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A multi-agent approach to the optimization of Intelligent Buildings Energy Management

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Abstract

The existing installations in buildings form a specific kind of mazes that are overcome by factors that are dedicated to them (heat, water, electricity, etc.) The present systems attempt to distribute sources in such buildings to the receivers as well as they can. The most sophisticated ones are based on the Building (Energy) Management Systems, i.e. *BEMS* located in modern intelligent buildings. The article proposes a new approach to the existing grids with the ant colony optimization (*ACO*). *ACO* agents are effective in overcoming existing grids. But they do need modification of their standard algorithms or parsed grids for energy savings. These questions constitute the hypothesis taken under examination. The expected solution is a challenge for different *ACO* techniques with an evolutionary or aggressive approach taken into consideration. Different opportunities create many latent patterns to recover, evaluate and rate. They can be recovered in nondeterministic polynomial time, but they occur as NP-hard problems, so they can consume a lot of time to be solved. It is extremely important to formulate more aggressive ways to find an approximation of the optimal pattern within an acceptable time frame. The options taken under examination show that there are a few interesting approaches to accelerate the *ACO* and reveal a solution in real time. In the article the results are presented as the results of the research.

Keywords: ACS; ACO; BEMS; Energy Optimization; TSP; Matrix-like grid; Central Heating System.

1. Introduction

Energy is the most important issue in the evolution of civilizations. Tremendous efforts are taken to produce energy in order to ensure that the needs of a civilization are fully met. Unfortunately, the increase of energy production leads to worrisome impacts on the environment. It is the reason why we should more responsibly consume energy resources

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and use it more efficiently through the optimization of the procedures. Nature-based methods such as swarm optimization are very promising in approximation of the function result, and some of these methods have been considered and adapted to other contemporary issues created by the civilization. The *ACO*, which is based on the behavior of ants, appears to be one of the most promising methods. Many civilizational activities take place in structures that can be represented as grid networks. Ants scour all of the possible paths in such a grid in order to determine the optimal path. A variety of *ACO* approaches have been tested in order to prove that some of them cannot be processed within a feasible time period. A building's grids are similar to a 3D matrix and therefore are too complex to be fully processed. On the other hand, simplified 2D pattern samples seems to be insufficient and inadequate. Also, other issues can appear like 2D patterns with additional factors that make them inadequate do be processed in a common way with the ordinary *ACO* algorithms and they are combined with, for instance, garbage utilization in modern towns or other acquisition or delivery roles. The quantum part of this assignment is similar to the asymmetric traveling salesman problem (*aTSP*) or the Chinese postman problem (route inspection problem *CPP/RIP*). However, the textbook example model of both the *TSP* and *CPP* has to be modified before being adapted to the expected objectives and an environment that users can change. Pattern modifications that are made by a user or system scheduler create new maps that must be re-evaluated. Each map shows a disjunctive part of the 3D or 2D Matrix-like grid that is used in evaluating the snapshot. Temporary maps are a specific *TSP/CPP* environment. Algorithms in individual maps work in parallel aggregate together in the entire grid. The problem of energy optimization is an important issue for many scientists around the world. There are numerous publications dedicated to the reduction in energy consumption. Many of them mention the usage of *ACO* or other algorithms like the *BFOA*[1] as a possible way to achieve the set goals [5, 12, 13]. The existing literature mostly treats about the environment to use the *ACO*, not about using the proper or modified algorithms of the *ACO* matching the properties of a dedicated system.

