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RFID systems optimisation through the use of a new RFID network planning algorithm to support the design of receiving gates

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23 June 2026

1 Introduction

RFID (Radio Frequency Identification) technology is used in many different industries to automate processes and increase inventory and process accuracy. Its applications include production and logistics [1], healthcare [2], and fashion and apparel retail [3]. An RFID system consists of readers and tags: RFID readers are characterised by internal or external antennas, linear and circular polarisation, antenna gain, and orientation (directional or omni-directional). RFID tags are divided into active, semi-active, and passive. Passive tags are not provided with their own battery and thus are much cheaper and easier to maintain. These characteristics have led to the widespread use of passive tags in many industrial applications [4].

A common RFID application is the automation of the goods receipt process by means of an RFID gate. This application allows reducing labour and costs, as incoming items or load carriers do not need to be individually scanned at the goods receipt. For this purpose, directional antennas are attached to the sides of the goods receipt gate, and they automatically read the tags attached to items or load carriers when they pass through the gate by, for example, means of a forklift. However, gate design is not a trivial task, as it must deal with several decisions, such as the number of antennas that are required and their mounting height. At present, this task is mostly performed based on estimates or tests [5]. In addition, the determination of the vertical and horizontal mounting angles, as well as adjustments of the height of the antennas, are often carried out during commissioning, using the time-consuming trial-and-error principle. In existing literature, this problem is known as RFID Network Planning (RNP). RNP is recognised as an important and challenging problem, because it has to meet many conflicting requirements, such as quality of service, coverage, and cost efficiency. Simply put, the RNP objective is to use as few antennas as possible while ensuring a very high coverage rate in the given area (i.e. the reading gate).

However, the RNP algorithms existing in the literature are not applicable to the design of RFID gates, because the existing algorithms assume omni-directional antennas and do not calculate mounting angles [6] [7]. The present work aims to answer the following research question: how can the number of RFID antennas, their mounting heights and angles for the automated goods receipt process with RFID gates be optimally designed using an RNP algorithm? We answer this research question by proposing a new RNP algorithm and by testing its effectiveness with a case study involving the logistics of the automotive industry.

The RNP algorithm we propose starts from the following hypotheses: (i) a tag coverage of 99% must be achieved to create optimal conditions for high detection rates and (ii) the algorithm we propose will minimise the number of antennas and, thus, the hardware costs. The remainder of the paper is structured as follows: the common problems of RFID systems and suggested solutions are discussed in Section 2; in Section 3, the methodology of the new RNP algorithm is described; the newly developed RNP algorithm is explained in detail in Section 0; its application is shown in Section 5; and finally the conclusion and future outlook follow in Section 6.

2 Common Problems of RFID Systems and Suggested Solutions

An overview of the existing problems with RFID systems and the solutions suggested to solve them is given in Table 1.

Table 1: Overview of RFID problems and suggested solutions

Problem	Description	Suggested solutions
Noise immunity not sufficient	RFID systems use electromagnetic fields for data transmission, which are disturbed by sources of interference, such as metallic environment, liquids, reflecting objects / surfaces, absorbing materials in the environment, tag-to-tag collisions, reader collisions, other radio	The solution depends on the source of interference. For example, tag-to-tag collisions are solved by anti-collision algorithms [12] and RFID network planning algorithms [13] can be used to minimise reader collisions and

	devices, interfering signals from attackers, or temperature changes [8] [9] [10] [11].	shielding material is used in practice to prevent reflections.
Low detection rates	The sources of interference affect the reading range of RFID readers and lead to low detection rates [14]. The distance, positioning and orientation of RFID readers and RFID tags can also have an influence on the detection rates [15].	The detection rate is improved by eliminating the sources of interference. A prerequisite for high detection rates is maximum tag coverage, which can be achieved by RFID network planning algorithms [13]. Another solution to improve the detection rate is to experimentally determine the optimal positioning between reader and tag [15].
Low cost efficiency	Another problem is the low cost efficiency, because RFID systems can be expensive to implement and maintain and therefore companies hesitate to switch to RFID technology [16] [10] [17].	Early cost estimations are necessary to solve this problem [17]. Since RFID network planning algorithms aim to minimise costs, they can help solve this problem [6].
Complex installation and commissioning	The installation and commissioning of RFID applications is complex, because there are many challenges that need to be overcome during the implementation of the technology, such as the lack of standards that can be used as guidelines [17] [18].	One suggested solution is the development of a standard for the assembly of various RFID applications using RFID network planning algorithms, as these automatically determine the number of antennas and their positioning and, therefore, require less trial and error during commissioning.
Lack of application experience and technical skills	The lack of application experience and technical skills is also a problem with RFID systems [16] [10].	This problem can be solved by consulting services and training of employees [17]. During the planning phase, RFID network planning algorithms can support the employees.
Low distribution of RFID technology	The problems described above lead to a low distribution of RFID technology. This is a problem because the possibilities and advantages of RFID technology only become apparent when it is used consistently in many areas [19].	By solving the problems described above, the benefits of RFID can be reaped, which should motivate companies to increase its use and improve its distribution.

Table 1 illustrates that RNP algorithms can solve several problems and thus optimise RFID systems in several different ways. Indeed, RNP algorithms are used in the design phase of RFID systems to determine the number of readers and antennas, their position, and sometimes also their power. Amongst the several different objectives pursued by RNP algorithms we might list: (i) maximising tag coverage, (ii) minimising the number of readers, (iii) minimising reader collisions, (iv) minimising reader power, (v) optimising load balance, (vi) avoiding power loss, and (vii) improving overall efficiency. Clearly, every algorithm can pursue several of these objectives, but maximum tag coverage is generally the most common and important objective [6] [7] [20]. As these goals are contradictory and numerous, the RNP problem is a NP-hard multi-objective optimisation problem, which cannot be solved in polynomial time [21].

Many swarm-based algorithms have been developed to solve the RNP problem, such as the Guided Fireworks Algorithm (GFWA) [22], the Multi-Objective Firefly Algorithm (MOFA) [6], the Self Adaptive

Cuckoo Search Algorithm (SACS) [23], the Indicator-Based Multi-Objective Bacterial Colony Foraging Algorithm (I-MOBCA) [20], and the Artificial Bee Colony (ABC) algorithm [24]. The principle of these algorithms is that a population is first initialised and, in each iteration, new individuals are generated and integrated into the population. The new individuals are found by different mechanisms inspired by nature and represent a new solution to the problem. The individuals are evaluated by the fitness function with respect to the pursued objectives. The fitness function is either based on a weighted sum, hierarchical prioritisation, or Pareto dominance. The existing RFID network planning algorithms use omni-directional readers, which are modelled on a circle whose radius indicates the reading range. The result of the algorithms is either an optimal solution or the Pareto front. Many of the algorithms have only been verified by benchmark tests. The MOFA has also been used in a practical use case to plan the LNG (Liquefied Natural Gas) training centre, where machines, employees, and LNG components are tagged and read to track movements and progress [6]. The SACS has been used in the planning of research laboratories to use RFID to track the stay of students, monitor instrument availability, and intelligently control the lights and air conditioning [23].
To the best of the authors' knowledge, however, no RNP algorithm available in the literature can be successfully applied to the design of RFID gates [6] [7]. Thus, in the remainder of the paper we will propose an RNP algorithm whose aim is to support the optimal design of an RFID gate, that is minimising the number of antennas and providing their mounting heights and angles within a gate that achieves excellent tag coverage rates and controls the overlapping rate of antennas' fields.

3 Methodology of the new RFID Network Planning Algorithm

In this section, the methodology of the new RNP algorithm is presented, which contains the modelling of the antenna field and RFID tag area as well as the process of the new RNP and the boundary and evaluation functions.

3.1 Modelling of the Antenna Field and RFID Tag Area

Notation definitions for the antenna field are reported in Table 2. We note that, with respect to the RFID gate, we will refer in this document to a left-hand side and a right-hand side. In figures, right- and left-hand sides will be derived from the figures themselves. The definition of a main direction of motion, in whose respect right- and left-hand sides shall be defined, can be decided when applying the suggested methodology and does not affect the generality of the approach.

