Holonic Execution System for Construction Management

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Abstract –

Ensuring high efficiency in construction through advanced planning techniques must be supported by the simulation of construction processes. In previous research, the potential for multi-agent based simulation to support the planning phase were successfully shown with regard to some typical construction tasks. Among the main benefits determined by this approach the following ones were reported: capability of simulating real-world processes and interaction among resources; powerful 3D visualization; optimal sizing of resources. However, those models are not easy to create, because of the absence of built-in blocks and the many relationships among single agents and between agents and context.

In this paper we propose the application of a novel holonic system for construction management, which is a sub-category of multi-agent systems. It combines the high and predictable performance promised by hierarchical systems with the robustness against disturbances and the agility of heterarchical systems. Holons are self-contained, stable, intermediate forms, that can be used to create a bigger whole. By using holons, designers aim to create complex systems that can be reused and redesigned much more rapidly than standard multi-agent systems. The approach was applied to the optimal scheduling of bored piles construction. Hence, a holonic construction execution system for bored piles tasks was developed. The holonic architecture was designed so as to integrate the DMAS pattern for scheduling optimization through stigmergy. The results of this paper showed the easy reusability of our simulation sub-systems and the potentials in terms of automatic optimal planning of construction works.

Keywords –

Construction management; holonic systems; multi-agent systems; VRP

1 Introduction

Lean construction principles are currently under development in order to improve the productivity of the construction industry. However, this process requires that general lean principles be adapted into practices that are tailored to the characteristics of construction projects. A number of initiatives are known in this field. An empirical study regarding the construction of a large hospital resulted in a set of lessons learned, which can be roughly grouped into three sections: lean engineering, logistics and purchasing, lean construction process [1]. A methodological and very popular approach, which was definitely organized by the lean construction institute, is the last planner system [2]: it helps increase the reliability of a planning system and thereby significantly improve its overall performance. Although really effective, implementing the last planner system in construction organizations over the long-term requires significant support for project teams by dedicated facilitators. Such levels of support are difficult to maintain, but in their absence teams tend to revert to traditional practices [3]. As a result, research is still very active in this field and novel methodologies are object of testing, such as the “kanBIM” prototype, which is a BIM-based workflow information system to help construction personnel implement pull flow strategies [4]. This latest approach highlights the importance of monitoring, control and continuous revision of the work plan, according to the status of work underway. Thanks to the advent of powerful computational tools, optimal work plans can be worked out by means of agent-based simulation approaches. This approach outperforms discrete event simulation, which, in fact, fails to incorporate the inherent variability that arises from the independent construction subjects’ behavior as they interact on a construction site [5]. On the contrary, multi-agent simulation is suitable for modelling resources’ behavior and interactions in complex settings, like in construction. These models are capable of specifying the characteristic of trade crews, their work methods, the amount of work, workspaces and dependencies between tasks. As a result, simulations encapsulate both variability and uncertainty of the construction workflow [6].

In this paper we study the feasibility of a new reference architecture for construction, that was successfully tested in manufacturing, and that can simulate the construction process. This new system is based on the use of holons, which can organize into holarchies, and own self-configuration and self-organization capabilities, thus resembling the behavior of the resources usually employed on and off-site, which must cope with the high variability and uncertainty typical of construction works [8]. In addition, simulation models are built on top of classes classified as agents, holons and functional blocks, which can be variously combined to perform optimal planning by means of optimization algorithms. In section 2 a brief overview of the scientific background will be provided. Section 3 will report on the basics of holonic systems and of the optimization algorithms we have analyzed. Then, Section 4 will present an application to the optimal planning of bored piles and presents a final discussion.