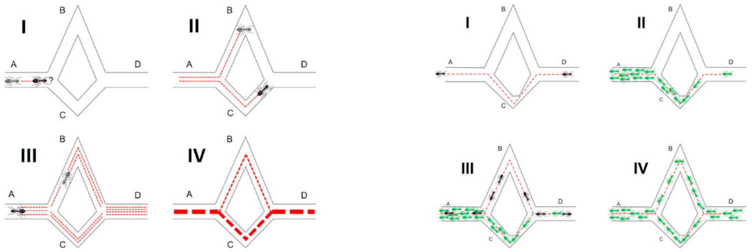
This article goes deeper into the *ACO* usage and tries to examine several ideas to speed up the *ACO* itself. The suggested improvements of the *ACO* algorithm seem to be generally not mentioned in the literature. The objective of this study is an examination the speed and behavior of modified *ACO* multi-agents to recover optimal path into three test structures (a) classical one similar to the existing one in buildings, (b) – the theoretically ideal one, (c) the classical with modification brings closer tested grid to ideal one. The contribution of this paper is the results of testing a behavior of *ACO* modified algorithm multi-agents in traversing grids existing in modern buildings with comparing to the theoretical grids, and disscussion with suggested solution for overcome the classical grid disadventages. The article consist of three main sections: In section 2 we present a brief introduction to the *ACO*. In section 3 and 4 we present a brief introduction to the *Extended Buildings' Energy Concept* [10] with 3D Matrix-like grids. In section 5 and 6 we present the case study after implementing the modified *ACO* algorithm [11] in a simulation as the proof-of-concept followed by a discussion and conclusion.

2. Ant Colony Optimization

Ants, which belong to social species, live in colonies and owing to their interaction and cooperation, are capable of complex behaviors that allow them to solve difficult problems from the point of view of a single individual. An interesting characteristic of several ant species is their ability to establish the shortest path between the anthill and the food source that was found [1] using chemical trails that are deposited as pheromone paths [6]. A pheromone path is the way that the ants in an anthill communicate in order to solve the problem of navigation. The communication methods and the use of pheromones that are deposited on the path by individual ants that is used to find the shortest path between two points is presented in Fig. 1a.

Ants are capable of complex behaviors that enable them to solve difficult problems from the point of view of a single individual. Ants use chemical trails (pheromone) to establish communication between them [6] for the purposes of navigation. Fig. 1a stage I presents a situation in which the ants that are traveling from point A to point D have to make a decision about whether to turn left or right in order to choose the way through point B or point C. This is a random decision and the ants choose to continue along (in this move) one of the two possible edges, each of which has a probability of approximately fifty percent. Fig. 1a stage II and Fig. 1a stage III present the process of depositing the pheromone trail in the paths that are selected. Due to the length of each path, on the path that is adjacent to point

[1] BFOA – bacteria foraging optimisation algorithm



(a) The classical ants pathing

(b) Decomposition of the roles – traffic clogging overcoming

Fig. 1: Two different approach to the ants pathing

C, more pheromone will be deposited because of the shorter length and the greater number of ants that have used it. The same number of ants traveling at the same speed on a shorter path means that the accumulation of pheromone is faster. The differences in the pheromone concentration on the paths are significant (Fig. 1a stage IV), which is then noticed by the others ants. As a result, ants take path ACD more often due to the stronger pheromone trail. This is the reason for individual ants to choose this path and to thus strengthen the decision that was made. This was the dawn of the paradigm for the metaheuristic algorithms that are used to solve various optimization problems. The *ACO* can be successfully used to solve the kind of problems described by graph.

The second example presented in Fig. 1b is one of the more aggressive *ACO* samplings used in revealing a pattern of real present grids with their capacity or throughput taken into account. The procedures of the *ACS, ACO* are well known, therefore their description has been omitted at this point after the brief introduction above. The full description can be obtained from abundant elementary bibliography [1, 4, 6], or more connected with the authors and the main theme of this article [2, 3, 7].