Table 2: Notation definition

Symbol	Definition
$i = 1, \ldots, n$	Number of the antenna, where $1, \ldots, n/2$ are the antennas positioned on the left-hand side and $(n/2) + 1, \ldots, n$ on the right-hand side
pos_i	Position of the antenna, $pos_i = 0$ means the antenna is on the left-hand side and $pos_i = width$ means the antenna is on the right-hand side.
h_i	Height of the i^{th} left or right side antenna
α_i	Vertical aperture angle of the i^{th} antenna
β_i	Horizontal aperture angle of the i^{th} antenna
γ_i	Vertical mounting angle of the i^{th} antenna
∂_i	Horizontal mounting angle of the i^{th} antenna
$f_i(x)$	Vertical upper line of the RF field of the i^{th} antenna
$g_i(x)$	Vertical lower line of the RF field of the i^{th} antenna
$k_i(x)$	Horizontal upper line of the RF field of the i^{th} antenna
$m_i(x)$	Horizontal lower line of the RF field of the i^{th} antenna
m_{f_i, g_i}	Slope of the upper (lower) line of the RF field (it applies to i^{th}, vertical and horizontal antennas)
s_{f_i}, s_{g_i}	Vertical intersection of the upper (f) or lower (g) line of the i^{th} antenna with the left-hand side of the gate.
t_{f_i}, t_{g_i}	Horizontal intersection of the upper (f) or lower (g) line of the i^{th} antenna with the left-hand side of the gate.
c	Conversion factor
l	Passage length of the gate
α_{f_i}	Gradient angle for the upper line of the RF field of the i^{th} antenna
α_{g_i}	Gradient angle for the lower line of the RF field of the i^{th} antenna

Typically, directional antennas are used for RFID gates, which are provided with a vertical and horizontal aperture angle, α and β respectively. The detection field of the directional antenna is simplified and modelled for the algorithm. Thereby, an ideal and abstracted antenna field without holes and overreaches is assumed. Due to the two different aperture angles, the vertical and horizontal antenna field are both considered as a two-dimensional area in a Cartesian coordinate system, as shown in Figure 1.
The vertical directional antenna field is defined by the upper straight line $f_i(x)$ and the lower straight line $g_i(x)$, which are defined in Eq. 1 and 2, respectively.

$$f_i(x) = \begin{cases} m_{f_i} \cdot x + h_i, \ pos_i = 0 \\ m_{f_i} \cdot x + s_{f_i}, \ pos_i = width \end{cases} \tag{1}$$

$$g_i(x) = \begin{cases} m_{g_i} \cdot x + h_i, \ pos_i = 0 \\ m_{g_i} \cdot x + s_{g_i}, \ pos_i = width \end{cases} \tag{2}$$

The horizontal antenna field is defined by the upper straight line $k_i(x)$ and the lower straight line $m_i(x)$, as it is shown in Eq. 3 and 4, where l is the passage length of the gate. Please note that, because of the physical characteristics of the RFID gate, antennas in Eq. 3 and 4 are positioned in the middle of the gate, which is $l/2$.

$$k_i(x) = \begin{cases} m_{f_i} \cdot x + (l/2), \ pos_i = 0 \\ m_{f_i} \cdot x + t_{f_i}, \ pos_i = width \end{cases} \tag{3}$$

$$m_i(x) = \begin{cases} m_{g_i} \cdot x + (l/2), \ pos_i = 0 \\ m_{g_i} \cdot x + t_{g_i}, \ pos_i = width \end{cases} \tag{4}$$

The gradient of the antennas is defined by the aperture and mounting angles and is calculated from the trigonometric properties as follows: $\alpha_{f_i} = 90° - mounting\ angle, \alpha_{g_i} = 90° - mounting\ angle - aperture\ angle$ and $m_{f_i} = \tan(\alpha_{f_i})$, $m_{g_i} = \tan(\alpha_{g_i})$. The phrase mounting angle always refers to the internal mounting angle, which is the real mounting angle plus the conversion factor, $c = \frac{(180° - aperture\ angle)}{2}$. For example, the conversion factor for an aperture angle of 70° would be 55° and for an aperture angle of 30°, it would be 75°. As soon as the mounting angle changes, the gradient of the straight line changes as a result. In addition to the straight lines, the antenna field is defined by the read range of the antenna.

In contrast to the existing RFID network planning algorithms, we do not consider individual tags within an area, but rather an area where the tags can be located, because the position of the RFID tags can be different depending on the carrier object, for example load carriers differ greatly in their height and width. As Figure 2 reports, the areas where tags could be found is a rectangle parallelepiped, whose rectangular side view depicts the height and the width of the tags area, and whose rectangular top view shows the width and the length of the tag area. Therefore, the minimum and maximum height, width and length of the gate must be specified as input parameters, which then define the Cartesian coordinate system. By this methodology, all possible tag positions within the gate are covered.