2 Scientific Background

Renovation works must be scheduled, budgeted and monitored and controlled until the end of work progress. The standard construction practice is commonly done applying diagram methods to sequence activities that are based on work packages defined according to a work-breakdown-structure. Then, progress management usually involves deviation analyses between the actual progress and the initial plan that is constantly being updated and revised. The scarce communication and the absence of automation requires the adoption of standard methods, such as face-to-face meetings and paperwork. This approach has been identified as an inhibitor to increasing productivity and a miscommunication and rework source, which can be improved by means of holonic execution systems. These systems are able to improve communication channels, coordination and cooperation, dynamic management. Also, they can take advantage of BIM-based structured information [8]. Several authors analyzed the great potentials of multi agent-based simulation, thanks to its ability of imitating real world process of systems, where the global behaviour emerges as a result of interactions of single agents [6, 9]. Agents can be active, proactive, autonomous, cooperative, adaptive and mobile. They interact to reach a global objective. However, holons can expose additional important features that resemble the real behaviour of construction execution, i.e. they organize into holarchies, where a system of holons cooperate to achieve an overall goal while negotiating with their own objectives [10]. Hence, they can reliably simulate the behaviour of cooperating agents in construction sites and the dynamics in such distributed operating environments [11] even if parameters change during the work progress [12]. Holonic models were successfully applied in manufacturing control, referring to the PROSA reference architecture [13]. In this application all entities in the "world of interest" were not only represented as agents, but also as entities in the environment, with which they communicate and interact. In addition, the Delegate multi-agent system (DMAS), that is part of holonic systems, allows any holons to delegate a responsibility to a swarm of "lightweight" agents [7]. This feature can be used to find out the optimal work planning prior to the execution phase, and to execute dynamic re-planning during work progress.

Automation in scheduling has been studied in the last three decades and several approaches were experimented [14]. Cased-based reasoning (CB) develops plans by remembering earlier and comparable situations. Genetic algorithms (GA) and neural networks (NN) perform optimization relying on a huge database, so their learning process must be fed by thousands of records. Hence, expert systems (ES, mainly using if-then-else structures) and model based approaches (MB, which simulate the execution process) look more reliable to be applied in construction. However, all these approaches tackle a unique aspect of the scheduling problem: CB is about optimal sequencing, GA on resource optimization and levelling, NN on time-cost tradeoff and optimization, MB on spatial reasoning. Some remarkable examples about MB simulated the construction process either by means of a set of differential equations [15], or an integrated mathematical model [16] or a probabilistic approach [17].

In this paper, we will study another approach and will test it in the execution of bored piles. Our model will conform to the PROSA reference architecture, which includes the DMAS approach, because it allows the re-planning occurring during execution. More importantly, this process allows us to evolve from single-objective optimization towards a multi-objective optimization problem based on ant-colony simulation. In this approach, every objective can be optimized by a different colony, that is cooperating and contributing to the whole process. In addition, every resource involved in the production process is capable of continuously re-planning her schedule as a result from unexpected occurrences, in fact performing dynamic scheduling. Finally, the setup of simulation models can be facilitated by the availability of a BIM model of the designed tasks.

3 Holonic Execution Systems

3.1 Description of Holonic Systems

In this paper we tested the feasibility of using the holonic reference architecture for the simulation of construction execution. The objective of a reference architecture is to specify a generic systems structure, the kinds of system components, their responsibilities, dependences, interfaces, data, interactions, constraints etc…[18]. Then, the reference architecture can be used as the basis for designing any system architecture, which refers to a particular system and focuses on a particular product.

Holonic architectures are made up of holons, which are autonomous self-reliant units, in the sense that they have a degree of independence and can handle contingencies without asking higher authority for instructions. They are stable intermediate forms, that can be used to create a bigger whole [13]. Holons are combined to form holarchies, which combine the positive characteristics of hierarchical and heterarchical systems. Hierarchical systems offer high and predictable performances thanks to their pyramidical structure (although they might lack in robustness). Heterarchical architectures allow for full cooperation between entities, that is arranged by means of negotiation, in fact increasing robustness [19]. Holons can function on their own, which increases robustness and, at the same time, it can function as a part of a bigger whole, forming a hierarchy with other holons for a certain period of time.

The three basic types of holons, which are adopted in the PROSA reference architecture for manufacturing systems, are order, product and resource, whereas staff is optional. Order holons are in charge of accomplishing tasks, they search for solutions and select among candidate alternatives the most attractive one; product holons provide order ones with knowledge about routing and processing sequences that are able to create proper products; resource holons drive their resource actuation and keep their internal state synchronized with the resource through appropriate inputs, such as sensor readings [7]. Holonic systems can operate just in case they include the world of interest, that is the part of reality in which the execution operates. As a result, the architecture of a holon usually comprises both the control system and the manufacturing system (Figure 1):

- The physical processing component, that is part of the world of interest;
- The physical control component;
- The decision making component that is part of the agent.