3. Aggressive *ACO* sampling in revealing a pattern

The NP-hard problems cannot be solved in short period of time, and such processes are very time-intensive. The next solution is to get close enough to the acceptable result with the classical *ACO*, but this might be still too time-intensive (too slow) in real existing, complex grids, and the time restrictions imposed. There are several possible solutions to prevent a system failure due to such inefficiency in the *ACO* time process [8, 9]. One of these is to use parallel threads in the *ACO* processing and/or a more efficient central computer system with greater computing power. Other more adequate and hardware independent prevention methods, which however do not fulfill the presented list, are: (a) ants' decomposition and specialization, (b) precognition paths and (c) ants spreading.

3.1. Ant decomposition and specialization

Ants are separated into specialized divisions that are aimed at testing the hypothesis that two independent groups of ants, *path-seekers* and *carriers*, are more efficient. In the first stage, the *path-seekers* traverse the edges of the weighted graph to pre-optimize the path (elaboration as an example with central heating system). The undertaken optimization problem of the study is (a) to determine the optimal path to explore grids with the smallest amount of energy losses, (b) to determine the best environment to be explored by the *ACO* agents, (c) to put forward and test the grids with minimal modification between the existing-ones and theoretically the best one. The success determinant is the time consumed to recover the path and delivery of all demanded load to the nodes of the graph.

In the second stage, the carriers try to deliver enough cargo (heating agent), which proves successful when no clogging occurs on the path. Should some edges be blocked due to their throughput capacity, the third stage is triggered with local path-seekers exploring to find another sub-path for the carriers and processing the return to the second stage. This principle is presented in Fig. 1b.

Stage I is shown in Fig. 1b I and Stage II is presented in Fig. 1b II in which clogging occurs. Stage III in Fig. 1b III shows the way to eliminate clogging by adding a sub-path to the BOP that were evaluated in Stage I. Stage IV is a representation of the return to Stage II with no clogging. Stages II and III are deployed repeatedly in the event of demand. The most significant point is that the carriers can move through an edge in only one direction, while the *path-seekers* can move in both directions.

3.2. Precognition paths

This section is located here in order to complete the list of the *TSP/CPP* modifications, however the concept of using precognition paths is discussed on the basis of a further mentioned topic. For full understanding it is recommended to familiarize oneself with section 4.1 first. It is based on the scheduler role in which the required human-comfort parameters are pre-ordered. Each node which is not in a "neutral" state is left and each node that is in a "neutral" state is removed from the grid. Thus, the "active" nodes are grouped in one graph, which is connected with tour optimization, by the nearest neighbor. After that, the graphs are transposed into the physical entity that existed from the initial state with "neutral" nodes and edges only needed to be a coupler between the "active" nodes.

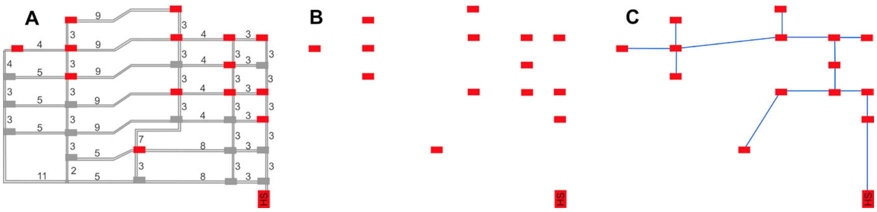


Fig. 2: Precognition paths generating – part 1

The process of creating paths is presented in Fig. 2 and Fig. 3. The starting point is presented in Fig. 2A – pre-ordered scheduled parameters (acquired from the users as required presets for human comfort) have been overlaid on a Matrix-like grid. The "active" nodes are only illustrated in Fig. 2B. The "active" nodes are the points of interest for users. They show where the users demand inner climate correction (i.e. temperature) due to the fact they occupy the lodging. At this moment what can be done is the linking of the "active" nodes in a graph by the immediate vicinity acquisition as it was presented in Fig. 2C. This process can be conducted in several ways, e.g. as the mathematical function of the closest neighbor measured by Euclidean metric or approximated by a colony of path-seeking (section 3.1) ants only. As the result of the operation an unweighted graph has been created.