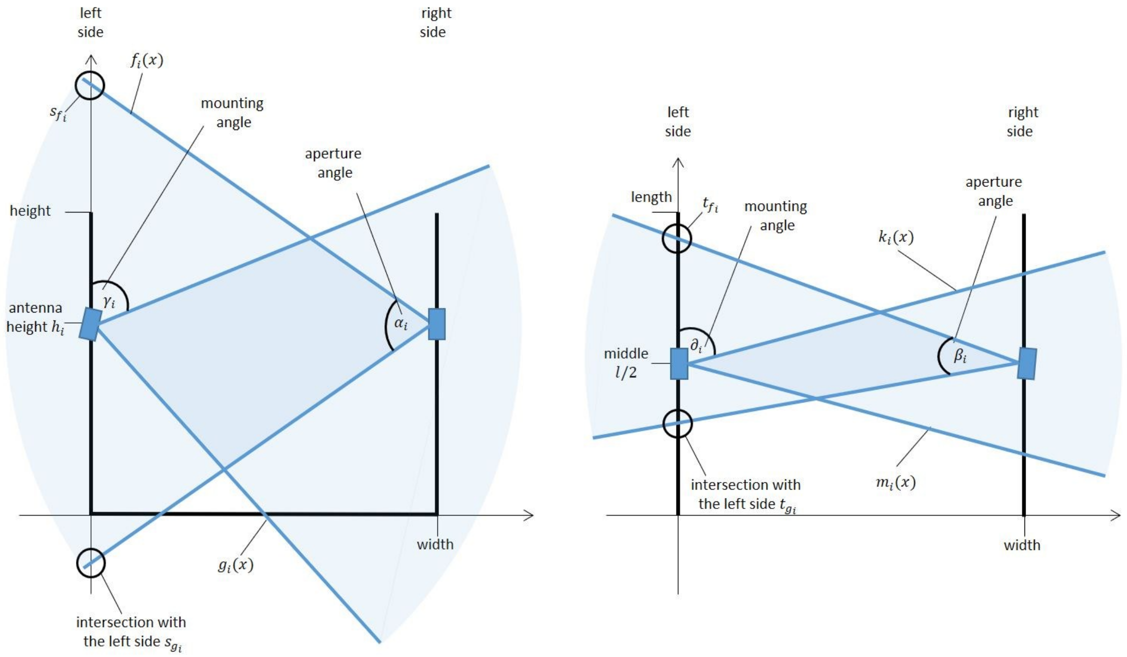

Figure 1: Modelled antenna fields from the side (left) and top (right) view

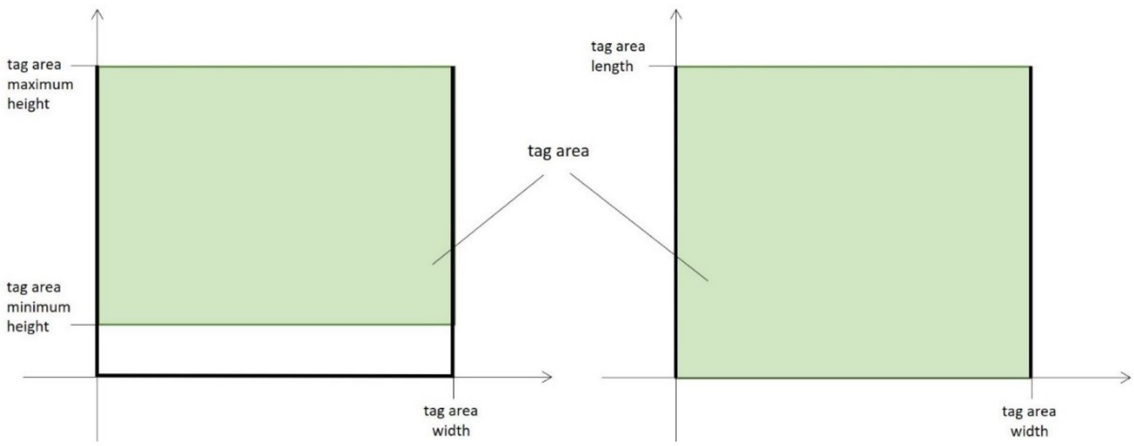

Figure 2: Gate with tag area from side view (left) and top view (right)

3.2 Procedure of the new RFID Network Planning Algorithm

The output of the new RNP algorithm are the number of antennas, their mounting heights as well as their vertical and horizontal mounting angles. The new RNP algorithm is divided into two parts to reduce complexity as the flowchart in Figure 3 shows. In Part 1, the required number of antennas, the mounting height of the antennas and the vertical mounting angles are determined. This is because the number of antennas is more important for the vertical area, where a coverage rate of 99% should be achieved. Since the RFID tags passes through the horizontal area, the number of antennas plays a subordinate role here. In Part 2, the number of antennas is used as input and the horizontal mounting angles are determined.

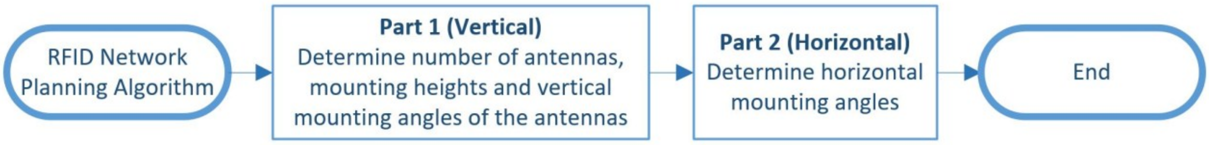

Figure 3: Flowchart of the new RFID Network Planning Algorithm

To determine the different parameters, Part 1 and Part 2 follow the same procedure, which is explained in Table 3 and Figure 4. This procedure is based on the steady state evolutionary algorithm with Pareto tournaments (stEAPT) which is described in [25] and determines the placement of the base station transmitter and takes application-specific knowledge into account. Our contributions to this procedure is the implementation of all application-specific parts, including the boundary conditions, evaluation functions, the initialisation of the population, the mutations and the selection of one individual as described in Section 4.

Table 3: Pseudo code of the procedure of Part 1 and Part 2 according to [25]

INPUT: population size N, maximum number of generations G, individual from part 1 (only in part 2)
Initialisation: create initial population
Calculate the rank (fitness) for each individual
t ← 0
while *t ≤ G* ***do***
    Select parents A, B: perform tournament selection
    Variation: create a new individual C by using one of the evolutionary operators
    Evaluation: compute objectives for the new individual C
    Replacement: integrate the new individual C and update the population and ranks
end while
Select one individual from the non-dominated set (current Pareto front)

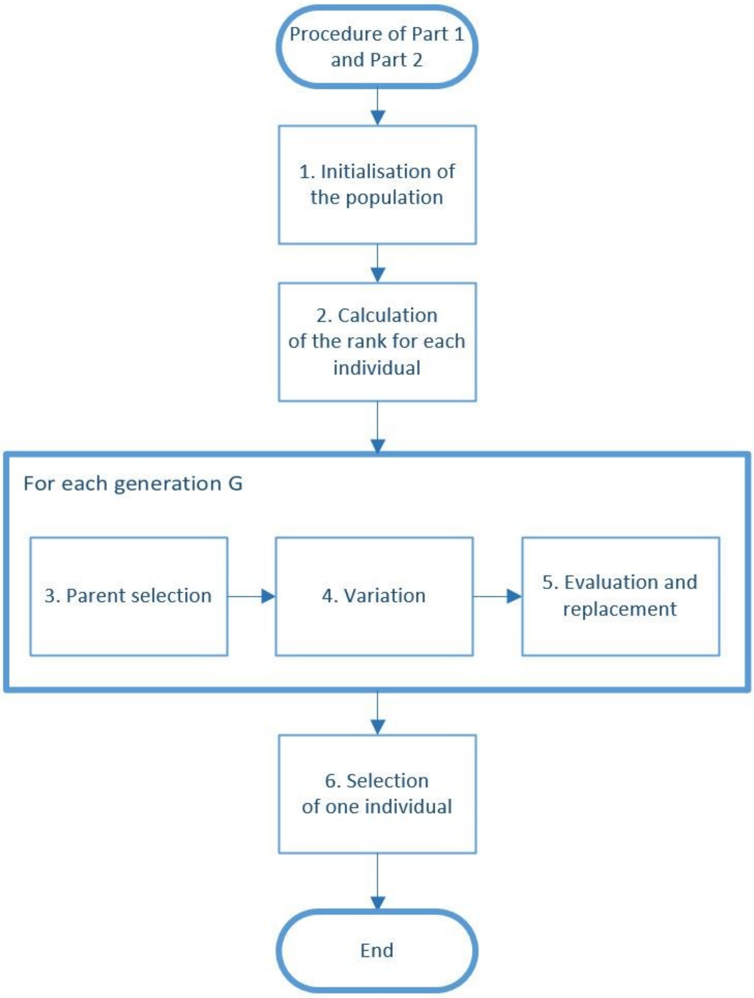

Figure 4: Flowchart of the procedure of Part 1 and Part 2

3.3 Boundary Conditions and Evaluation Functions

The RNP algorithm we propose optimises the design and commissioning of an RFID gate by minimising the hardware and installation cost, while keeping the tag coverage above a certain percentage. Without loss of generality, we consider a minimum tag coverage of 99%, which is typically considered as an optimal value. To achieve these objectives we use boundary conditions and evaluation functions for Part 1 and Part 2 of the RNP algorithm.

3.3.1 Boundary Conditions

The boundary conditions serve not only to achieve the objectives described above, but also to ensure that the solution of the RNP algorithm is feasible in practice.

The following boundary conditions must be met for the **Part 1**:

1. A tag coverage rate of 99% must be achieved to be able to read all tags. Since the modelled antennas are an approximation of reality, 99% is considered to be sufficient.
2. Since reflections lead to interfering waves and thus to holes in the antenna field and overreaches outside the antenna field [26], reflections with the ground must be prevented. Reflections on the side of the gate or the ceiling could be prevented by using shielding material.
3. The mounting angle γ must be $\rho \leq \gamma \leq 180 - \alpha - \rho$, where ρ is the minimal possible mounting angle so that the antenna field lies inside the gate and only angles within the distance of the defined mounting angle step are allowed.
4. The distance between the two antennas, which is measured from the centre of the antennas, has to be defined and must be at least the antenna height, measured from the centre of the antennas.

5. There must be the same number of antennas on each side of the gate.

Boundary condition 1 is ensured by the repair function and boundary conditions 2, 3, 4, and 5 are considered during the initialisation of the population and during later configurations, which is explained in Section 4.1.
In **Part 2**, the only boundary condition is that the mounting angle must be between the defined minimum and maximum possible mounting angle, so that the antenna field lies inside the gate and only angles at a distance of the mounting angle step are allowed. This is ensured during initialisation and later configurations (see Section 4.2).