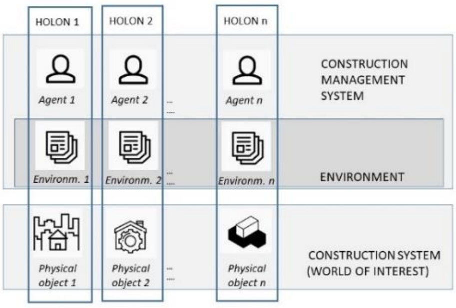


Figure 1. Holonic architecture (adapted from [13])

3.2 Holonic Execution Systems for Construction Management

Most construction tasks are affected by disturbances and variations in their operating environment. As a consequence, work plans that are generated before the process starts, are based on approximate resource performance and predicted operating conditions. For that reason, they need re-planning any time unexpected occurrences cause deviations from what expected. In addition, not two construction sites can be planned in the same way. Hence, multi-objective optimization problems must be integrated in management systems, in order to adapt the crews number and mutual organizations, according to real boundary conditions. In sub-section 3.2.1 an approach that is general enough while being capable of integrating optimization algorithms will be presented. Then, in sub-section 3.2.2 the multi-objective optimization algorithm that we used in this research work will be detailed.

3.2.1 The Architecture of the Holonic Execution System

The holons mentioned in sub-section 3.1 are expected to interact and share data with each other. Three basic types of interaction can be recognized [7]:

- Product-order interaction: the order holons interact with their corresponding product holon on how to correctly execute their task by using certain resources. In other words, the product holon provides the order holon with all possible next operations, and the order holon keeps track of the task being executed.
- Product-resource interaction: the product holon provides the resource holon with technological aspect to correctly process an order, e.g. the necessary process parameters to perform an operation.
- Resource-order interaction: resource and order holons mainly interact to commit operations to the resources. To this purpose, the resource holons provide the order holons with the results of virtually executed operations and reserve capacity when requested. Once a task is executed, the resource holon informs the order holon about the execution result and progress. Hence the desired coordination and control emerges in a self-organizing way from the interaction between the various holons.

In order for the above mentioned interactions to be effective, order holons must be able to reserve resource so as to optimize the overall schedule. In other words, holons must interact while seeking global optimization. Research manufacturing, found out that the behaviour of food-foraging ants, called stigmergy, is the best approach because it is capable of incorporating nonlocal information while employing only local reality-mirroring components [7]. To sum up, the following steps are performed in a stigmergic approach:

- In absence of any signs in the environment, ants perform a randomized search for food;
- When an ant discovers a food source, it drops a smelling substance, called pheromone, on its way back to the nest while carrying some of the food. The pheromone trail evaporates if no other ant deposits fresh pheromone;
- When an ant senses a pheromone trail, it will be urged by its instinct to follow this trail to the food source and will deposit pheromone itself on its way back to the nest.

This pattern is an emergent behavior of the ant colony, that is ordered and is robust against the uncertainty and the complexity of the environment. Although information about the presence of food is made available locally, it affects the global behavior of the colony and the state of the environment.

In order to integrate this behavior within the holonic architecture, the deposit of pheromones can be translated into order holons reserving time slots in these local schedules. In other words, "ant agents" travel virtually and execute virtually what an order holon might do for real. Finally, the order holon picks out the best solution among available alternatives. This architectural pattern is represented as Delegate MultiAgent System (DMAS), and is sketched in Figure 2. According to this pattern, the DMAS allows a holon to delegate a swarm of lightweight agents to perform an action to support the issuing holon in fulfilling its functions.