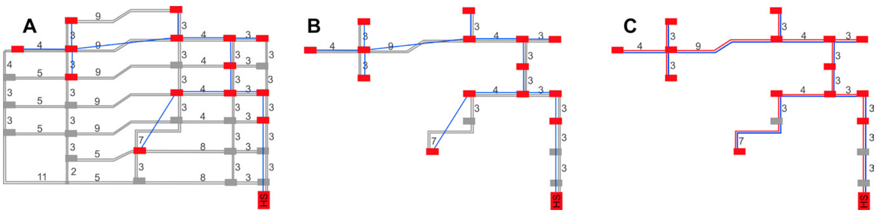


Fig. 3: Precognition paths generating – part 2

Subsequently, this result has become once again overlaid on a pre-ordered Matrix-like grid as in Fig. 3A, and the shaped grid is reduced to a pre-relict graph by adjusting the graph presented in Fig. 3C into the actual existing routes; as it is shown in Fig. 3B. All of the unexplored or explored routes with lower than expected frequencies are eliminated from the graph, which leads to a simplification of the graph. Finally, the created graph is reduced to the relict graph like in Fig. 3C. The process of the simplification is based on the *ACO*. The unweighted graph from the previous phase is treated as the presets of the pheromone trail – the edges covered by this graph receive additional significant pheromone injection before the agents will be launched to explore the grid.

3.3. Ants spreading

The last presented (but not last existing) technique for overcoming time execution limit deadlock is the ants spreading to the nodes of the grid and beginning to evaluate the paths separately for each node with a mutual pheromone trail information exchange, with a common *TSP* path search in the first stage and a modified second stage with examining the path found for agent delivery or acquisition purposes with one starting point. This technique is mentioned as an entry point for future study and testing. At this time, it is a concept only and it must be confirmed or rejected.

3.4. The aim of improvements

The most significant issue in revealing a pattern and achieving the best optimal solution is time required to evaluate the algorithm. The *ACO* needs time to recover the paths and to test them. Time restrictions between the phase iterations (scheduler service) that are too narrow can cause some paths to remain unprocessed and therefore the optimal pattern will not be revealed. Due to the *Extended Buildings' Energy Concept* [10], this problem can lead to insufficiency in energy distribution and a total system failure. A state in which there are unprocessed nodes (vertices) in a building is unacceptable. The same restrictions are crucial in other areas of life.

4. Real-life civilizations made mazes

The Humanity is trying to give an order to what is not organized, transform the chaos into repetitive order. It can be noticed that a lot of paths are organized in specified nets. The routes, rails, footpaths are connected with one another and form connection grids. In the following chapters several grids will be described and the modification of the classical *TSP* (or *CPP*) will be presented.

4.1. Building's installation as 3D Matrix-like grids

The *ACO* can be used as an optimization technique in modern buildings that are equipped with any type of an Energy Management System. Intelligent buildings have a large number of various installations such as electrical, ventilation, drainage, water-heating, etc. One of the most promising kinds of grids for energy optimization is water-heating.

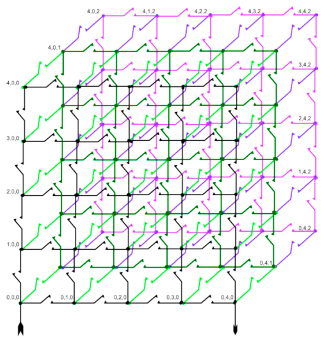


Fig. 4: 3D matrix-like grid with regular spread nodes

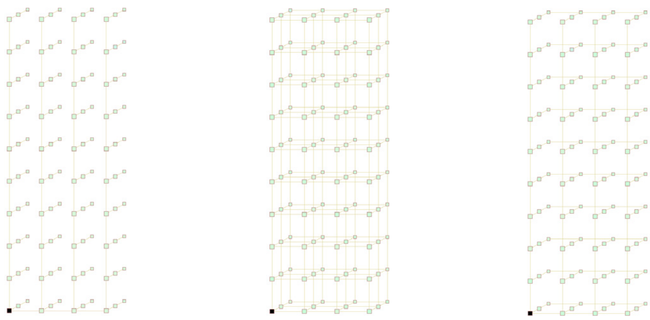
4.2. Central Heating System (particularly the HVAC component)