3.3.2 Evaluation Functions

The evaluation functions are used during the evaluation and replacement to compare the individuals and should be minimised or maximised.
The evaluations functions for **Part 1** are the following:

1. The number of antennas should be minimised in order to save costs (see Eq. 5).
2. The load balance of the antennas should be as evenly distributed as possible, and this is achieved by minimising the standard deviation of the area per antenna, which is reported in Eq. 6, where:
   μ: $Average\ area\ per\ antenna$;
   n: $Number\ of\ antennas$, and
   x_i: $Area\ covered\ by\ antenna\ i$.
3. In order to use the antennas efficiently and to reduce the number of antennas, the overlapping of the antenna fields (Eq. 7) should be minimised by covering as little area as possible by more than one antenna.

$$f_{numAntennas}(A) = \sum Antenna \quad (5)$$

$$f_{loadBalance}(A) = \sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\mu)^2}{n}} \quad (6)$$

$$f_{overlappingArea}(A) = \frac{Area\ covered\ by\ more\ than\ 1\ antenna\ field}{Area\ where\ a\ tag\ can\ be\ located} \quad (7)$$

The evaluation functions for **Part 2** of the new RNP algorithm are as follows:

1. The coverage rate, which is calculated through Eq. 8 should be maximised. Unlike Part 1, no specific coverage rate is defined as a boundary condition because in Part 2 the number of antennas is already fixed and the forklift driver drives through the horizontal area.
2. The utilisation of the antennas should be as evenly distributed as possible by minimising the load balance, which is the standard deviation, as in Part 1 and Eq. 6.
3. The overlapping of antenna fields should be minimised by covering as little area as possible by more than one antenna, as in Part 1 and Eq. 7.

$$f_{coverage}(A) = \frac{Area\ covered\ by\ antennas}{Total\ tag\ area} \quad (8)$$

4 Implementation of the new RFID Network Planning Algorithm

The new RNP algorithm was implemented as a prototype in the programming language Java. The structure of the prototype is shown in the class diagram in Figure 5. Since Part 1 and Part 2 contain the same methods (see Section 3.2), these methods are defined in the interface *EvolutionaryAlgorithm.* The classes *VerticalPart1* and *HorizontalPart2* implement this interface and contain further private methods for better readability and reusability of the code. The class *Individual* contains all parameters that describe a possible solution of the RNP problem and the associated getter and setter methods.

Therefore, the class *Individual* contains a parameter with a list of antennas. The class *Antenna* contains all parameters that define an antenna e.g. vertical aperture angle and its getter and setter methods. The input variables for the RNP algorithm are all stored in the class *Parameters*. The execution of the individual methods is done in the main class *RNPAlgorithm*. The methods from Part 1 and Part 2 are described in more detail in the following sections.

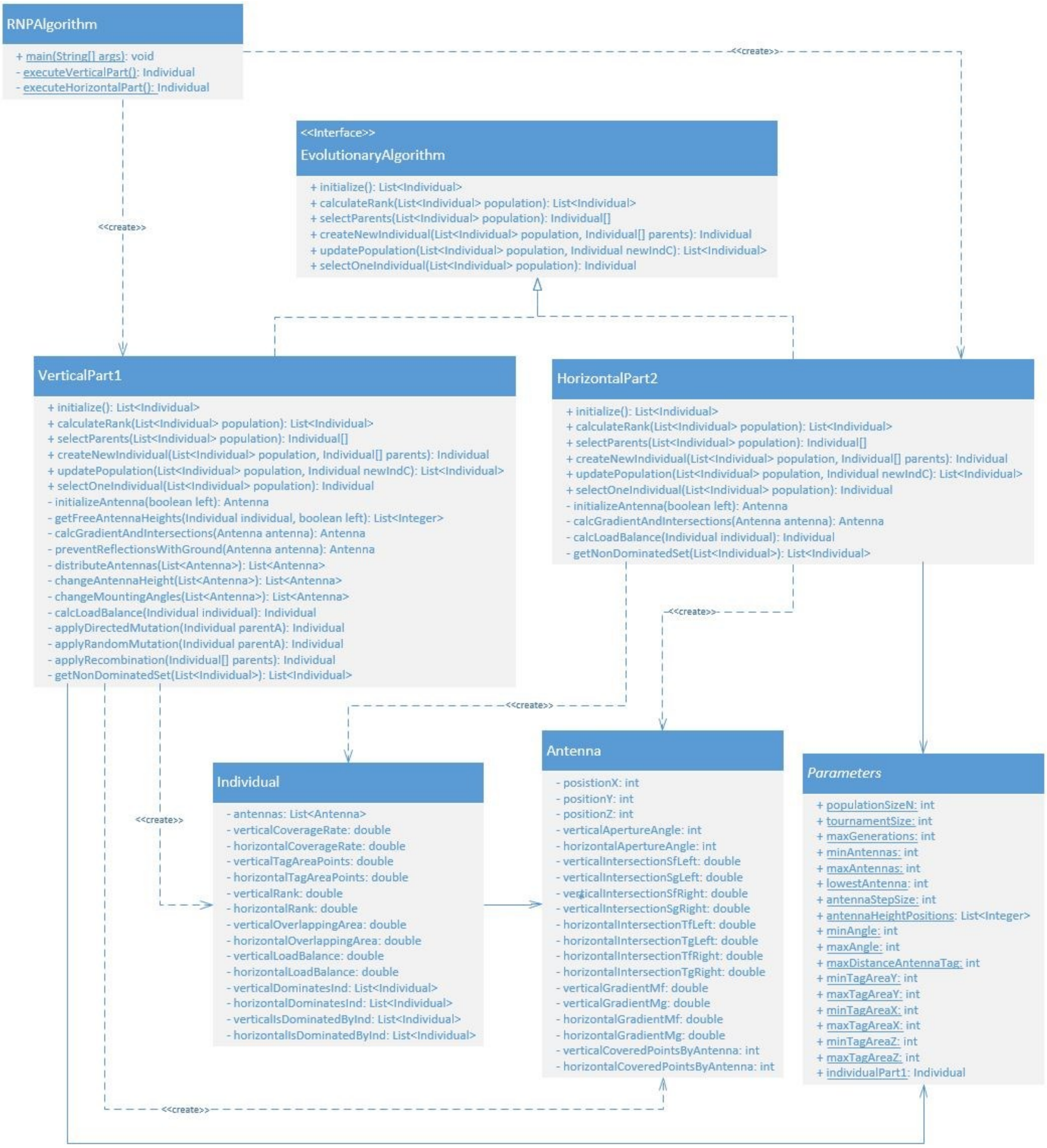

Figure 5: Class diagram of the new RFID network planning algorithm

4.1 Vertical Implementation: Part 1

In Part 1, the number of antennas, the height of the antennas and the vertical mounting angles are determined.

4.1.1 Initialisation of the Population

The initialisation process is shown in Figure 6. The population size N is specified as an input parameter. First, for each individual of the population the **number of antennas** is chosen randomly within defined limits and, for each antenna, the **height and the mounting angle** is defined randomly while maintaining the boundary conditions. For this purpose, predefined positions for the heights and mounting angles in a distance of the mounting angle step are used. Afterwards, the **gradient m** of the upper and lower straight lines of each antenna field and the **intersection points** of the straight lines with the left and right side of the gate are calculated for later computations. Then, reflections with the ground are eliminated. To determine whether a **reflection on the ground** is present, the intersection of the lower straight line with the ground is calculated for each antenna. If the intersection is inside the gate, the vertical mounting angle is reduced by the mounting angle step. Then, the gradient of the line and the intersection with the ground is updated, and this is repeated until the intersection with the ground is outside the gate, as shown in Figure 7. After that the repair function is called to achieve a coverage rate of at least 99%. At the end of the initialisation the load balance for each individual is calculated because this is needed later to calculate the rank of the individual.

