Dynamic maintenance grouping and routing for geographically dispersed production systems

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Abstract

This paper presents a dynamic grouping and routing approach for the maintenance optimization of a geographically dispersed production system (GDPS) consisting of several production sites located far apart from each other. Only one maintenance center is in charge of the preventive maintenance of the system. Maintenance grouping and routing are two interrelated processes but often investigated separately in literature. In this paper, these two processes are jointly studied and integrated in a global model considering economic and geographical dependencies at both component and site levels. The optimal maintenance grouped plan and routes are then determined by a combination of the Local Search Genetic Algorithm (LSGA) and Branch and Bound method (BAB). Moreover, several dynamic contexts impacting the current optimal maintenance grouped planning and routing, which may occur with time, are also studied and integrated in the joint optimization process. Thanks to this consideration, the proposed approach allows updating the grouped maintenance planning and routing to take into account the impacts of dynamic contexts when they occur. The uses and advantages of the proposed approach are illustrated through a numerical example of a GDPS consisting of 15 components located in five different sites.

Keywords: Grouping maintenance, Route scheduling, Economic dependence, Geographical dependence, Geographically Dispersed Production Systems, Local Search Genetic Algorithm.

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1 Introduction

In the recent years, with the growth of international trade, the development of distributed control, information, and logistic technologies, many manufacturing companies pursued the goal of building geographically dispersed production systems (GDPS) to ensure their competitiveness [1, 20]. According to this concept, the production is done over a number of production sites which are geographically located far apart from each other. On the one hand, the GDPS is a key solution for optimizing production cost and product delivered cost as well as adapting customer's demands. On the other hand, the GDPS has to face many challenges concerning standards, regulation, production management, and especially, maintenance planning and optimization.

Firstly, in the framework of maintenance optimization, the dependencies between components have important impacts on the performance of a maintenance planning and need to be considered in the maintenance modelling and optimization [14, 5]. Unlike centralized systems, a GDPS system can be divided into two abstraction levels. At site level, a production site contains different components to perform specific production or service functions [1, 18]. Therefore, each site can be seen as a multi-component system whose components may depend on each others. These dependencies are classically classified into three main types as in [14, 5, 26]: structural dependence (e.g. maintenance of a failed component implies maintenance of working components or, at least, dismantling them); stochastic dependence (i.e the condition of components influences the life distribution of other components) and economic dependence (i.e the cost of joint maintenance of a group of components does not equal the total cost of individual maintenance of these components). Recently, a fourth type of dependence, namely logistic dependence, has been introduced in [6]. Logistic dependence exists when executing maintenance of several components require a same maintenance skill and/or a same type of spares parts. At GDPS system level, another dependence, called geographical dependence, exists if the total distance/time of the joint maintenance group of several components is smaller than the total distance/time of each individual component. This type of dependence may impact the maintenance planning and/or total maintenance cost. This is specially true when only one maintenance team located far from production sites is available for performing the maintenance on different sites. It should be noticed that, in literature, a large number of maintenance approaches has been introduced, developed and successfully applied to multi-component systems considering several types of dependencies. A relevant overview on this topic is given in [6]. Among existing maintenance approaches, dynamic grouping maintenance approach initially proposed in [14] seems to be an efficient one since it can take into account several kinds of dependencies between components and easily update the maintenance planing in dynamic contexts (varying deterioration rate of components, maintenance opportunities, etc.) [26, 15]. However, this approach cannot be directly applied for the maintenance optimization of a GDPS due to the geographical dependence between components and sites.

Another challenge concerns the maintenance routing problem. It is interesting to determine the optimal route that the maintenance team should follow to maintain several production sites. To solve this problem, several studies focus on finding the optimal route that minimizes the travel distance/travel cost, see for instance [16, 17, 19, 21]. Unfortunately, in the models proposed, the maintenance is usually considered as a constraint rather than the second optimization objective. Recently, papers [13, 22] try to integrate both maintenance planning and routing into a global model. However, in these works, the dependencies between components do not count. Therefore, the issue on joint consideration of maintenance scheduling and routing of GDPS with taking into account the component dependencies remains widely open.

To face with the above challenges, the paper is addressing a dynamic grouping maintenance approach well adapted for GDPS systems. Maintenance planning and maintenance routing are jointly studied in a global model, considering several types of dependencies between components and sites (economic and geographical dependencies). For this purpose, cost structures and dependencies modelling are formulated and used as a basis for the development of the global model. A combination of the Local Search Genetic Algorithm (LSGA) and Branch and Bound method (BAB) is implemented to optimize the proposed model and determine the optimal maintenance routes and schedules. Moreover, several dynamic contexts which may occur with time are also studied and integrated in the optimization process. Thanks to this consideration, the proposed approach allows updating optimally the grouped maintenance planning and routing in presence of the dynamic contexts.

In relation to the approach proposed, the remainder of this paper is organized as follows. Section 2 is devoted to describe general assumptions and problem statement. The maintenance cost structure and dependencies modelling and formulation are presented in Section 3. A maintenance grouping and routing approach is then developed for GDPS in Section 4. Some numerical examples are investigated to illustrate the use and the performance of the proposed approach in Section 5. Finally, the conclusions deduced from this work are presented in the last section.

2 General assumptions and problem statement

2.1 System description

We consider a GDPS consisting of several independent production sites geographically located far apart from each other. Each production site is supported by several machines whereby each machine is composed of a set of components. In this study, only several critical components for each site are investigated. Indeed, a component is considered as a critical once if (i) its failure leads to a shutdown of the corresponding production site and (ii) the component's failure occurrence without any preventive maintenance intervention is important. In this context, the maintenance plays an important role to keep the components' proper operation and also to avoid their failure. Both corrective and preventive maintenance actions are therefore considered.

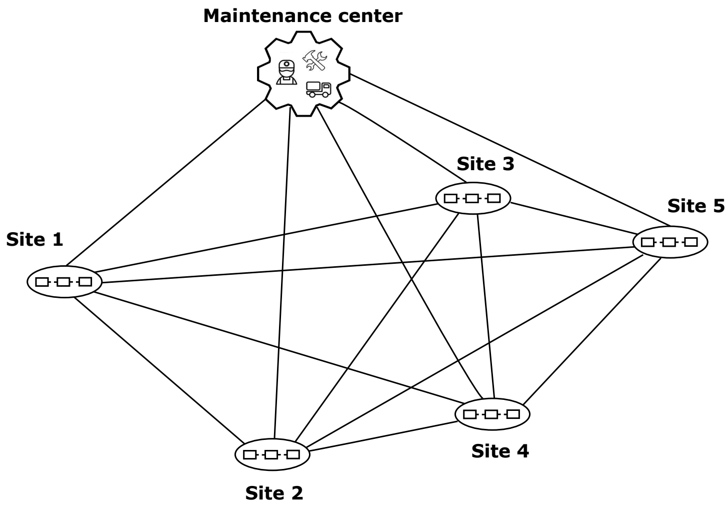

Figure 1: A typical GDPS containing 5 production sites and a centralized maintenance center

For corrective maintenance (CM), as all components are critical, if a component fails, it is necessary to repair it as soon as possible to bring the corresponding production site to an operating state. In that sense, it is reasonable to assume that immediate minimal repair actions are performed on the failed components and that each CM action restores the failed component to "as bad as old" state. All CM maintenance actions are done by a local maintenance team at each production site. The CM maintenance duration is short and can be neglected. To avoid the failure of components and sites, preventive maintenance (PM) actions are performed mainly on the critical components. Each PM action on a component brings the maintained component to be a new one (replacement action). All PM actions are done by a maintenance center team which may located far from production sites. This assumption is realistic because PM maintenance resources are centralized at one maintenance center that can save logistic and maintenance cots. In that way, to perform a PM action on a given component of a production site, the maintenance team and all necessary maintenance resources (spare part, maintenance tools, etc.) need to be transported from the maintenance center to the maintained production site. As an example, a typical GDPS system composed of five production sites and one maintenance center are shown in Figure 1. The connections between production sites and maintenance center represent the possible routes to be followed by the maintenance team.

From an economical point of view, when several components are jointly maintained, the total maintenance cost may be reduced because (i) the maintenance preparation cost related to logistic preparation (e.g, scaffolding erecting, machine opening, maintenance tools, etc) can be shared (economic dependence) and (ii) the total travel distance/cost can be reduced (geographical dependence).

Since CM actions are performed by a local maintenance team as soon as each component's failure occurs, the paper is addressing a maintenance approach well adapted in finding an optimal maintenance and routing plan for all preventive maintenance actions of a GDPS system. Of course, the impacts of such a CM action and its cost need to be considered in the proposed maintenance model, see Section 4.

2.2 Problem statement and assumptions

In the framework of maintenance optimization for "centralized" multi-component system, economic dependence between components is investigated and integrated in various maintenance models through setup cost which is the cost paid for all logistic preparation of each maintenance action [14, 5]. In these maintenance models, single setup cost model (or identical setup cost) is used for all maintenance activities. This model cannot be directly applicable in the context of GDPS systems since the logistic preparation may be different for components located in different production sites. Moreover, as a characteristic of GDPS systems, geographical dependence, whereby the total travel distance/time can be reduced when several components are preventively maintained together, often exists between components. The latter need to be modelled and considered in the maintenance optimization process.