One alternative to the classical concept was introduced in [7] where a water-heating installation is represented as a 3D Matrix-like grid that is illustrated in Fig. 4. This representation leads to the creation of multi-way paths that reach every node in the matrix. As it can be noticed, this notation in connection with the building's plans creates a non-regular structure with undefined ways to reach the nodes in an energy optimized manner. A visual comparison of both of the attempts: classical non-Matrix and Matrix ones was thoroughly explained in [8, 9]. In short, it can be observed that the non-Matrix grid only has a vertical heat factor supply with one horizontal source line for all of the vertical ones, which is usually placed in the basement of a building. The nodes are placed in the line of the vertical supply. By contrast to this, a Matrix-like grid has multiple vertical and horizontal connections in each node and can offer many different configurations for heating water. The algorithms and the simulator created for the study are presented and described in the previous publication [11] and are omitted here for clarity purposes.

5. The study

The study was undertaken due to the topics presented above in order to explore the effectiveness of the classical and Matrix-grid based nets with the offered algorithm. Subsequently, they were designed as three grids for implementation in a real building. One as a classical approach to the main issue. The second one as the Matrix-like-grid mentioned above in section 4.1. For the purpose of the study the same kind of basics were taken into consideration i.e. a 10-floor building with 4-rooms width and 3-rooms depth. The differences are the results of the assumptions – classical or Matrix-like grid. Moreover, it was assumed that the range of the heating process is from $0°CC$ to $15°CC$. The test consists in registering the time required to fulfill the assumptions within three ranges: 90% of the entire number of rooms have achieved the expected conditions, 98% of the entire number of rooms have achieved the expected conditions and 100% of the entire number of rooms have achieved the expected conditions. The formed grids are presented in Fig. 5. The parameters and algorithm modification used for simulation were the results of the previous experiments [7, 11] and were set as:

- $\alpha = 1, \beta = 1, \delta = 5, evaporationFactor = 0.1, minPheromoneLevel = 0.01$
- $PatchSeekersMultiplier = 1, PathSeekersPercentage = 40\%$
- $chargeLoad = 250, heatDissipationFactor = 2,$
- $startTemperature = 0°C, stopTemperature = 15°C$



(a) Classical grid (b) Matrix grid (c) Modified Classical

Fig. 5: Grids taken under examination

The study was based on 10 measurements for each grid, and progression time registration. The results are subjected to further statistical processing, and specifying the mean result. The graphical representation of the results is shown in Fig. 7, snapshots of the simulation process from stage "the first" to the stage "the last" are presented in Fig. 6.

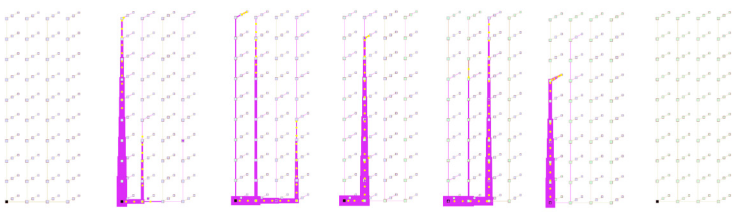


Fig. 6: A few snapshots of simulation for the Classical-style grid

The registered times for the Classical-style approach are presented in table 1.