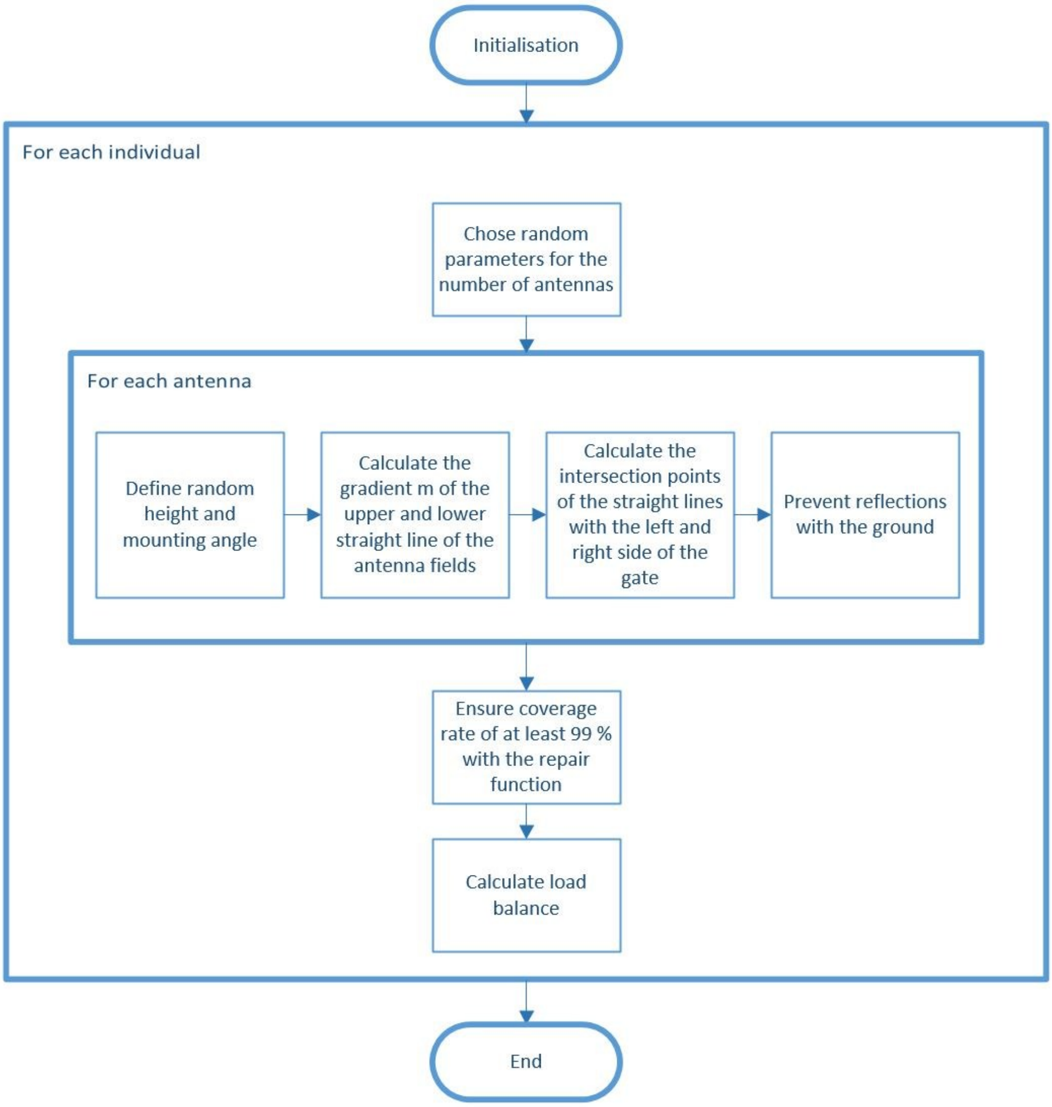

Figure 6: Flowchart of the initialisation of Part 1

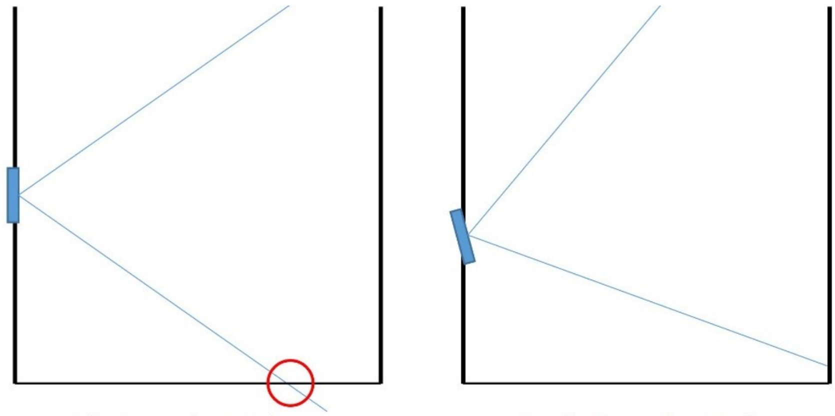

Figure 7: Impact of the algorithm on reflection on the ground - reflection vs. no reflection on the ground

The flowchart of the **repair function** is shown in Figure 8. Inside the repair function, the coverage rate is calculated first. Therefore a maximum read range between the antenna and tag is required. Since the maximum read range depends not only on the reader power, the gain of reader and tag antennas, the frequency, and the sensitivity but also on the carrier material, e.g. plastic, ESD (Electrostatic Discharge), metal, and the environmental influences, the maximum read range has to be defined as an input parameter. The coverage rate is calculated by checking whether each integer coordinate (x/y) within the tag area, which is given in cm, is covered by an antenna field. For this purpose, the x-value of the coordinate is inserted into the formula of the straight lines $g(x)$ and $f(x)$ of the respective antennas to calculate y_g and y_f. If the y-value of the coordinate is larger than y_g and smaller than y_f and the distance between the antenna and the coordinate is smaller than the maximum possible, then this coordinate is covered by the antenna field. The number of covered coordinates divided by all coordinates of the tag area gives the coverage rate. It is simultaneously determined how many coordinates are covered by more than one antenna field, and the overlapping rate is thus calculated, which is later used in the evaluation. The pseudo code of the calculation of the coverage and overlapping rate is shown in Table 4.