Concerning maintenance approaches, dynamic grouping maintenance trying to group several components to be jointly maintained to reduce maintenance costs seems to be a promising maintenance approach for maintenance optimization of "centralized" multi-component systems since it can better take into account the economic dependence between components and allows updating a maintenance planing in a dynamic context [14, 5, 26, 15]. However, to develop such an approach for the maintenance of a GPDS system faces many challenges in modelling, formulation and optimization process to take in consideration of geographical dispersion between the production sites and the maintenance center. Indeed, given a number of possible maintenance routes (the itineraries that the maintenance team should follow to perform the preventive maintenance of one or several components which may be located in different production sites) with different impacts on the setup cost and maintenance dates, the maintenance routing should be considered in the development of the maintenance grouping approach. The joint consideration of maintenance grouping and routing makes the developed model become a hyper-complex one. The finding of the optimal grouping solution and optimal maintenance route from the developed model is a NP-complete optimization problem. The latter leads to implement an intelligent search algorithm.

In addition, due to the characteristics of a GDPS system, several following situations may happen with time in reality:

1. *Change of route and weather conditions:* the maintenance routes and/or travel durations between different sites/sites and maintenance center may be changed over time due to specific reasons such as failure of a maintenance team's vehicles, bad weather conditions, or interruption of specific routes between production sites and maintenance center [23, 24];
2. *Change of transportation capacity:* the transportation means may be changed due to economic and/or technical reasons, e.g., failure or replacement of a vehicle with lower or higher capacity [23, 24].

These kinds of the above situations, referred to "dynamic contexts" in this paper, may have significant impacts on the maintenance planning and routing. In the presence of such a dynamic context, the current maintenance grouped plan and maintenance route may be no longer optimal ones and need to be updated. The proposed maintenance grouping and routing approach should be a dynamic one which allows considering the impacts of a dynamic context and optimally updating the maintenance plan and route when the dynamic context occurs. In addition, according to different types of dynamic contexts, an appropriate updating process needs to be developed.

To answer these above scientific issues, the main objective of the paper is to develop a dynamic maintenance grouping and routing approach for a GDPS system. The proposed approach allows considering both economic and geographical dependencies between components, the impacts of maintenance routing on the grouping performance, and also the impacts of a dynamic context that may occur with time.

To develop our grouping and routing maintenance approach, the following additional assumptions are considered:

- Only several critical components are considered in each production site;
- Interruption of a production site does not impact the normal operation of the others;
- Only one maintenance team (repairman) of the maintenance center located far form production sites is considered;
- The maintenance team and necessary resources are always available and ready for all planned preventive maintenance actions;
- A specific repairman skill is required to perform the preventive maintenance of each component;
- Minimal repair CM actions with negligible duration are executed by local maintenance team.

3 Costs structures and dependencies modeling

3.1 Maintenance cost structure

As mentioned above, to do the PM of a component, the maintenance team and spare part have to be transported from the maintenance center to the production site where the component is located on. The transportation costs should be included in the PM cost. Let C_i^p denote the cost of a PM action of component i located at site j.

$$C_i^p = C_i^{sp} + C_{ij}^{dt} + C_i^{lb} + S_{ij}^0 + S_i^{tr}, \tag{1}$$

where,

- Spare part cost, C_i^{sp}, is the cost of buying a new component which is used to replace the old one;
- C_{ij}^{dt} denotes the downtime cost which occurs when site j is stopped during the maintenance of component i. C_{ij}^{dt} can be calculated as $C_{ij}^{dt} = R_j^{dt} \cdot \omega_i$, where R_j^{dt} and ω_i are respectively the downtime cost rate of site j and the PM duration of component i;
- Labor cost C_i^{lb} is paid for the related works of maintenance team. It is reasonable to consider that the higher the repairman skill is required, the more expensive the labor cost is. In this way, $C_i^{lb} = R^{lb}(l_i) \cdot \omega_i$, where $R^{lb}(l_i)$ is the labor cost rate associated with the required repairman skill level l_i. This skill level is the lowest one that guarantees the success of the PM action on the component;
- Site-preparation cost, S_{ij}^0, is associated with preparation tasks at site j such as scaffolding erecting, machine opening, etc. S_{ij}^0 can be shared when several components of the same site are preventively maintained together. Note that the site-preparation cost may be different for different components located in the same site or even for identical components located in the different sites;
- Transportation cost, S_i^{tr}, is paid for the transportation of spare parts, repair tools and repair team from the maintenance center to the maintenance site j. Let L_{0j} and L_{j0} be the travel distances from the maintenance center (denoted by "0") to site j and back again respectively, the transportation cost can be calculated as $S_i^{tr} = R^{tr} \cdot (L_{0j} + L_{j0})$, where R^{tr} is the transportation cost rate. When several components are jointly maintained, S_i^{tr} can be reduced.

3.2 Dependencies modelling and formulation

Consider a group of several components G^k, the economic dependence between the components indicates that the PM cost of the group ($C^p_{G^k}$) is not equal to the total PM cost of all the components in isolation, i.e. $C^p_{G^k} \neq \sum_{i \in G^k} C^p_i$.

In literature, most of grouping maintenance models developed for "centralized" multi-component systems consider that the economic dependence comes from the saving of the setup cost $\Delta S^0_{G^k}$, and the penalty cost ΔH_{G^k} related to: *(a)* the reduction of components useful life if the maintenance dates are advanced; *(b)* the increase of component failure probability if the maintenance dates are postponed (see [14] for more details). Consequently, we have:

$$C^p_{G^k} = \sum_{i \in G^k} C^p_i - \Delta S^0_{G^k} + \Delta H_{G^k} \tag{2}$$

From this model, in the case of GDPS system, it is necessary to extend it with regards to both geographical dependence and the repairman skill required for each preventive maintenance actions. More precisely:

- Labor cost penalty $\Delta C^{lb}_{G^k}$. When components are jointly maintained, the maintenance team needs to complete all the maintenance tasks associated with the components group . Therefore, a polyvalent skill may be required. As consequence, the labor cost may be directly penalized.
- Transportation cost saving $\Delta S^{tr}_{G^k}$. It should be noticed that to replace an individual component, the maintenance team has to travel from the maintenance center to the maintenance site where the component is located on, and then come back to the maintenance center when the maintenance is completed. Otherwise, to do the PM on a group of several components, the maintenance team replaces sequentially all components of the group and returns to the maintenance center only when the maintenance of all the group's components is completed. The travel distance and travel time are reduced due to the geographical dependence between the components.

For these above reasons, in the frame of a GDPS, the equation (2) should be rewritten as follows:

$$C^p_{G^k} = \sum_{i \in G^k} C^p_i - \Delta S^0_{G^k} + \Delta H_{G^k}(I_{G^k}) + \Delta C^{lb}_{G^k} - \Delta S^{tr}_{G^k}(I_{G^k}) \tag{3}$$

In the above equation, the penalty cost ΔH_{G^k} and the transportation cost saving $\Delta S^{tr}_{G^k}$ are introduced as the functions of the maintenance route (I_{G^k}), because it has direct impacts on the PM dates of components and on the travel distance of the maintenance team. For more explanation, let's consider the example in Figure 2. Assume that three components located in three different sites 1, 2 and 3 are preventively maintained together. To perform jointly the PM actions of the three components, the maintenance team can follow different maintenance routes from the maintenance center (MC): MC$\rightarrow$ 1 $\rightarrow$ 3 $\rightarrow$ 2 $\rightarrow$ MC (Figure 2a), MC$\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 1 $\rightarrow$ MC (Figure 2b), and MC $\rightarrow$ 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ MC (Figure 2c). It is clear that, with the same departure time from the maintenance center t_{G^k}, the arrival times at each site and the travel distance of the maintenance team depend on the selected maintenance route (see Figures 2a and 2c). In addition, it should be noted that, in figures 2a and 2b, two different maintenance routes with the same travel distance can lead to different arrival times, in other words, different executed PM dates. The latter may impact the penalty cost which depends strongly on the change of executed PM dates.