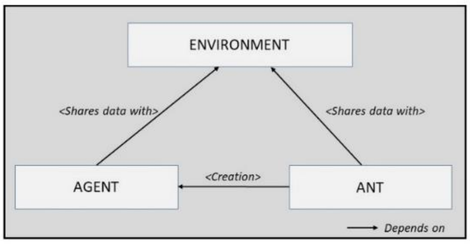


Figure 2. Delegate MultiAgent System (adapted from [7])

In the application reported in this paper, we developed a model involving resource, order and product holons (Figure 3), where the product holon exposes attributes that can be retrieved directly from a BIM model, and the holon order applies the ant-colony optimization algorithm described in the next sub-section to find out the optimal schedule. The architecture depicted in Figure 3 was built according to the PROSA reference architecture, which was successfully applied in manufacturing. The order holon is in charge of managing the schedule. It commits resources, both those ones which are in charge of executing the tasks and the resources that are consumed by construction works (e.g. excavated or drilled soil). To be noticed that there are several instances of "product holons", because each of them includes information about a possible technology for constructing the several types of piles that can reasonably be found in a building detailed design. Resources are sized according to the specific technology and to parameters, which can be inputted directly from the BIM model.

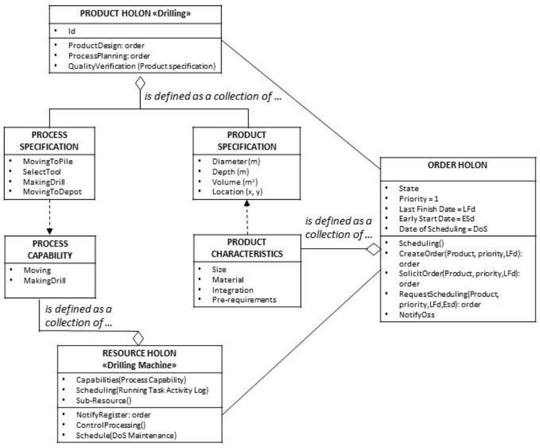


Figure 3. Suggested UML architecture for pile construction (adapted from PROSA)

3.2.2 Multi-objective Optimization Algorithm

As the case study analysed in this paper is the first task of bored piles execution (i.e. drilling), optimization was performed by means of vehicle routing problems. Indeed, driving drilling machines along the most cost-effective path recalls problems about routing optimization. More specifically, we refer to the multiple ant colony system for vehicle routing problems with time windows (MACS-VRPTW), which performs ant colony optimization [20]. Basically MACS-VRPTW is organized with a hierarchy of artificial ant colonies designed to successively optimize a multiple objective function: the first colony minimizes the number of vehicles while the second colony minimized the travelled distance. Basically, a VRP is composed of n customers served from a unique depot. Each customer asks for a quantity q_i of goods and a vehicle capacity Q is available for delivery. Each delivery cannot be split and the vehicle has to periodically return to the depot for reloading. On the overall, the problem is represented as a graph made of a node set $C = \{c_0, c_1, \ldots, c_n\}$ and arcs $L = \{c_i, c_j\}$ to which a matrix of travel time values t_{ij} is associated. The goal is to find a set of tours of minimum total travel time, where each tour starts and ends at the depot c_0. Extensions to the basic problem include: service time for each customer; duration limit of each tour. But in this paper we applied the VRP with time windows, i.e. VRPTW. This problem includes for the depot and each customer c_i a time window $[b_i, e_i]$, during which the customer has to be served between starting time b_i and end time e_i. The tours are performed by a fleet of identical vehicles. This approach is applied to the case study presented in this paper, and optimization is performed by means of ant colony optimization (ACS), and both the number of vehicles and travel time are to be minimized (i.e. multi-objective). To this purpose, two measures (i.e. heuristics) are associated to each arc: closeness (η_{ij}) and pheromone trail (τ_{ij}). The first is the inverse of the distance, the second one is dynamically changed by ants at runtime. Pheromone trails are used in conjunction with the objective function to construct new solutions: a higher probability is given to elements with a strong pheromone trails. Pheromone levels give a measure of how desirable it is to insert a given arc in a solution. At runtime, *m* ants build tours in parallel. Each ant is randomly assigned to a starting node and has to build a solution, by adding iteratively new nodes until all nodes have been visited. When ant *k* is located at node *i*, it chooses the next node *j* probabilistically in the set of feasible (i.e. have not been visited, yet) nodes N_i^k. The probabilistic rule is defined by Equation 1:

$$p_{ij} = \begin{cases} \dfrac{\tau_{ij}\cdot[\eta_{ij}]^{\beta}}{\sum_{l\in N_i^k}\tau_{il}\cdot[\eta_{il}]^{\beta}} & if\ j\in N_i^k \\ 0 & otherwise \end{cases} \qquad (1)$$