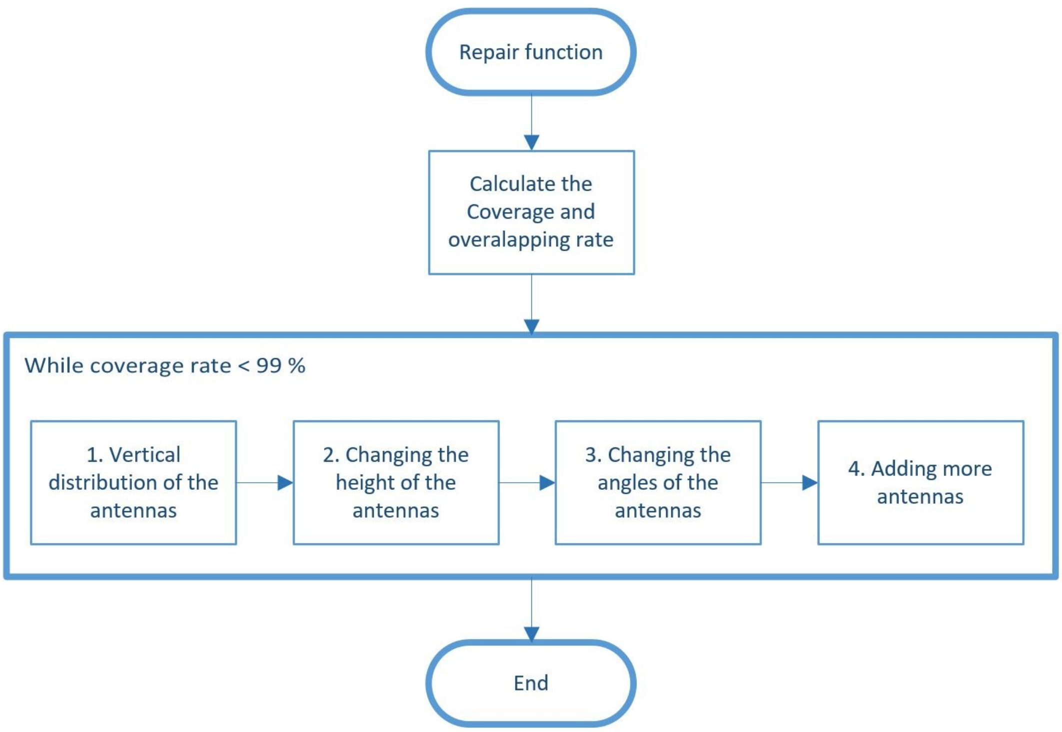

Figure 8: Flowchart of the repair function

Table 4: Pseudo code of the calculation of the coverage and overlapping rate

```
for x = 1; x < maxXTagArea; x++
    for y = 1; y < maxYTagArea; y++
        for each Antenna a
            if Point(x, y) is inside antenna field && distance < maxDistance:
                pointCovered = true
                coveredPointsByAntenna++;
                coveredPointsByMoreThan1Antenna++;
        end
        if pointCovered:
            counterCoveredPoints++
            if(coveredPointsByMoreThan1Antenna > 1):
                counterCoveredPointsByMoreThan1Antenna++;
        counterTotalPoints++
    end
end
coverageRate = counterCoveredPoints/counterTotalPoints
overlappingRate = counterCoveredPointsByMoreThan1Antenna / counterTotalPoints
```

After the calculation of the coverage rate, the following four functions are executed one after the other in a loop until the required coverage rate of 99% is achieved.

1. **Vertical distribution of the antennas:** First, the distribution of the antennas in their height is improved so that several antennas are not placed directly above each other. For this purpose, for each antenna, the free positions to the lower and upper antenna/limit are calculated, starting with the lowest one. Then, the antenna is moved to the middle position, as shown in Figure 9, and possible reflections with the ground are prevented. This feature reduces the overlapping of antenna fields and improves the coverage rate.
2. **Changing the height of the antennas:** Experiments showed that when the coverage rate is low, often the lower part of the gate is not covered by an antenna field because the mounting angle is reduced by avoiding reflections on the ground. For this reason, the lowest antenna on each side is moved to the lowest possible height, thus improving the coverage rate.
3. **Changing the angles of the antennas:** In this function, the mounting angle is increased by 2*mounting angle step for all antennas. Then, reflections on the ground are prevented and the coverage rate is determined. This process is repeated for all possible mounting angles and the configuration with the highest coverage rate is selected.
4. **Adding more antennas:** If the three previous functions could not achieve a coverage rate of at least 99%, the number of antennas is probably too low to cover the entire tag area. Therefore, in this function, a new antenna is added on each side, whose height and mounting angle are determined analogous to the ones in the initialisation.

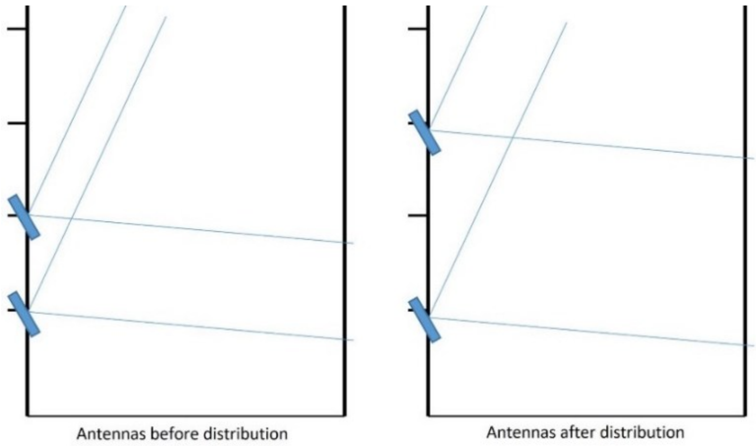

Figure 9: Impact of the algorithm on antenna distribution - before vs. after distribution of antennas

4.1.2 Calculation of the Rank for each Individual

The selection of parents and replacement of individuals for the next generation is based on the rank. For calculation of the rank the evaluation functions (see Section 3.3.2) are used. The rank is calculated for each individual as described below for the example of individual A.
For the individual A, the number of individuals that are dominated by A and the number of individuals that dominate A are determined. The rank for each individual is then calculated by Eq. 9, as in [25].

$$Rank(A) = \sum IsDominatedBy(A) * PopSize + \sum Dominates(A) \quad (9)$$

Definition of Pareto dominance and Pareto-optimal: If two n-tuples $m_i = (x_1, \dots, x_n), m_j = (y_1, \dots, y_n)$ are given, then the following applies: m_j **dominates** m_i **strictly**, exactly when m_j is better in all values (evaluation functions) and strictly better in at least one, i.e. $\forall k: y_k \leq x_k$und $\exists I: y_I < x_I$) [27]. If an individual is not dominated by any other, it is called **Pareto-optimal** [28].

4.1.3 Parent Selection

For the **parent selection**, a tournament selection is performed as in [25], which uses the rank (fitness). Therefore, ϑ individuals are randomly selected from the population, where ϑ is the tournament size and the best individual (A), that is the one with the lowest rank, is chosen. Then, the second best individual (B) is selected. Thus, the parents A and B are selected and an evolutionary operator can be applied to A or A and B to create a new individual within the search space.

4.1.4 Variation

To find new solutions for the RNP problem the population must be varied. For this purpose, an evolution operator is used, which is either a directed mutation, random mutation or recombination which generates a new individual C in every generation. The directed mutation and random mutation are applied with a probability of 30% to the individual A, and the recombination is performed with a probability of 40% with the individuals A and B, as it is done in [25].

The **directed mutation** (DM, see Table 5) allows application-specific knowledge to flow into the newly created individuals in order to efficiently find an optimal solution. For this purpose, actions are executed depending on defined conditions.

Table 5: Directed mutations in Part 1

Name	Condition	Action	Comment
DM1	The area of the largest antenna field minus the area of the smallest	Every possible mounting angle is tested for the antenna with the smallest antenna field, and the one	The goal is to increase the coverage rate and improve the load balance.

	antenna field is > $small\ coverage\ area\ threshold$.	with the best coverage rate is selected.	
DM2	The overlapping rate is > 90%.	The antenna with the lowest coverage rate is removed on each side of the gate.	This minimises the number of antennas.
DM3	The standard deviation of the area per antenna is > $vertical\ standard\ deviation\ threshold$.	For the antenna with the least covered area, each height is tested and the best one in terms of coverage rate is selected. The same is done for each possible mounting angle at intervals of the $mounting\ angle\ step$.	The goal is to increase the covered area of this antenna and thus improve the standard deviation.
DM4	Two antennas are positioned directly above each other.	Move the upper antenna up one position.	The goal is to improve the coverage rate.

Random mutations (RM, see Table 6) are needed, because with directed mutations, not all points in the search space can be covered. The selection of which RM (RM1, RM2 or RM3) is used is random.

Table 6: Random mutations in Part 1

Name	Action	Comment
RM1	Add a new antenna randomly on each side.	This creates the balance to DM2.
RM2	Move the position of a randomly selected antenna up by one.	This leads to new solutions within the search space.
RM3	The mounting angle of a randomly selected antenna is increased by the mounting angle step. If it is outside the limits, it is set to the minimum possible mounting angle.	In this way, new genetic material flows into the search for the optimal solution.

The **recombination** has been greatly simplified from [25] and creates the new individual C by combining the antennas of the left side of individual A and those of the right side of individual B. In order to maintain boundary condition 1, the repair function is executed.