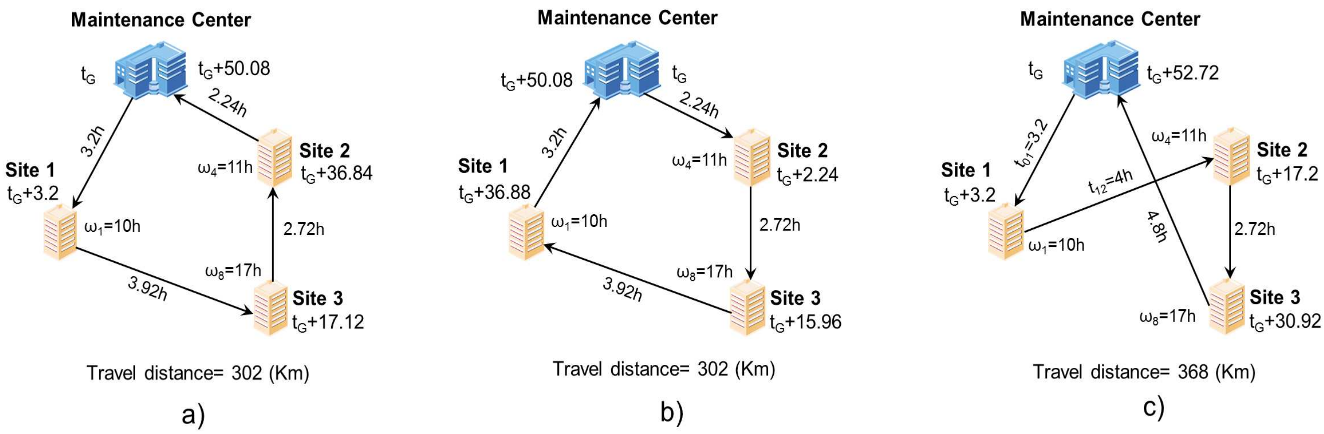

Figure 2: Impacts of maintenance routes on the PM dates and travel distance

Given these above impacts of maintenance routes on the grouping performance, the maintenance routing optimization need to be jointly considered with the maintenance planning optimization.

The cost model for joint preventive maintenance of several components shown in Equation (3) is used to calculate the total cost of a maintenance planning within a given horizon. The detailed description is presented in Subsection 4.3.

4 Dynamic maintenance grouping and routing approach for GDPS

The proposed approach is structured in 4 phases supporting both the maintenance grouping and routing planning (see Figure 3). In the first phase, the PM cycle/interval of each component is determined by minimizing its long-term maintenance cost rate (see Section 4.1). This PM cycle is then used to determinate the individual PM dates of each component in the planning horizon in phase 2 (see Section 4.2). In the third phase, the economic profit associated with the joint preventive maintenance of a group of components is firstly formulated based on the individual PM dates obtained in the previous phase. Optimization tools such as Local Search Genetic Algorithm and Brand and Bound are then applied to find the best grouping solution GS^* (a set of exclusive groups), the optimal PM date of each group in GS^*, and the optimal maintenance routes of each group in GS^*. The best grouping structure is found by maximizing the total grouping economic profit in the considered horizon (see Section 4.3). Finally, the last phase is devoted to update the maintenance grouping and routing planning when (i) occurring a dynamic information related to maintenance resources or traffic conditions impacting the current maintenance grouping and routing planning, or (ii) a new planning horizon is needed (rolling horizon), see Section 4.4.

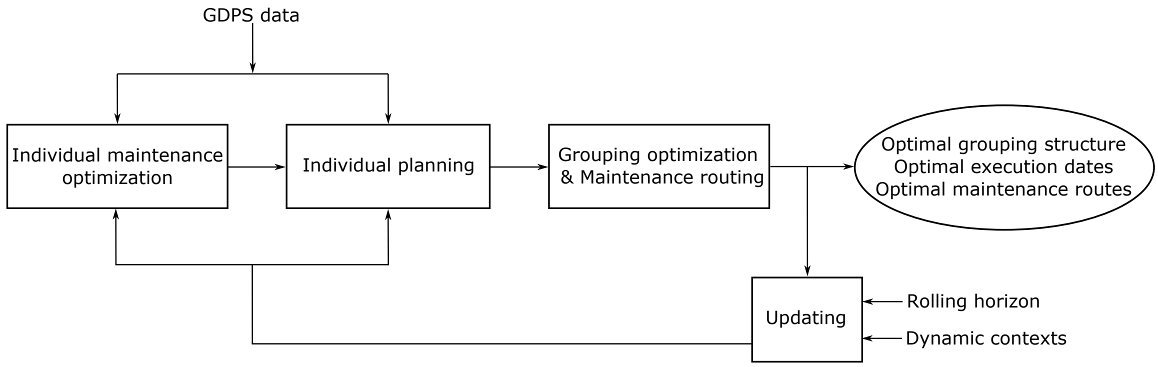

Figure 3: Dynamic grouping and routing for the maintenance of GDPS

4.1 Individual maintenance optimization

The objective of this phase is to determine the optimal PM cycle of each component, which minimizes its long-term maintenance cost rate. Without loss of generality, Weibull distribution law is herein used as an example to model the components' failure behavior. The failure rate of component i, denoted $r_i(t)$, is given as follows

$$r_i\left(t\right) = \frac{\beta_i}{\lambda_i}\left(\frac{x}{\lambda_i}\right)^{\beta_i - 1} \tag{4}$$

where, $\lambda_i(\lambda_i > 0)$ and $\beta_i(\beta_i > 1)$ are scale and shape parameters respectively.

It is assumed that component i is preventively replaced at every x_i time unit. Its long-term maintenance cost rate can then be calculated as

$$\phi_i(x_i) = \lim_{t \to +\infty} \frac{C_i(t)}{t} = \frac{C_i^p + C_i^c \cdot \int\limits_0^{x_i} r_i(t)dt}{x_i + w_i} = \frac{C_i^p + C_i^c \cdot \left(\frac{x_i}{\lambda_i}\right)^{\beta_i}}{x_i + w_i}. \tag{5}$$

where:

- $C_i^c \cdot \int\limits_0^{x_i} r_i(t)dt$ is the average corrective cost of component i within the period $[0\ x_i]$;
- $C_i(t)$ is the cumulative CM and PM maintenance costs of component i until t;

- ω_i denotes the PM duration of component i.

The optimal PM cycle of component i, denoted x_i^*, can be then determined by solving the following equation

$$x_i^* = \arg\min_{x_i} \phi_i(x_i) \Longrightarrow \left.\frac{d\phi_i(x_i)}{dx_i}\right|_{x_i=x_i^*} = 0 \Longleftrightarrow \tag{6}$$
$$C_i^c \cdot (\beta_i - 1) \cdot (x_i^*)^{\beta_i} + C_i^c \cdot \beta_i \cdot \omega_i \cdot (x_i^*)^{\beta_i - 1} - C_i^p \cdot \lambda_i^{\beta_i} = 0$$

The minimum maintenance cost rate is $\phi_i^* = \phi_i(x_i^*)$.

4.2 Individual planning

The objective of this step is to build an individual maintenance plan in a finite planning horizon $PH = [t_{begin}, t_{end}]$ based on the optimal PM cycle obtained in the previous step. To do this, the first PM date of each component i in the planning horizon is calculated as $t_{i^1} = x_i^* + t_{begin} - t_i^e$, where t_i^e is the total operational time of component i elapsed from the last replacement. The execution date of the m^{th} PM of component i ($m > 1$) in the planning horizon is $t_{i^m} = t_{i^{m-1}} + x_i^* + \omega_i^\Sigma$, where ω_i^Σ is the cumulative downtime of component i within interval $[t_{i^{m-1}}, t_{i^m}]$. The downtime can result from the PM maintenance of other components located on the same site. It is shown in [14, 26] that to ensure all components are taken into account in the maintenance decision, the planning horizon should be chosen in the way that each component is preventively carried out at least one time within the planning horizon. Therefore, $t_{end} = (t_{j^1} + \omega_j)$ with $t_{j^1} = \max_{i=1:n} t_{i^1}$.

It should be noticed that the individual PM dates of the tentative plan have to be redetermined when the next planning horizon is considered, or when short-term information (e.g., in presence of a dynamic context, maintenance opportunities, etc.) occurs. In the next subsection, these individual PM dates will be modified such that they can be jointly executed to reduce the maintenance cost.

4.3 Grouping optimization and maintenance routing

The objective of this step is to find the optimal way to group the above individual PM dates, which maximizes the grouping economic profit in the planning horizon. Moreover, in the GDPS context, the components of a group may be located in the different sites. So, the finding of the optimal maintenance routes that minimize the travel distance of the maintenance team is an important issue to be solved. For these objectives, the maintenance grouping and routing model as well as optimization methods are presented in the next subsections.

4.3.1 Concept of maintenance group and economic profit formulation

Grouping concept Let's firstly consider a group G^k of several components, which are tentatively maintained at their individual PM dates t_{i^m} with $i \in G^k$. To be jointly maintained, each component of the group may be maintained earlier or latter regarding to its tentative PM date. Let t'_{i^m} indicate the executed PM date of component i (t'_{i^m} may differ from t_{i^m}). To perform the components group, the maintenance team needs to go from the maintenance center to all the maintained sites by following a specific route before coming back to the maintenance center. The maintenance route prescribes the sequence of the sites that the maintenance team has to follow. A large number of possible routes usually exist that across all the maintenance sites with different travel distances. Let t_{G^k} denote the time that the maintenance team leaves the maintenance center (departure time) to maintain group G^k, and $I_{G^k}(j) = v$ means that with respect to the route I_{G^k}, site j is visited by the maintenance team at the v^{th} order.

- If $I_{G^k}(j) = 1$, the maintenance team will visit first site j after leaving the maintenance center. The maintenance team will arrive at site j at $TAS_j = t_{G^k} + d_{0j}$, where d_{0j} is the travel time from the maintenance center to site j. TAS_j is also the grouped PM date of components of group G^k located at site j: $t'_{i^m} = TAS_j$. The maintenance team will leave site j at time $TLS_j = TAS_j + \sum_{i \in G^k \text{and site } j} \omega_i$, and move to the next maintenance site.
- If $I_{G^k}(j) = v > 1$, the maintenance team will visit site j at the v^{th} order. The actual PM dates of components of group G^k located on site j are then $t'_{i^m} = TLS_q + d_{qj}$, where q is the site that the maintenance team has previously visited at the $(v-1)^{\text{th}}$ order.

