital transformation with over 110,000 employees in 73 countries and annual revenue of over € 11 billion.

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