Table 1: The measured time results of test for the Classical-style grid

ID	Time for 100%	Time [m]	Time for 90%	Time [m]	Time for 98%	Time [m]
1	17:00:00	1020	02:50:00	170	04:10:00	250
2	09:32:00	572	02:51:00	171	04:15:00	255
3	16:25:00	985	02:51:00	171	05:56:00	356
4	04:11:00	251	03:15:00	195	03:44:00	224
5	03:29:00	209	02:54:00	154	03:21:00	201
6	03:21:00	201	02:39:00	159	03:10:00	190
7	06:32:00	212	02:36:00	156	03:17:00	197
8	11:12:00	672	03:52:00	232	11:11:00	671
9	11:28:00	688	02:36:00	156	09:42:00	582
10	03:26:00	206	02:25:00	145	03:04:00	184

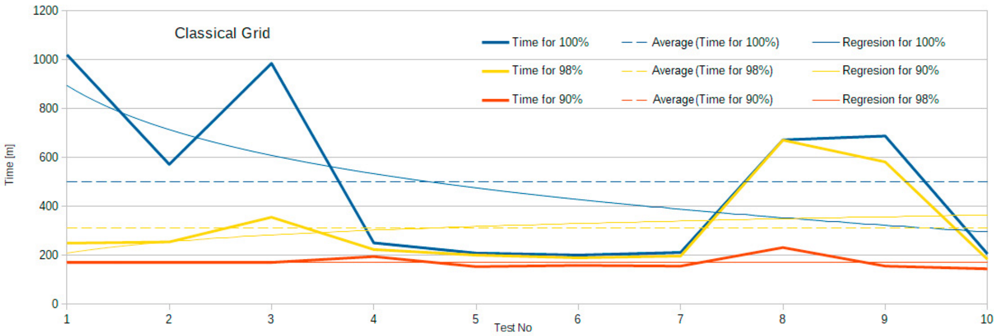


Fig. 7: The results of test for the Classical-style grid

The graphical representation of the results for the Matrix-like-style are shown in the Fig. 9, snapshots of the simulation process from stage "the first" to the stage "the last" are presented in the Fig. 8.

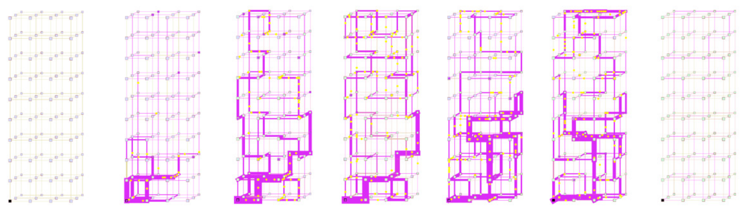


Fig. 8: A few snapshots of simulation for the Matrix-like-style grid

The registered times for the Matrix-like approach are presented in table 2

Table 2: The measured time results of test for the Matrix-style grid

ID	Time for 100%	Time [m]	Time for 90%	Time [m]	Time for 98%	Time [m]
1	00:39:00	39	00:32:00	32	00:37:00	37
2	00:45:00	45	00:34:00	34	00:44:00	44
3	00:43:00	43	00:37:00	37	00:42:00	42
4	00:42:00	42	00:30:00	30	00:35:00	35
5	00:44:00	44	00:32:00	32	00:40:00	40
6	00:59:00	59	00:37:00	37	00:43:00	43
7	00:44:00	44	00:35:00	35	00:41:00	41
8	00:45:00	45	00:37:00	37	00:41:00	41
9	00:45:00	45	00:34:00	34	00:37:00	37
10	00:44:00	44	00:36:00	36	00:42:00	42