From the above analysis, each maintenance group G^k is characterized by the four following parameters: components of group, departure time of the maintenance team t_{G^k}, and maintenance route I_{G^k} as well as the repairman skill level.

Economic profit of group G^k. According to equation 3, the economic profit of group G^k, denoted by EPG_{G^k}, can be determined as:

$$EPG_{G^k}(t_{G^k}, I_{G^k}) = \sum_{i \in G^k} C_i^p - C_{G^k}^p = \Delta S_{G^k}^0 + \Delta S_{G^k}^{tr}(I_{G^k}) - \Delta H_{G^k}(I_{G^k}) - \Delta C_{G^k}^{lb} \tag{7}$$

Now we have to calculate each part of the economic profit.

- The site-preparation cost saving $\Delta S_{G^k}^0$. This saving exists when several components of the same site are jointly maintained. Let nc_i^k denote the number of components of group G^k located on site i, and ns_k denote the number of sites containing, at least, one component of group G^k. If the preparation tasks at a site i are the same for the PM of a component as for a group of components located on the site, $S^0_{ij} = S^0_{ik} = S^0_i$, the site-preparation cost saving can be then calculated by the following equation:

$$\Delta S^0_{G^k} = \sum_{i \in G^k} S^0_{ij} - S^0_{G^k} = \sum_{i=1}^{ns_k} S^0_i \cdot (nc^k_i - 1) \tag{8}$$

- The transportation cost saving $\Delta S^{tr}_{G^k}(I_{G^k})$. This saving comes from the reduction of the travel distance of the maintenance team. Let $L_{G^k}(I_{G^k})$ denote the total travel distance when the maintenance team follows the maintenance route I_{G^k}. We have:

$$\Delta S^{tr}_{G^k}(I_{G^k}) = \sum_{i \in G^k} R^{tr}_i \cdot (L_{0j} + L_{j0}) - R^{tr}_{G^k} \cdot L_{G^k}(I_{G^k}) \tag{9}$$

where $R^{tr}_{G^k}$ denotes traveling cost rate for the PM of group G^k. Without loss of generality, it is assumed that $R^{tr}_i = R^{tr}_{G^k} = R^{tr}$. The transportation cost saving can be then rewritten as follows:

$$\Delta S^{tr}_{G^k}(I_{G^k}) = R^{tr} \cdot \Big[\sum_{i \in G^k} (L_{0j} + L_{j0}) - L_{G^k}(I_{G^k}) \Big] \tag{10}$$

- The penalty cost $\Delta H_{G^k}(t_{G^k}, I_{G^k})$. This penalty cost occurs due to the changes of the PM dates from the tentative ones t_{i^m} to the grouped ones t'_{i^m} and depends on both the departure time t_{G^k} and maintenance route of the repair team. The penalty cost can be calculated as, [14]:

$$H_{G^k}(t_{G^k}, I_{G^k}) = \sum_{i^m \in G^k} \Big[C^c_i \cdot [(\frac{age_i(t'_{i^m})}{\lambda_i})^{\beta_i} - (\frac{age_i(t_{i^m})}{\lambda_i})^{\beta_i}] - (t'_{i^m} - t_{i^m}) \cdot \phi^*_i \Big] \tag{11}$$

where, $age_i(t)$ denotes the total operational time of component i until t.

- The labor cost penalty $\Delta C^{lb}_{G^k}$ can be expressed as:

$$\Delta C^{lb}_{G^k} = R^{lb}_{G^k} \omega_{G^k} - \sum_{i \in G^k} R^{lb}_i \cdot \omega_i \tag{12}$$

where ω_{G^k} is the maintenance duration of group G^k. If only one maintenance team is considered, it is then reasonable to assume that $\omega_{G^k} = \sum_{i \in G^k} \omega_i$.

Economic profit of a grouping structure. A grouping structure is defined as a collection of mutually exclusive groups $GS = \{G^1, G^2, ., G^{ng}\}$ satisfying the two following conditions: $G^1 \cap G^2 \cap \ldots \cap G^{ng} = \varnothing$ and $G^1 \cup G^2 \cup \ldots \cup G^{ng}$ covers all individual maintenance activities in the planning horizon. The total economic profit of a grouping structure GS can be calculated as:

$$EPS(GS) = \sum_{G^k \in GS} EPG_{G^k}(t_{G^k}, I_{G^k}) \tag{13}$$

$EPS(GS)$ represents the performance of grouping structure GS. The grouping performance depends on grouping structure (GS), departure time of the maintenance team (t_{G^k}) and maintenance route (I_{G^k}) to maintain each group G^k of GS.

4.3.2 Maintenance grouping and routing optimization

The issue to be solved at this step is how the optimization tools can be implemented to support the grouping and routing optimization problem, which is defined as:

$$(GS^*, t^*_{G^k}, I^*_{G^k}) = \underset{GS, t_{G^k}, I_{G^k}}{\arg\max} \sum_{G^k \in GS} EPG_{G^k}(t_{G^k}, I_{G^k}) \tag{14}$$

A combination of the Local Search Genetic Algorithm (LSGA) and Branch and Bound method (BAB) is proposed in this paper as an intelligent search approach to find the optimal grouping structure (GS^*), and the optimal maintenance routes $I^*_{G^k}$ (Figure 4). It should be noticed that the joint consideration of LSGA and BAB is well adapted for the GDPS problem because it allows reducing the search space of potential solutions (GS^* and $I^*_{G^k}$).

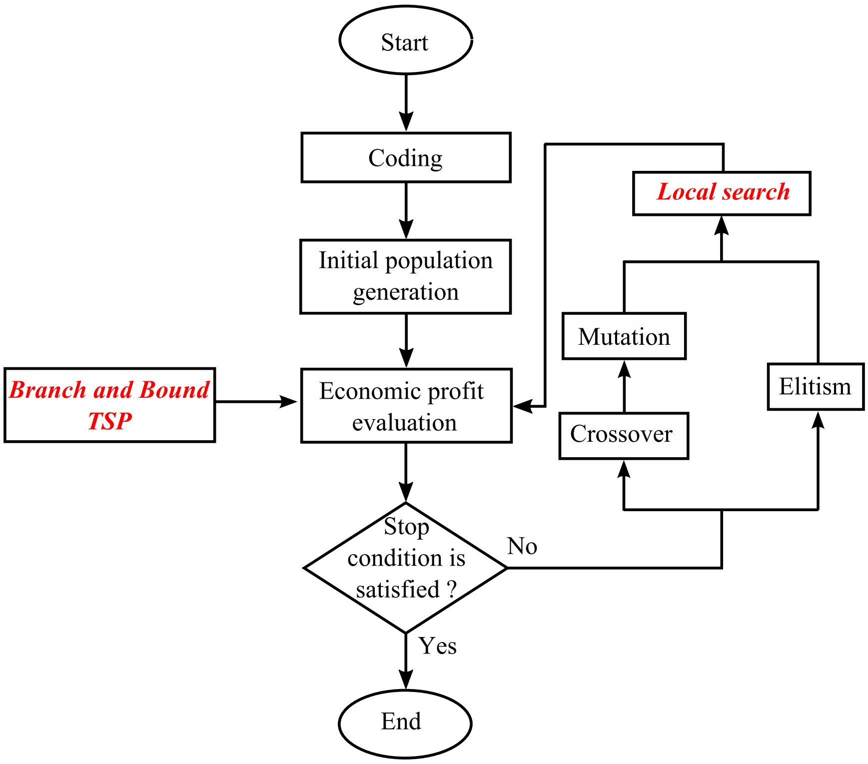

Figure 4: The principle of LSGA for the maintenance grouping and routing optimization problem

GA starts by randomly creating a set of possible grouping structures. At each GA's iteration, the grouping structures are compared based on their total economic profit (EPS). The relevant grouping structures with higher economic profits will be saved and improved by applying genetic operations such as crossover, mutation, and elitism. GA is stopped when stopping criteria such as the maximum iteration number is reached.

It should be noted that, at each iteration of GA, the calculation of the total economic profit of a specific grouping structure is not evident. Indeed, with the same grouping structure, the economic profit values can be different depending on the choice of departure times of the repair team, and the choice of maintenance routes. Consider a specific group G^k of grouping structure GS, BAB algorithm should be applied to find the optimal maintenance route ($I^*_{G^k}$).

Remember that BAB algorithm may provide a set of routes, denoted SI_{G^k}, with the same shortest travel distance, but the grouped PM dates of components are not the same (See again the example in Figure 2). That is the reason why the Local Search is integrated into the GA to search the best route among SI_{G^k}. The special settings of BAB and LSGA for the maintenance grouping and routing optimization problem are presented in annexes A and B.