4.1.5 Evaluation and Replacement

To decide whether the newly created individual C should be included in the population, it is first calculated how many other individuals C dominates and by how many it is dominated (evaluation). Then, a distinction is made between the following three cases, as in [25]:

- **Case 1**: *IsDominated(new) == 0 && Dominates(new) == 0:* If the new individual is not dominated by any other individual and it does not dominate other individuals, then it is included into the population with rank 0. The worst individual of the population is deleted and the rank of all individuals who are dominated by the worst individual is reduced by one.
- **Case 2**: *Dominates(new) > 0:* If the new individual dominates at least one other individual, it is added to the population. The worst individual is deleted and the rank of the individuals *IsDominated(worstInd) \ IsDominated(new)* is reduced by 1. The rank of individuals dominating C is increased by the population size.
- **Case 3:** *IsDominated(new) > 0 && Dominates(new) == 0:* If the new individual does not dominate other individuals but is dominated by others, then there is no improvement and the new individual is not integrated into the population.

4.1.6 Selection of one Individual

The Part 1 of the algorithm returns the set of Pareto-optimal individuals. However, since only one solution is needed as input for Part 2, it is selected with a hierarchical approach, as it is described in Table 7. The advantage is that no weights have to be determined for the individual evaluation functions.

Table 7: Pseudo code for the selection of one individual in Part 1

```
1: INPUT: individuals ← non-dominated Pareto front
2: individuals ← Select individuals with minimum number of antennas
3: individuals ← Select individuals with minimum load balance
4: individuals ← Select individuals with minimum overlapping area
5: individuals ← Select individuals with highest coverage rate
6: individuals ← Select individuals with best rank
7: OUTPUT: individual ← Select first individual from list
```

4.2 Horizontal Implementation: Part 2

After the optimal number of antennas, mounting heights, and vertical mounting angles of the antennas have been determined, the horizontal mounting angles are determined in Part 2.

4.2.1 Initialisation of the Population

The flowchart of the initialisation of the population in Part 2 is shown in Figure 10. During the initialisation of the population with size N, the parameters of the input individual from Part 1 are assigned to each individual. Each antenna of an individual is assigned a random horizontal mounting angle, considering the boundary condition. Then, the intersections of the antenna field of each antenna with the right and left side of the gate are calculated. After that the coverage rate, overlapping rate and load balance for each individual are determined. The tag coverage rate and overlapping rate are calculated in the same way as in Part 1 and the passage length becomes the y-axis, resulting in a 2-dimensional area within the Cartesian coordinate system that represents the top view of the gate.

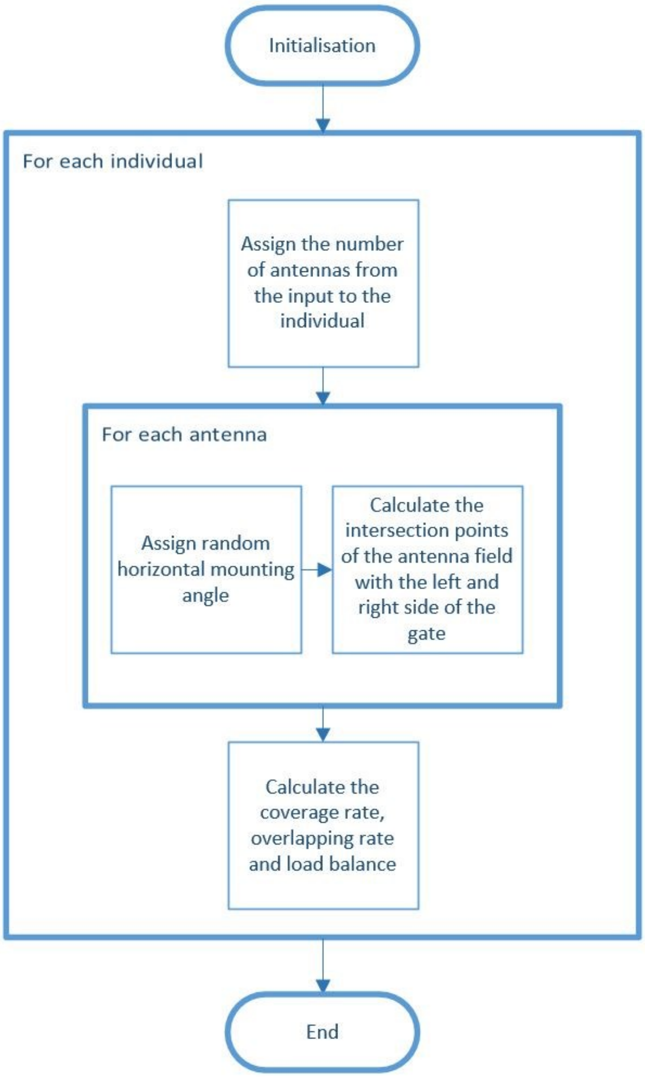

Figure 10: Flowchart of the initialisation of Part 2

4.2.2 Calculation of the Rank for each Individual

The calculation of the rank is similar to that in Part 1, with the difference that the evaluation functions for Part 2 described in 3.3.2 are used.

4.2.3 Parent Selection

The parent selection is done exactly the same as in Part 1.

4.2.4 Variation

The selection of the evolution operator is done as described in Part 1. Since application-specific knowledge is incorporated into the directed mutation, the DM operators differs from what was reported in Part 1, as it is reported in Table 8.

Table 8: Directed mutations in Part 2

Name	Condition	Action	Comment
DM1	Two antenna fields of one side overlap strongly if the difference $diff$ of the two mounting angle < $horizontal\ overlapping\ angle\ threshold$.	Set the mounting angle of one antenna to $aperture\ angle - diff$. If this violates the boundary condition, then set it to $-aperture\ angle - diff$.	This minimises the overlapping of the antennas.

DM2	The coverage rate is < 60 %.	Each mounting angle is increased by the mounting angle step size and the coverage rate is calculated until all possible angles have been tested. The configuration with the best coverage rate is selected.	This has the goal to improve the coverage rate.
DM3	The load balance is > $horizontal\ standard\ deviation\ threshold$.	Change the mounting angle from the antenna with the lowest coverage rate in order that the standard deviation is decreased.	This mutation operator improves the load balance.

Also, to insert new genetic material into the optimisation, the random mutation operator RM1, which is reported in Table 9, enables to cover more points within the search space.

Table 9: Random mutation in Part 2

Name	Action	Comment
RM1	The horizontal mounting angle of a randomly selected antenna is increased by the mounting angle step. If this violates the boundary condition, the mounting angle is set to the minimum possible mounting angle.	The randomly generated new solution covers another point within the search space.

During the recombination, the antennas with their mounting angles of the left side of parent A and the antennas of the right side of parent B are combined to create the new individual C, as it is done in Part 1.

4.2.5 Evaluation and Replacement

The evaluation and replacement for the next generation is done analogous to Part 1.

4.2.6 Selection of one Individual

Thus, since the algorithm provides the set of Pareto-optimal individuals but only one solution is needed in practice, it is determined using the hierarchical approach, as described in Table 10.

Table 10: Pseudo code for the selection of one individual in Part 2

*1: **INPUT**: individuals ← non-dominated Pareto front*
2: individuals ← Select individuals with highest horizontal coverage rate
3: individuals ← Select individuals with minimum overlapping area horizontal
4: individuals ← Select individuals with minimum load balance horizontal
5: individuals ← Select individuals with best rank
*6: **OUTPUT**: individual ← Select first individual from list*