The graphical representation of the results are shown in the Fig. 9

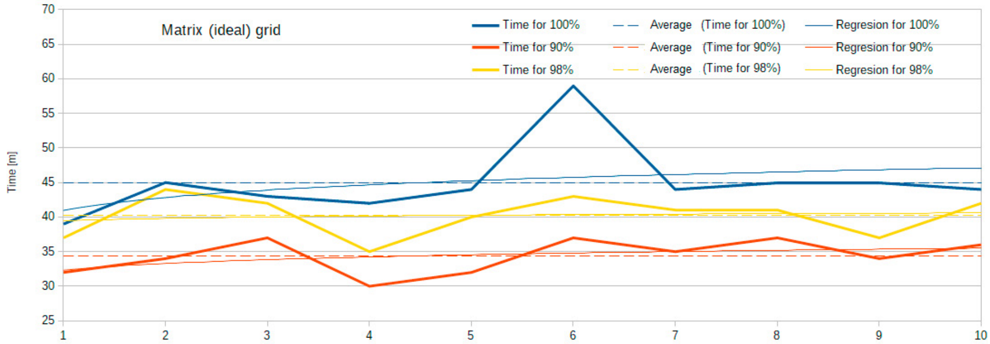


Fig. 9: The results of test for the Matrix-style grid

The results show that the Classical-style approach is much worse than the Matrix-like-style with the usage of the ant-optimization algorithm. There is no comparison to the currently existing analog *HVAC* systems, because of the lack of existence of parallel analogous points of systems that could be compared. The present systems are completely different in assumption and a comparison of such different systems would require the construction of two grids based on each assumption from scratch. Therefore, the study is limited to testing the behavior of agents (led by algorithm) in various grids.

It is commonly known that the Matrix-like-style grids are almost impossible to be implemented in modern buildings due to their style of connection: each node with its neighbors. The solution is as usual the Golden mean. Therefore, the study focused on a grid which cannot be called a classical any more, but is far from the Matrix-like grid. The next grid is a slight modification of the classical one, presented in Fig. 5 part (c).

The graphical representation of the results is shown in Fig. 11, snapshots of the simulation process from stage "the first" to the stage "the last" are presented in Fig. 10.

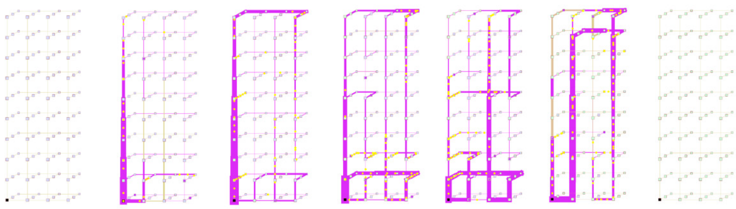


Fig. 10: A few snapshots of simulation for the Classical-style with modification grid

The registered times for the Classical-style with modification approach are presented in table 3.

Table 3: The measured time results of test for the Classical-style with modifications grid

ID	Time for 100%	Time [m]	Time for 90%	Time [m]	Time for 98%	Time [m]
1	00:39:00	39	00:32:00	32	00:37:00	37
2	00:45:00	45	00:34:00	34	00:44:00	44
3	00:43:00	43	00:37:00	37	00:42:00	42
4	00:42:00	42	00:30:00	30	00:35:00	35
5	00:44:00	44	00:32:00	32	00:40:00	40
6	00:59:00	59	00:37:00	37	00:43:00	43
7	00:44:00	44	00:35:00	35	00:41:00	41
8	00:45:00	45	00:37:00	37	00:41:00	41
9	00:45:00	45	00:34:00	34	00:37:00	37
10	00:44:00	44	00:36:00	36	00:42:00	42