4.4 Update and rolling horizon

The optimal grouping structure and maintenance routes obtained from the previous step need to be updated according to one of the two following reasons:

1. *in presence of a dynamic context:* As mentioned before, a dynamic item such as change of maintenance routes, change of transportation capacity or change of components characteristics (see again Section 2.2) may occur with time. In presence of such a dynamic context, the current grouping structure may no longer be the optimal one or even unusable. An adaptive maintenance planning is needed. To integrate such a dynamic context, we need to go back to "Individual planning" step and so on. A detailed illustration is presented in Subsection 5.4.

2. *at the end of the current planning horizon:* A new maintenance planning for the next horizon is needed. New horizon can be constructed based on new required missions' interval. For this purpose, the rolling horizon procedure is used by going back to phase 2 of the optimization scheme to redefine all preventive maintenance activities in the new individual planning horizon and so on. The rolling horizon updating is illustrated in Subsection 5.4.

5 Numerical examples

The aim of this section is to show how the proposed grouping and routing approach can be used for the maintenance planning and maintenance updating of a GDPS with generated data, and to verify its performance in different maintenance cost settings.

5.1 Given data

Consider a typical GDPS in Figure 1 containing 5 geographically dispersed sites, and one maintenance center located far from these sites. The detailed distances between sites and between sites and maintenance center (MC) are given in Table 1. It should be noticed that, in this study, all parameters are given in arbitrary units, e.g., arbitrary time unit (atu), arbitrary distance unit (adu) or arbitrary cost unit (acu).

The average speed in moving of the maintenance team is $AS = 25$ (adu)/(atu). The travel time then can be easily determined by dividing the travel distance by the average speed, i.e. $d_{ij} = L_{ij}/AS$. The transportation cost rate is considered to be the same for all components $R_i^{tr} = R^{tr}$, and is equal to 18 (acu/adu).

Table 1: Travel distances between the production sites and their maintenance center

Site	MC	1	2	3	4	5
MC	-	80	56	120	131	152
1	80	-	100	98	87	250
2	56	100	-	68	103	154
3	120	98	68	-	54	161
4	131	87	103	54	-	209
5	152	250	154	161	209	-

For each site, 3 main critical components are considered in this study. The main characteristics related to the components site, the down time cost rate (R_j^{dt}) and the preparation cost (S_j^{Site}) are given in Table 2.

Table 2: Components, downtime cost rate and site-preparation cost of each production site

Site	1	2	3	4	5
Component	1, 2, 3	4, 5, 6	7, 8, 9	10, 11, 12	13, 14, 15
R_j^{dt}	295	315	348	364	206
S_j^{Site}	200	160	120	80	160

Table 3: Components' data and individual maintenance optimization results

Component	λ_i	β_i	C_i^{sp}	C_i^c	w_i	t_i^e	l_i	S_i^{tr}	x_i^*	ϕ_i^*	t_{i^1}
1	2497	2.86	1745	568	10	1401	1	2880	5229.2	2.5727	3828.2
2	3258	2.76	2526	672	16	2730	2	2880	7868.4	2.6872	5169.4
3	2422	3.71	3250	632	21	782	3	2880	4613.7	5.5512	3841.7
4	2812	2.86	1845	676	9	2421	1	2016	5307.7	2.2411	2886.7
5	3507	2.73	2626	732	15	2656	2	2016	8110.5	2.4302	5485.5
6	2322	3.68	3407	625	22	1139	3	2016	4491.4	5.8042	3361.4
7	2649	2.81	1695	514	11	3278	1	4320	6387.2	2.6818	3109.2
8	3059	2.75	2325	552	17	3807	2	4320	8495.8	2.9651	4723.8
9	2623	3.55	3325	601	24	1041	3	4320	5637.8	5.7239	4607.8
10	2448	2.89	1645	449	10	2506	1	4716	5950.3	2.8403	3466.3
11	2962	2.73	2456	642	15	3004	2	4716	7808.9	3.1655	4836.9
12	2328	3.72	3325	685	22	1159	3	4716	4552.3	6.7836	3393.3
13	2697	2.86	1645	697	12	1556	1	5472	5680.5	2.9542	4141.5
14	3358	3.13	2426	612	17	3604	2	5472	7314.8	2.9951	3710.8
15	2482	3.64	3525	315	24	819	3	5472	6040.8	4.8354	5250.8

The data related to each component such as the shape and scale parameters of Weibull distribution, the spare part cost, the CM cost, PM time, the age at t_{begin} as well as the repairman skill level are all reported in Table 3.

Finally, the labor cost rates R^{lb} are fixed at 100, 200, 300 (acu) regarding to the required skill levels $l_i = 1$, $l_i = 2$ and $l_i = 3$ respectively.

5.2 Optimal maintenance grouping and routing

The proposed grouping and routing approach is applied for the maintenance grouping and route scheduling of the considered GDPS. The results obtained from the individual maintenance planning, grouping maintenance planning and maintenance routing are all reported in the following paragraphs.

Individual maintenance planning. The PM is assumed to be carried out separately for each component of the GDPS. The maintenance team has to go to the maintained site and go back again each time whenever a component of the site is preventively maintained. By using the equations 1, 4, 5, 6, the transportation cost (S_i^{tr}), the optimal PM cycle (x_i^*) and the minimum maintenance cost rate (ϕ_i^*) of each component are calculated and shown in Table 3. Based on the obtained PM cycle and given values of t_i^e, all individual PM dates are identified and reported in the same table.

In this example, each component is maintained only once in planning horizon $PH = [0, t_{5^1} + \omega_5] = [0, 5500.5]$ (atu). If this individual maintenance plan is used, the average maintenance cost that has to be paid is equal to:

$$\phi_{sys}^{individual} = \sum_{i=1}^{15} \phi_i^* = 56.2\ (acu) \tag{15}$$

It should be noted that the transportation and setup costs respectively take 18.82% and 19.06% of the above cost. The reduction of the two costs are then crucial from the economic point of views. The grouping maintenance is a promising solution to solve this problem.

Grouping maintenance planning. In order to reduce the setup and transportation costs, the individual PM activities determined in the previous phase are grouped. The joint use of LSGA and BAB is applied to find the optimal grouping structure. The obtained results are shown in Table 4 and Figure 5.

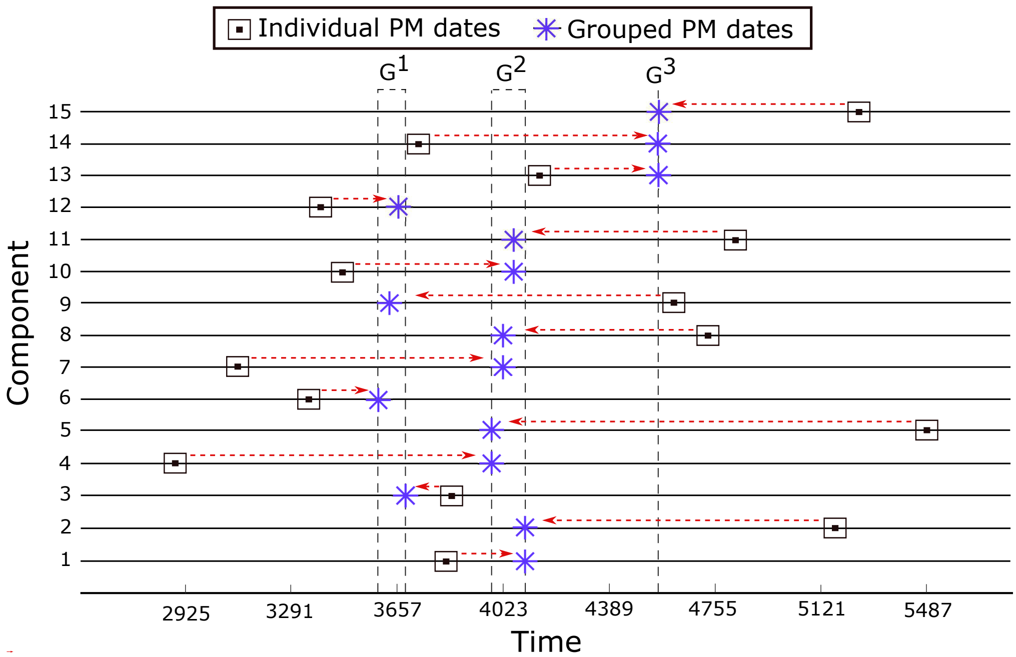

Figure 5: Individual maintenance plan and optimal grouped maintenance plan

Table 4: Optimal grouping structure and its economic profit

G^k of GS^*	ΔS_{tr}	ΔS_{Site}	ΔC_{lb}	H	EPG	EPS
$G^1 = \{3^1, 6^1, 9^1, 12^1\}$	7722	0	0	1385.7	6336.3	28592.2
$G^2 = \{1^1, 2^1, 4^1, 5^1, 7^1, 8^1, 10^1, 11^1\}$	21654	560	4000	2235.9	15978.1	
$G^3 = \{13^1, 14^1, 15^1\}$	10944	320	4100	886.2	6277.8	