5 Case Study in the Logistics of the Automotive Industry

For demonstration of the algorithm, we applied it to a goods receipt gate in the logistics of the automotive industry. The gate is located at the goods receipt of the automatic small parts warehouse, where the materials are delivered in small load carriers and stored for the assembly of vehicles. In this use case, a forklift driver unloads the truck and drives tagged load carriers through the RFID gate (an example of an RFID gate is shown in Figure 11) and the RFID tags are read automatically by the antennas, and their content is written in some database of the company information system. Table 11 shows the parameter settings used for this case study. The tag area of the gate has a minimum height of 40 cm, maximum height of 350 cm, width of 400 cm, and passage length of 300 cm, where RFID tags can be located. The maximum read range between the antenna and tag is set to 450 cm. In this case study, directional Wide Range RFID UHF Antennas from Kathrein are used, which have a height of 27 cm. Therefore, the distance between two antennas is set to 30 cm, which is also the step size of the

antenna heights. The lowest possible antenna position is defined as 60 cm. The Wide Range UHF Antennas from Kathrein have a vertical aperture angle of 70° and a horizontal of 30°. The minimum mounting angle is set to 5° and the maximum to 105°, so that the antenna field is inside the gate area and the mounting angle steps are 5°. The minimum number of antenna is set to 2 because at least one antenna should be placed on every side, and the maximum number is set to 8, as this is considered sufficient to achieve the required coverage in the gate. The population size was set to 80, the number of generations to 150, and the tournament size to 5 after some experiments. The vertical standard deviation threshold is set to 10 000 cm², the horizontal to 20 000 cm², the small coverage area threshold to 30 000 cm², and the horizontal overlapping angle threshold is 15°.
The algorithm produced the results presented in Table 12. Figure 12 shows the corresponding antenna fields, and the results from the evaluation functions are given in Table 13. Firstly, we note that the algorithm respects all boundary conditions by deploying only four antennas. The vertical coverage rate, which is calculated according to Section 4.1.1, is 99.96% and it exceeds significantly the required coverage rate of 99%. Also, the vertical load balance is below the threshold value, but the overlapping rate is high (95.81%), as this cannot be avoided without reflections on the ground of the antenna fields. With respect to the horizontal values, the horizontal coverage rate is close to 90%, the load balance is way below the threshold value, and the overlapping rate is just below 40%.

Figure 11: Goods receipt with RFID gate (Source: Mercedes-Benz AG)

Table 11: Parameter settings

Parameter	Value
Tag area width	400 cm
Tag area minimum height	40 cm
Tag area maximum height	350 cm
Tag area length	300 cm
Maximum read range	450 cm
Antenna	Kathrein Wide Range RFID UHF Antenna
Antenna height	27 cm
Distance between two antennas	30 cm
Lowest possible antenna position	60 cm
Vertical aperture angle of the antenna α	70°
Horizontal aperture angle of the antenna β	30°
Minimum mounting angle ρ	5°
Maximum mounting angle $(180 - \alpha - \rho)$	105°
Mounting angle steps	5°
Minimum number of Antennas	2
Maximum number of Antennas	8
Population size N	80
Number of generations G	150
Tournament size ϑ	5
Vertical standard deviation threshold	10 000 cm²
Horizontal standard deviation threshold	20 000 cm²
Small coverage area threshold	30 000 cm²
Horizontal overlapping angle threshold	15°

Table 12: Results of the RFID network planning algorithm

	X-Position	Y-Position	Vertical Mounting Angle	Horizontal Mounting Angle
Antenna 1	0	60	25°	60°
Antenna 2	0	150	40°	90°
Antenna 3	400	60	25°	85°
Antenna 4	400	150	40°	55°

Table 13: Results of the evaluation functions

Vertical Evaluation Function			Horizontal Evaluation Function		
Number of Antennas	**Load Balance**	**Overlapping Rate**	**Coverage Rate**	**Load Balance**	**Overlapping Rate**
4	4685.5 cm²	95.81%	89.66%	3439.6 cm²	39.7 %

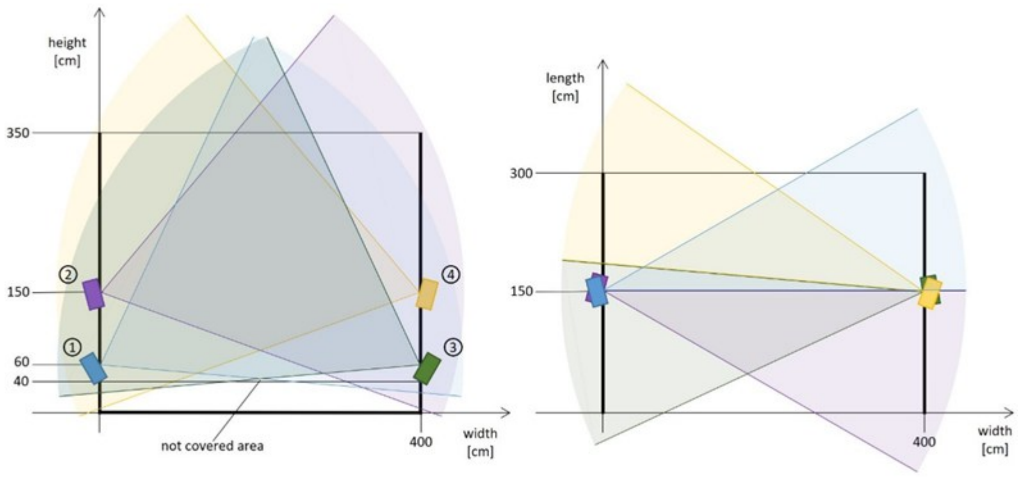

Figure 12: Result of the RFID network planning algorithm - antenna fields

6 Conclusion and Future Outlook

RFID is a central auto-ID technology whose numbers and sectors of use have been growing enormously in the last decades. One of the most common RFID application in logistics is to deploy RFID gates and automate the goods receipt process. The processes of design and commissioning of RFID gates, however, is at present not covered by the classical RFID network planning, or RNP, algorithms.

In this study, we investigated how an RNP algorithm could generate the optimal design of an RFID gate, taking into account the number of RFID antennas, as well as their mounting heights and angles, with the aim of satisfying some evaluation functions. The algorithm we proposed has been prototyped, and then tested within a case study in the logistics of the automotive industry to prove its effectiveness, that is to achieve a given tag coverage while minimising the number of deployed antennas, the overlapping rate and the load balance evaluation functions. The proposed RNP algorithm ensures that reflections with the ground are avoided and a tag coverage of at least 99% is achieved, thus confirming the first hypothesis. Also, the second hypothesis is confirmed, since the minimisation of the antennas is achieved by the evaluation function. In detail, the application to our case study resulted in a vertical coverage rate of 99.96%, thus respecting the boundary condition, and a maximised horizontal coverage rate of 89.66%, which is deemed to be satisfactory because tags pass through the whole horizontal area. Also, the number of antennas deployed to achieve such results in the case study is four.

The RNP algorithm we propose could be used in the future to define a standard for the planning and commissioning of RFID gates, both for standardised and non-standardised goods receipt gates. By using our RNP algorithm, in fact, the number of antennas, and therefore the hardware cost, could be minimised. Furthermore, the time required for gate commissioning could be significantly reduced, due to the fact that our RNP algorithm already suggests optimal mounting heights and angles of antennas, instead of the time-consuming trial-and-error principle for the installation and alignment of the antennas. Also, the use of the proposed algorithm for planning and commissioning new RFID gates could mean that hardly any technical knowledge about RFID is required by the technicians. This eases the commissioning of new RFID gates and allows it to be carried out by less experienced personnel. Finally, since the algorithm covers the entire tag area and prevents reflections on the ground, the detection rate should be improved significantly as compared to existing RFID systems with reflections on the ground. This key point, however, must be verified in future studies using a real test setup and comparing the detection rates of existing *trial-and-error, do-it-yourself* RFID gates with those of a gate built according to the algorithm. We note that this point is still unanswered by our research, as the overall goal of RFID deployments would be that of minimising reading errors, both in terms of missed reads and unwanted reads, but both those values were not considered yet in our study.

Other limitations of this study can be summarised as follows. First, an algorithm could be developed to determine the maximum read range between the RFID antenna and tag depending on the power, gain of the antennas, sensitivity, communication profile and material of the objects or carriers. Also, some field applications use RFID gates with direction recognition, where two RFID gates are built one after the other. Therefore, the algorithm we propose could be extended in these directions: on the one hand, it could strive towards a maximised read range, e.g. by considering the environment, such as metal pillars in the antenna field or by adding collision protection. On the other hand, the algorithm could be improved to consider direction detection. Finally, further practical improvements of the algorithm could take into account converting mounting angles (which are hardly measured on the field) into distances between elements of the gate or the antenna holder and of the antenna itself, to simplify the installation. Indeed, the authors are considering some of those improvements for future works.

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