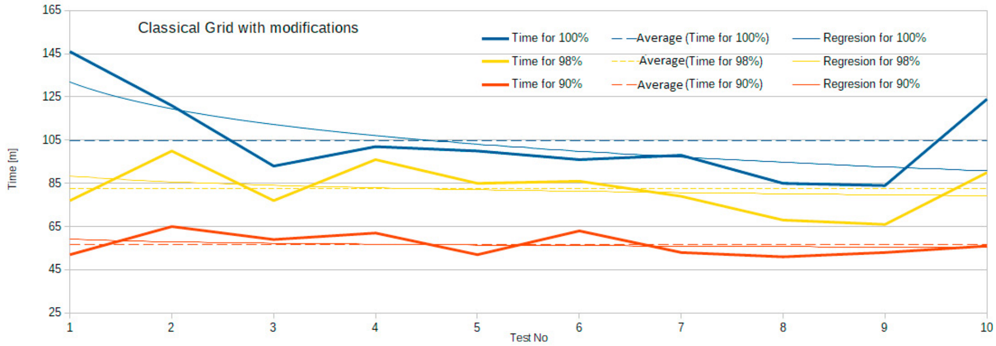


Fig. 11: The results of test for the Classical-style with modification grid

6. Discussion concerning the study

The result of the first study shows that the *ACO* agents can successfully traverse existing grids and reveal an optimal path as the result of iterations. This is a proof that the *ACO* can be used as the solution to the *BEMS*. The results are presented in Table 1. It can be noticed that the chosen aims are reached and only the time needed to traverse is questionable. Further study consisted in the grid modification toward the one suggested to be the ideal one – Matrix-like grid for comparing the results. The second study results with the Matrix-like grid are presented in Table 2 and it is possible to notice the difference in the consumption of time needed to reach the same goals. These two studies are completely different for an order of magnitude, and it is obvious that the Matrix-like grids are ideal for the *ACO* agents' environment. These types of grids are at the same time the rarest and inadequate for implementation in a real environment. This is an entry point to the third study – the connection between the real existing grids and the advantages that stem from the Matrix-like grid. The results are presented in Table 3. The modified *ACO* algorithm is better then unmodified one because of giving the emulation of real state of whole *BEMS* system thanks to work of carier agents, and is able to quick parse grids to recover the optimal path by path-seeker agents and ensure that the system requirements were met. Taking the collected result under analysis shows that even a slight modification of the standard Classical-like grids leads to huge time saving. These modifications are easy to implement even in present and working systems. The tested algorithm is not good enough to be used as support under standard classical grids. Such an ideal solution as Matrix-like grid is not necessary to be implemented in its entirety, even small amounts of similarity to the Matrix-like grid leads to big improvement in the processing of the entire system. The comparison of the results is shown in Fig. 12 (the higher the worse).

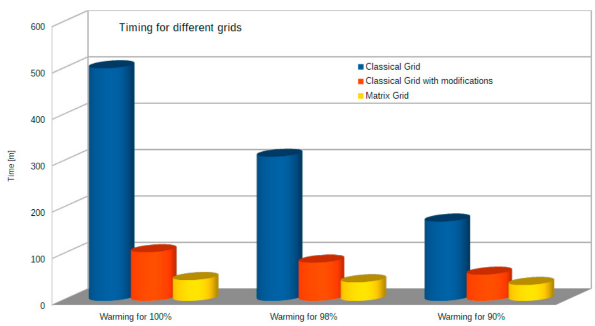


Fig. 12: The timing comparision for grids taken under examination

7. The future directions of the study of the *ACO* behavior and conclusion

The article is a snapshot of the present results of the study of the *ACO* agents' behavior for the *BEMS*. The closest survey should address the mentioned in sections 3.2 and 3.3 Precognition Paths and the Ants Spreading modification of the algorithm for the same environment for the comparison of the results and selection of the best algorithm. Subsequently, the focus of the study is intended to be moved to the municipal waste management problem and the crowd flow management issue to test and obtain the results of the same algorithms in a different environment. In the article the hypothesis – the ACO agents are effective in overcoming the existing grids, and they do need modification of their standard algorithms or parsed grids – was undertaken and examined. The results were recorded and presented in section 5. It was confirmed that the Matrix-like grids are the best environment for ants optimization. The Classical approach has existed for years, and there is no place for improvement with standard systems. Moreover, these kinds of grids are the worst environment for the *ACO* support. However, even the slightest modification of the existing installations into Matrix-like grids can lead to a significant acceleration of the whole system usage.

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