The optimal grouping structure contains three groups. The components in each group are optimally selected to satisfy a number of factors such as the saving of transportation cost, the penalties related to PM execution and labor costs. Among these factors, the transportation cost saving takes the most important part (the highest value), and has the strongest impact on the composition of the groups. Indeed, the results in Figure 5 show that even the individual PM dates of components 13, 14, 15 of site 5 (the farthest site from the maintenance center) are not close to each other, these components are still grouped in a same group (group G^3). This is because the grouping of these components can help to significantly reduce the transportation cost. For this reason, the individual PM dates of components in an optimal group are not necessary to be close to each other as underlined by the other existing papers focusing on the grouping maintenance of centralized multi-component systems [14, 26]. From the economic point of view, the grouping maintenance plan helps to reduce 69.26% travel distance of the maintenance team as well as the transportation cost, and save up to 68.24% setup cost when compare to the individual maintenance. The reduction of travel distance is very important since it is not only meaningful from the economic point of view, but also sustainability one (reduce energy consumption, travel-related risks, environmental negative impacts). Along with the above advantages, the grouping maintenance also leads to some disadvantages and penalties. In fact, it makes the labor cost and the CM cost increase 14.70% and 259% respectively. Overall, the grouping maintenance helps to save up to 9.24% total maintenance cost when compare to the individual one. The average maintenance cost of the system, when the individual PM activities are grouped, is:

$$\phi_{sys}^{grouping} = \phi_{sys}^{individual} - \frac{EPS}{t_{end}} = 51.0\ (acu) \tag{16}$$

Maintenance route scheduling. To guarantee the above grouping performance, the maintenance team has to respect the optimal maintenance routes and the optimal departure times reported in Table 5.

Table 5: Optimal maintenance itineraries of the maintenance team

G^k of GS^*	Departure time ($t^*_{G^k}$)	Optimal maintenance route $I^*_{G^k}$	$L^*_{G^k}$
$G^1 = \{3^1, 6^1, 9^1, 12^1\}$	3649.4	MC $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 4 $\rightarrow$ 1 $\rightarrow$ MC	345
$G^2 = \{1^1, 2^1, 4^1, 5^1, 7^1, 8^1, 10^1, 11^1\}$	3972.0	MC $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 4 $\rightarrow$ 1 $\rightarrow$ MC	345
$G^3 = \{13^1, 14^1, 15^1\}$	4585.6	MC $\rightarrow$ 5 $\rightarrow$ MC	304

According to the obtained results shown in Table 5, for example, to perform the PM of group G^1, the maintenance team has to start from the maintenance center at 3649.4 (atu), then travels across the sites 2, 3, 4, 1, and returns to the maintenance center. The total travel distance of the round trip is equal to 345 (adu). When compared to the individual maintenance, the total travel distance is saved up to 55.42%. It should be noted that this optimal maintenance route is determined by the two following steps: the BAB is firstly looking for the shortest travel route (MC$-2-3-4-1-$MC), the

LSGA then decides in which direction the maintenance team has to go on. The saving of the group equals 6336.3 and 6291.2 with respect to the two directions (MC $\rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1 \rightarrow$ MC) and MC ($\leftarrow 2 \leftarrow 3 \leftarrow 4 \leftarrow 1 \leftarrow$ MC) respectively. The final decision is then to go on the first direction.

Consider group G^2, with the same optimal maintenance route as group G^1, the travel distance as well as transportation cost can be saved up to 77.71%. Finally, for group G^3 containing 3 components of the same site number 5, the maintenance team has to go to the site only one time instead of three. The travel distance and transportation cost are then reduced about 66.67% thanks to the grouping of these PM activities.

5.3 Sensitivity analyses

As mentioned before, the main intent of grouping maintenance is to save the transportation and setup costs. The grouping performance then strongly depends on the transportation cost rate and site-preparation cost.

5.3.1 Sensitivity analysis to the transportation cost rate

The aim of the subsection is to study the impact of transportation cost rate (R^{tr}) on grouping optimization process. To do this, the proposed grouping strategy is applied for different cases where the transportation cost rate is varied from 10 to 100 (acu), while the other given data remain unchanged. The case where $R^{tr} = 0$ is not considered because it rarely occurs in real life.

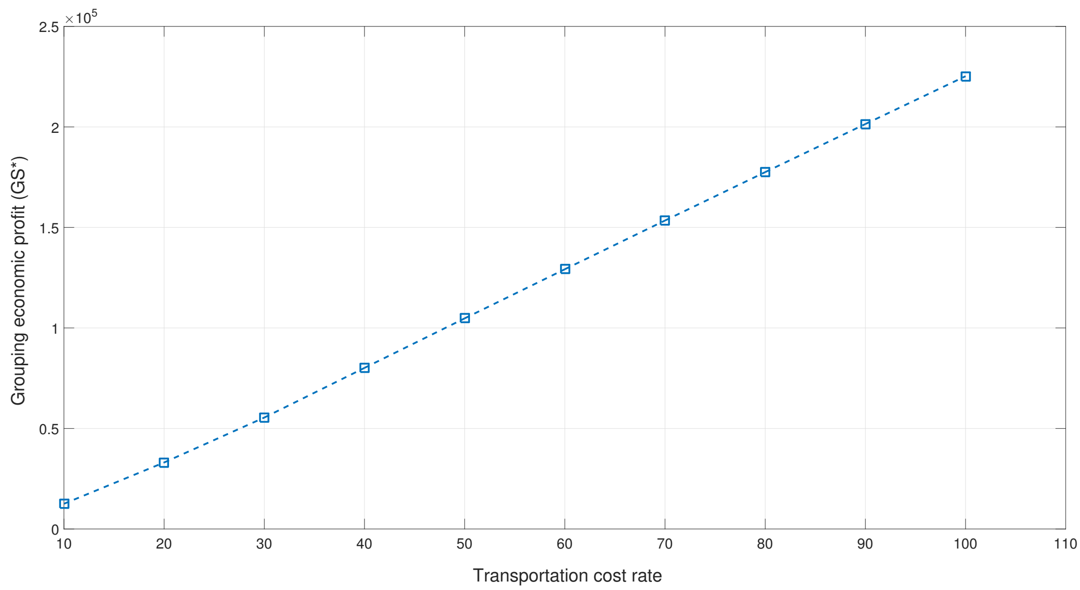

Figure 6: Sensitivity analysis of grouping economic profit to transportation cost rate

The evolution of grouping economic profit when the transportation cost rate increases from 10 to 100 is plotted in Figure 6. The obtained results show that the bigger the transportation cost rate is, the higher the grouping economic profit is given. The grouping maintenance is therefore recommended for the GDPS with high transportation cost rates.

In addition to the grouping performance, the optimal grouping structure is also studied and reported for different values of transportation cost rate in Table 6. From the table, we can observe that when the transportation cost rate increases, the optimal grouping structure is configured such that the saving of the travel distance is maximal.

Table 6: Sensitivity analysis of grouping structure to transportation cost rate

R^{tr}	GS^*	Distance saving
$(0, 10]$	$G^1 = \{1^1, 4^1, 7^1, 10^1\}$ $G^2 = \{3^1, 6^1, 9^1, 12^1, 13^1, 14^1, 15^1\}$ $G^3 = \{2^1, 5^1, 8^1, 11^1\}$	1952
$(10, 30]$	$G^1 = \{3^1, 6^1, 9^1, 12^1\}$ $G^2 = \{11^1, 2^1, 4^1, 5^1, 7^1, 8^1, 10^1, 11^1\}$ $G^3 = \{13^1, 14^1, 15^1\}$	2240
$(30, 100]$	$G^1 = \{1^1, 2^1, 3^1, 4^1, 5^1, 6^1, 7^1, 8^1, 9^1, 10^1, 11^1, 12^1\}$ $G^2 = \{13^1, 14^1, 15^1\}$	2585

5.3.2 Sensitivity analysis to the site-preparation cost

The same study is carried out by varying the site-preparation cost from 0 to 500 (acu). Note that in this study, the site-preparation cost is considered to be the same for all sites, for all components, and denoted by S^0. The proposed grouping strategy is applied for each value of the site-preparation cost. The obtained results are presented in Table 7 and Figure 7.

Table 7: Sensitivity analysis of grouping structure to site-preparation cost

Site-preparation cost	GS^*	Site-preparation cost saving
$[0, 200]$	$G^1 = \{3^1, 6^1, 9^1, 12^1\}$ $G^2 = \{1^1, 2^1, 4^1, 5^1, 7^1, 8^1, 10^1, 11^1\}$ $G^3 = \{13^1, 14^1, 15^1\}$	$6.S^0$
$(200, 500]$	$G^1 = \{3^1, 6^1, 9^1, 12^1, 13^1, 14^1, 15^1\}$ $G^2 = \{1^1, 2^1, 4^1, 5^1, 7^1, 8^1, 10^1, 11^1\}$	$6.S^0$

The same conclusion as in the case of the transportation cost rate can be deduced from the obtained results. The bigger the site-preparation cost is, the higher the grouping performance is. The grouping maintenance is therefore a powerful solution for the maintenance planning of GDPS with high transportation or setup costs.