In fact, the process goes through two steps: exploration and exploitation. During exploration, with probability q_0 a node with the highest $\tau_{ij}[\eta_{ij}]^{\beta}$ is chosen, with the purpose of selecting the components to be used to construct a solution. During exploitation, the next components is chosen by maximizing a blend of pheromone trail values and heuristic evaluations. More specifically, with probability (1- q_0) the node *j* is chosen with a probability p_{ij} (Eq. 1). The procedure exploits two parameters: β weighs the relative importance of the heuristic value, while q_0 determines the relative importance of exploration versus exploitation. Once each ant has built a complete solution, this is tentatively improved using a local search procedure. Next, the best solution found from the beginning of the trial is used to update the pheromone trails. Then, the process is iterated starting again *m* ants until a termination condition is met. The best solution is used to modify the pheromone trail matrix (τ_{ij}), future ants will use this information to generate new solutions in the neighborhood of the best solution, as follows:

$$\tau_{ij} = (1-\rho)\cdot\tau_{ij} + \frac{\rho}{J_{\Psi}^{gb}}, \qquad \forall\ (i,j)\epsilon\Psi^{gb} \qquad (2)$$

Where $0<\rho<1$ and J_{Ψ}^{gb} is the length of J^{gb}, i.e. the shortest path generated by ants since the beginning of computation. Locally, when an ant moves from node *i* to node *j*, the amount of pheromone trail on arc (*i*, *j*) is decreased by the amount:

$$\tau_{ij} = (1-\rho)\cdot\tau_{ij} + \rho\cdot\tau_0 \qquad (3)$$

Where τ_0 is the initial value of trails. This algorithm was used with two objective functions: minimization of the number of tours and minimization of the total travel time. To this purpose, two independent colonies are used, one per each objective, but both share the variable Ψ^{gb}. Finally, time windows are used to limit the duration of the path. To this purpose, an active procedure is inserted in the algorithm, which, at every step when and ant moves between nodes *i* and *j*, it checks whether the movement violates time window constraints. Optionally, even vehicle capacities (i.e. payload) can be checked for violation, but it was not used in the application that will be shown in this paper.

3.3 Implementation of the Holonic Execution System

The MACS-VRPTW algorithm detailed in sub-section 3.2.2 was integrated in the DMAS architecture (Figure 3), as depicted in Figure 4. The order holon gets an order from the master schedule with task description, start and end dates. At time step t_0, the order holon delegates ant colonies to search for the best path. After the drilling process starts and disturbances or unexpected occurrences can take place changing boundary conditions, the order holon runs more simulations and performs on-line planning, i.e. continuous improvement of the initial work plan. The resources in charge of drilling piles were committed according to the best solution found out by the holon order itself. The algorithm was implemented in Matlab™ environment, because it facilitates the prototyping of the code. In the near future, integration within a multi-agent simulation environment (e.g. Anylogic) will be carried out. The main boundary conditions were:

- no maximum payload was assigned to drill resources, in fact assuming that they never come back to the depot until they finish their tasks;
- drills were not allowed to follow a path overlapping the nodes were piles had already been drilled; this was done by using a dynamic cost matrix;
- As all the parameters are dynamic (e.g. time window, cost matrix) when the algorithm updates the current best solution with a new one, the cost of the current solution is re-computed at each iteration.