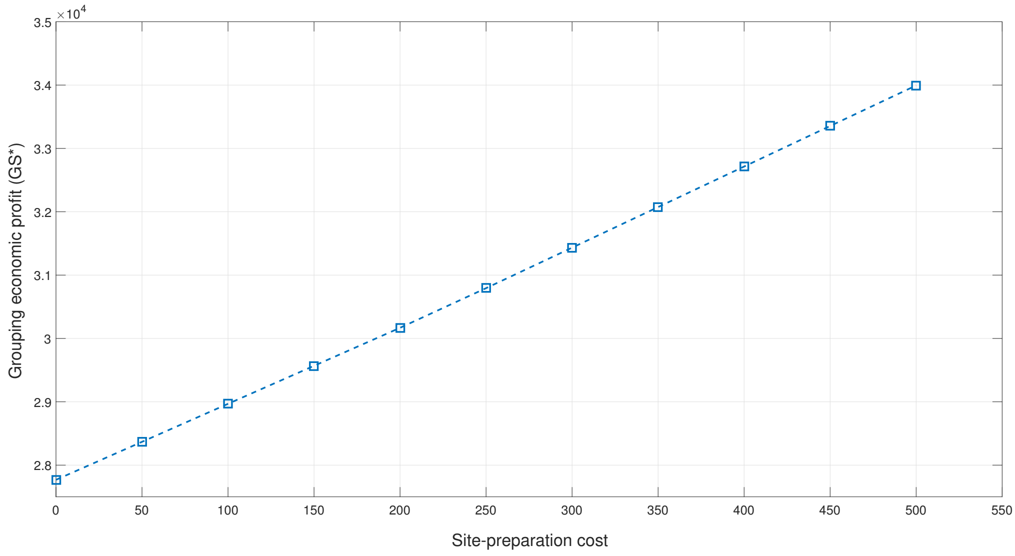

Figure 7: Sensitivity analysis of grouping economic profit to site-preparation cost

5.4 Grouping maintenance updating in dynamic contexts

The objective of this subsection is to present how the grouping maintenance plan can be updated when dynamic contexts occur. For this purpose, a dynamic context n^o 1 "Change of maintenance routes" (see again Section 2.2) is considered.

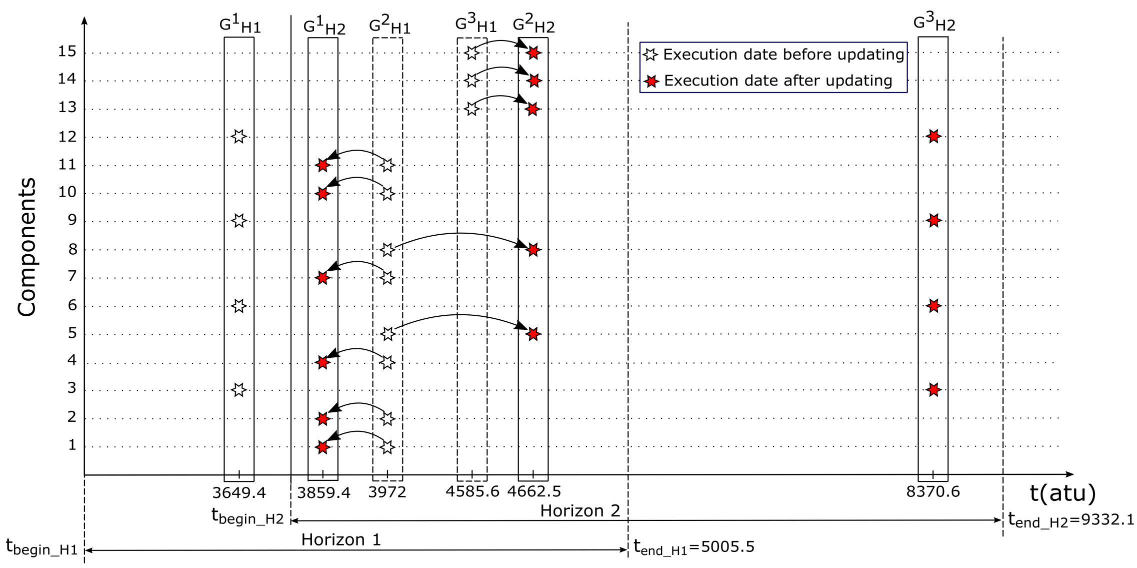

Figure 8: Grouping maintenance updating in the presence of a road interruption

Assume that the optimal grouping solution presented in Table 5 is selected. After the maintenance of group G^1, at 3849.4 (atu), the direct road between the maintenance center and site 5 is interrupted for a long period due to road maintenance activities. As a consequence, to go to site 5 from the maintenance center, the maintenance team has to travel on another road via site 2 with a longer distance. The travel distance of the new road is $L'_{05} = L_{02} + L_{25} = 210$ (adu). This means that a new logistic dependence between sites 2 and 5 occurs. In the presence of this situation, the current grouped maintenance planning and routing may be no longer optimal and need to be updated as soon as possible. To do this, the proposed grouping strategy is re-executed. The optimization process starts from the "Individual planning" step with a new horizon, namely H2, for which the beginning is equal to $t_{begin\_H2} = 3849.4$ (atu) and so on. At the end of the process, a new optimal grouped maintenance planning is provided and sketched in Figure 8. G^i_{Hj} indicates the group i of the horizon j. The maintenance routing results are shown in Table 8.

Table 8: Optimal maintenance itineraries after updating

G^k of GS^*	$t^*_{G^k}$	$I^*_{G^k}$	$L^*_{G^k}$
$G^1 = \{1, 2, 4, 7, 10, 11\}$	3859.4	MC $\to$ 2 $\to$ 3 $\to$ 4 $\to$ 1 $\to$ MC	345
$G^2 = \{5, 8, 13, 14, 15\}$	4662.5	MC $\to$ 2 $\to$ 5 $\to$ 3 $\to$ MC	491
$G^3 = \{3, 6, 9, 12\}$	8370.6	MC $\to$ 1 $\to$ 4 $\to$ 3 $\to$ 2 $\to$ MC	345

The new results underline that components 1, 2, 4, 7, 10, 11 are maintained sooner than before, while the maintenance of components 5 and 8 are postponed and grouped to group G^2_{H2}. From the logistic point of view, the new configuration of the group is reasonable. In fact, given the interruption of the direct road between the maintenance center and site 5, the maintenance team now starts from the maintenance center and then directly goes to site 2 instead of site 5. The solution with the direct connection between the maintenance center and site 5 no longer exists in the new grouping and routing solutions.

6 Conclusions

In this work, a dynamic maintenance grouping and routing for a geographically dispersed production system (GDPS) is proposed. The proposed approach provides simultaneously an optimal grouped maintenance planning and an optimal maintenance routing that the maintenance team has to follow during their maintenance works. The optimal solutions are reliable since the interactions between the maintenance planning and routing are jointly studied and integrated in the optimization process by proposing a combination of LSGA and BAB methods. Moreover, economic and geographical dependencies which have significant impacts on maintenance planing and routing are investigated and integrated in the proposed global maintenance model. Finally, several dynamic contexts which often occur in reality are also studied and make the proposed maintenance approach more flexible for real applications. To highlight the use and the advantages of the proposed grouping approach, a numerical example of a GDPS system consisting of 15 components located in five different sites is investigated. The obtained results show that the proposed maintenance strategy can help to reduce significantly the transportation and the preparation costs. The grouping performances have also been studied through different sensitivity analyses with different settings of the transportation cost rate and site-preparation cost. The dynamic grouping is then recommended for the maintenance planning of GDPS with high transportation and preparation costs from an economic point of view. Moreover, the ability to update the maintenance grouping and route plans in presence of a dynamic context.

This paper extends the development of our research in the framework of a grouping maintenance and routing for a GDPS system which has been presented partially in [2]. Our future research work will focus on the further investigations on the grouping maintenance planning and maintenance routing of GDPS with consideration of other dependencies such as stochastic and functional dependencies between components and sites.

Acknowledgements

The authors would like to thank the Government of Vietnam for its partial financial support to this research.

A Implementation of Branch and Bound

The most natural way to present the algorithm is to use search tree language. An example of the search tree for TSP with three sites and one maintenance center is shown in Figure 9. In the Figure, the root node (maintenance center) at the top of the tree represents the maintenance center, the nodes at level one represent all the sites that could be visited first (node 1, node 2, and node 3), the nodes at level two represent all the sites that could be visited in second (node 4, node 5, node 6, and node 7), etc. Generally, the horizontal set of all nodes at level v is denoted by HN_v. Otherwise, the vertical set of nodes, denoted $VN_{a \to b}$, represents an entire route ($a \equiv b \equiv 0$) or a part of route from node a to node b. For example, in Figure 9, $VN_{0 \to 8}$ denotes the part of route where the maintenance team travels from the maintenance center to node 3, node 6, and node 8 consecutively.