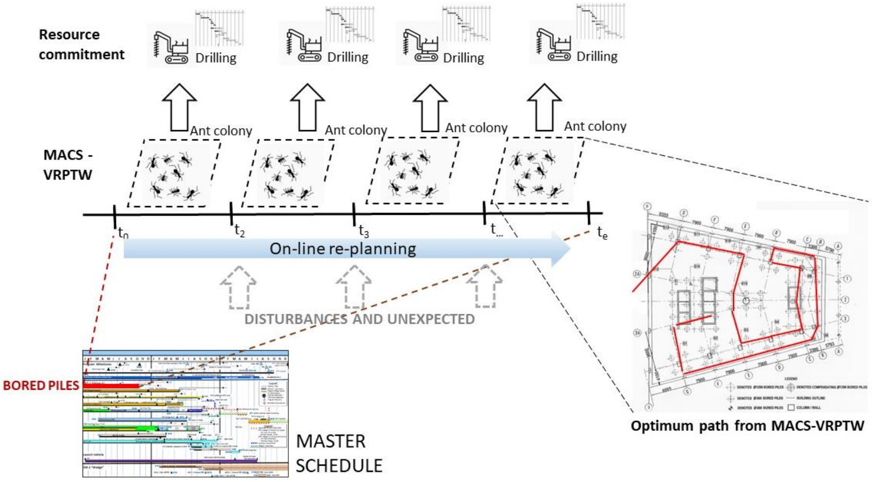


Figure 4. Sketch of the overall logic underlying the MACS-VRPTW algorithm.

The termination condition was set at 300 iterations. The main outputs provided by the algorithm are: sequence of nodes forming the best solution; overall cost of the solution; service (i.e. delivery) time to perform each pile drilling.

4 Testing of the Holonic Execution System

4.1 On-line Planning of Construction Works

4.1.1 The Case Study

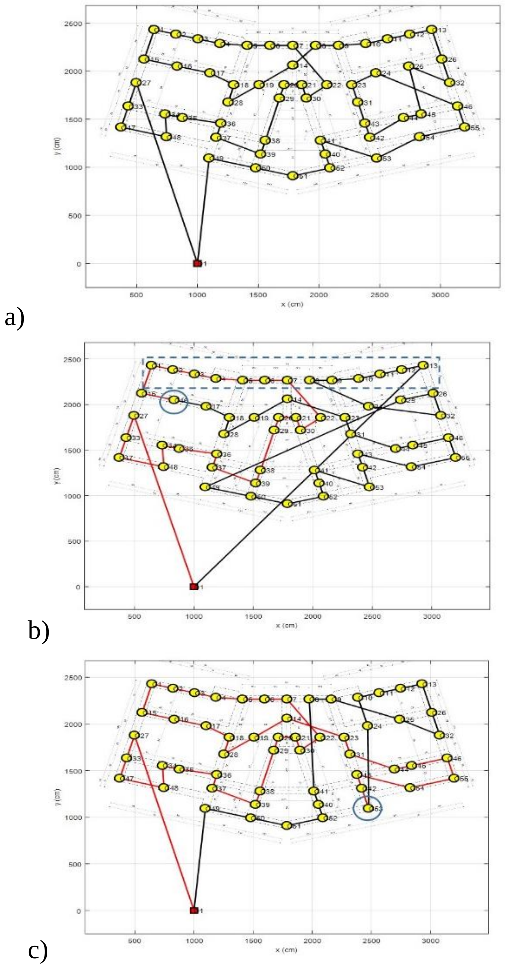
Pile construction was chosen as the test case for our proof of concept, because it poses several challenges: uncertainty generated by soil type, equipment efficiency and weather conditions; again, unexpected occurrences like site restriction and disposal of excavated soil ask for the application of a reliable on-line planning scheduling [18]. The drilling task only was simulated (excluding rebar cage positioning and concrete pouring). The resource holon assigned to each pile contained information about the volume, type of concrete, soil type, location, that were used by drills to estimate their task duration. This information was used as input for the application of the MACS-VRPTW algorithm. The set of piles was assumed to be arranged as shown in Figure 5.

4.1.2 Simulation of Scenarios

Two scenarios were simulated:

1. The site is initially fully available for drilling and there are no space restrictions; then, due to interferences with other crews, part of the site is restricted to access, so re-planning is necessary; after some time, the site becomes fully available again and the task is accomplished.
2. Drilling starts when the previous task is not finished, yet. So, just a portion of the site is available for drilling. After a while, the previous task gets accomplished and the whole site becomes fully available again and the drilling task can be accomplished, too.

Before starting the drilling process, the HES finds that the path marked on Figure 5-a and superimposed to the foundation plan is the best one, where the red squared node is the depot and the yellow circle nodes are the piles. In all figures, black lines form the path to be executed, whereas red lines form the accomplished path. While pile no. 16 is in progress (marked in a blue-coloured circle in Figures 5-a and 5-b), the site area within the boundaries of the blue dashed rectangular shaped area marked on Figure 5-b becomes restricted. As a result, the best path is re-planned, whose outcome is shown on Figure 5-b (piles between no. 1 and no. 13) and the drilling machine continues working according to this second work plan. The restricted area becomes available again while the drilling machine is doing pile no. 53 (blue-coloured marked circle on Figure 5-c). Hence, the on-line planning system computes again a new solution for the best path and the whole job is accomplished. In the second scenario, the site area included within the boundaries marked by the blue dotted polygon (Figure 6-a) is restricted due to the previously scheduled task. So the drilling machine is sent into the left side area of the site. Such a site area becomes unrestricted while the machine is drilling pile no. 4 (blue circled on Figure 6-b). As a result, the best solution is promptly updated and changes as shown on Figure 6-b. Also, the overall cost is updated as shown on Figure 6-c. Until the restricted area was not accessible, the best solution found was as costly as shown by the plot at iteration no. 150. But, on-line re-planning, which involved the second block made up of 150 iterations, caused the overall cost to decrease down to the value $1.8 \cdot 10^4$, which corresponds to iteration no. 300.



a)

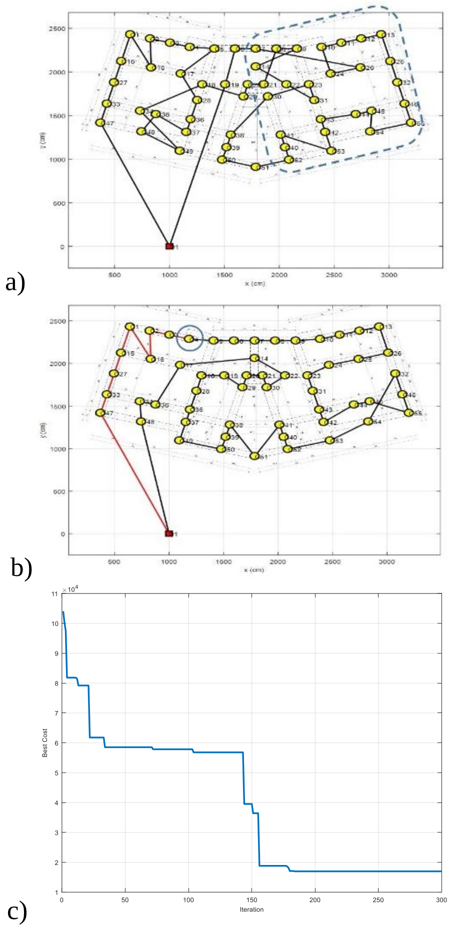
b)

c)

Figure 5: on-line re-planning relative to the Scenario no. 1.

4.2 Results and Discussion

This paper focused on the preliminary development of a holonic execution system (HEM) to implement on-line re-planning of construction activities.



a)

b)

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Figure 6: on-line re-planning relative to the Scenario no. 2.

The architecture used in this paper was adapted from the PROSA approach and the ACS-VRPTW algorithm was integrated to simulate the DMAS pattern. Simulation results are referred to the case of pile construction in the foundation of a building. It was shown that the HES is highly resilient to uncertainty and can cope with unexpected events, while minimizing the overall cost function. Thus, it is a good candidate for the implementation of lean management policies. In addition, the proposed architecture defines a valid general framework, based on which system frameworks specialized to several tasks can be developed. Further research will focus on the extension of the proposed architecture towards the realization of different construction tasks, for its enhancement and generalization. Finally, this approach is capable of facilitating the development of simulation scenarios relative to construction tasks, thanks to the reusability of the components forming the overall system architecture.

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