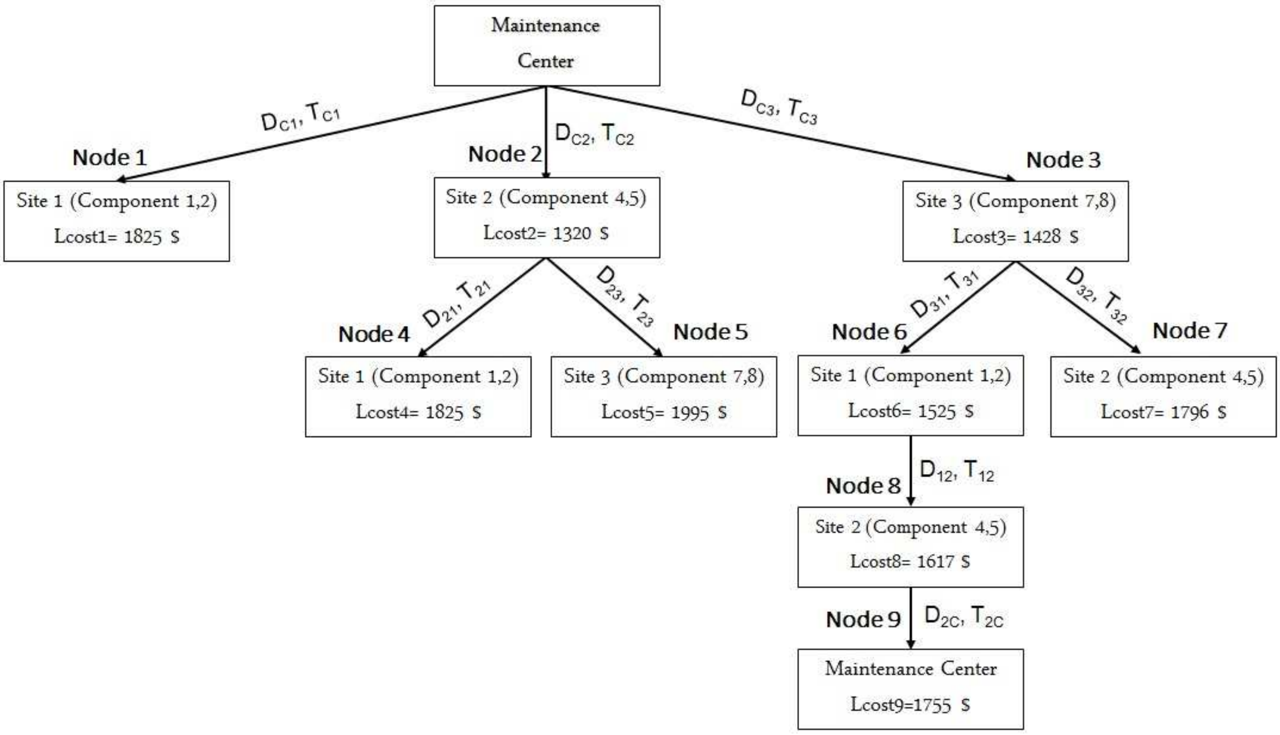

Figure 9: Search tree for the group $G^k = \{1, 2, 4, 5, 7, 8\}$

The BAB algorithm iteratively solves the maintenance routing problem by considering one level at a time starting from the top of the search tree (level 0) to the last level (level $ns_k + 1$). In Figure 9, we consider the maintenance routing of group G^k containing components 1, 2, 4, 5, 7, and 8 located in three different sites 1, 2 and 3. The BAB is done from the maintenance center (level 0) to the last level (level 4).

At a considered level v, the following steps are done:

- Estimate lower bound value of each node $q \in HN_v$. The lower bound value of node q, denoted $LB(q)$, indicates the minimum logistic cost (minimum travel distance), that we can obtain if we decide to travel across the node q.
- Select a node for expansion. Let EHN_v be the set containing all nodes of level v (HN_v) and all unexpanded nodes of the previous levels. The node with the lowest value of the lower bound among all nodes in EHN_v (the most promising node) is selected for the expansion.
- Expand the selected node. The node expansion is to identify all possible nodes that the maintenance team can directly travel from the selected node. The expanded node is called parent node, and the generated nodes are child ones. The BAB process then jumps to the level of the child nodes.

The only one problem now is how to estimate the lower bound value. Firstly, let L_{uv} denote the distance between two sites u and v. $L_{uv} = +\infty$ if there is no direct route connecting the two sites. The lower bound represents the smallest travel distance, that the routes traveling across node q can obtain, is calculated as:

$$LB(q) = R^{tr} \cdot (L_{0\to q} + \widehat{L}_{q\to 0}) \tag{17}$$

- $L_{0\to q}$ is the total travel distance of the planned part of the routes from the maintenance center to node q. Consider node 2 in Figure 9, we have $L_{0\to 2} = L_{02}$.
- $\widehat{L}_{q\to 0}$ is the expected total travel distance of the unplanned part of the routes from node q to the maintenance center. Since the route from node q to maintenance center is still unknown, the calculation of its total distance has to be done approximately. Consider a site u that the maintenance team has not yet visited $u \notin VN_{0\to q}$, it is clear that the shortest distance to go to site u is $L_u^{min} = \min\limits_{v\in U} L_{vu}$. U is the set of sites in which the maintenance team could be before visiting site u. Consequently, we have:

$$\widehat{L}_{q\to 0} = \sum_{u\notin VN_{0\to q}} L_u^{min} \tag{18}$$

  For example, consider again node 2 in Figure 9, the maintenance team has already visited site 2. The expected travel distance of the unplanned part is:

$$\widehat{L}_{2\to 0} = \min(L_{10}, L_{30}) + \min(L_{21}, L_{31}) + \min(L_{23}, L_{13}) \tag{19}$$

After application of the above BAB, we obtain the optimal routes with the shortest travel distances for each group of grouping structure. However, the direction to go in each route has not been decided yet.

B Implementation of Local Search Genetic Algorithm

In this section, the main steps of LSGA is detailed knowing that LSGA is implemented to find not only the optimal grouping structure, but also the optimal maintenance routes. The principle of LSGA is summarized in Figure 4.

- *Step 1: Coding.* This step is aiming at defining the way to introduce a grouping structure in LSGA. A grouping structure is here represented by an array M. $M(i^m) = j$ if maintenance activity i^m is in group j.
- *Step 2: Generating a population of grouping structures.* LSGA creates randomly an initial population of grouping structures. To generate a grouping structure, the number of groups is randomly chosen in $[1, n]$. Next, all PM activities are randomly put into the chosen groups. Note

that the number of components in a group cannot be bigger than the capacity of transportation vehicles (m_{sp}).

- *Step 3: Evaluating the performance of grouping structure.* The performance of a grouping structure in the population is assessed by its total profit economic EPS. To do this, for a group G^k, the BAB is firstly applied to find the set of itineraries with the shortest distance (SI_{G^k}). At the beginning, a route in SI_{G^k} is randomly chosen for each group G^k. Based on the grouping structure and all selected routes, the grouping economic profit can be evaluated as follows:

$$EPS(GS) = \begin{cases} \sum_{G^k \in GS} EPG_{G^k}(t_{G^k}, I_{G^k}) & \text{if } \forall k,\, nc^k \leq m_{sp} \\ -\infty & \text{if } \exists k,\, nc^k > m_{sp} \end{cases}$$

where, nc^k is the number of components in group G^k.

- *Step 4: Elitism.* The two best grouping structures of the current population are directly copied to the next generation in order to protect them from the high level of disruption.

- *Step 5: Crossover.* Crossover is performed to combine a pair of parent grouping structures to generate better grouping structures. To do this, two PM activities are firstly randomly chosen as the crossover points. And then, the elements between these points of the selected parent grouping structures are exchanged (see Figure 10A). The probability that the crossover is done for a pair of grouping structures is around 80%.

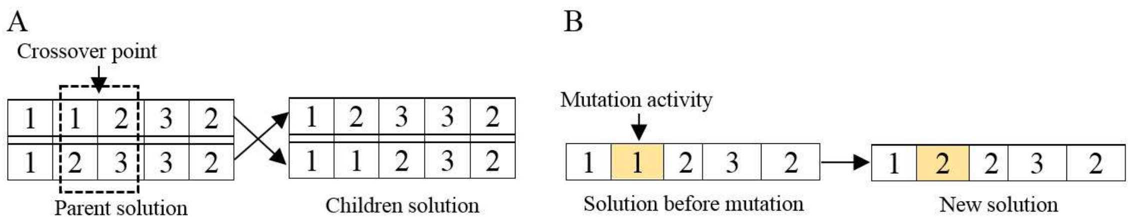

Figure 10: Example of crossover and mutation operators.

- *Step 6: Mutation.* Mutation helps to prevent LSGA from capturing local optima. For each selected grouping structure, a maintenance activity of a group is randomly selected and then moved to another group (see Figure 10B). Mutation probability should be small to prevent LSGA from random search. It is usually chosen from 0.1% to 1%.

- *Step 7: Local search.* For each grouping structure in the new generation, Local Search is applied to choose and evaluate several routes in SI_{G^k}. The best route is saved for the next generation.

- *Step 8: Stopping.* LSGA is stopped when the maximum number of generations is reached.

References

[1] D.T. Matt, E. Rauch and P. Dallasega. Trends towards distributed manufacturing systems and modern forms for their design. *Procedia CIRP*, 33, 185-190, 2015.

[2] H. S. H. Nguyen, P. Do, B. Iung and H. C. Vu. A dynamic grouping maintenance strategy for geographically dispersed production systems. *10th International Conference on Mathematical Methods in Reliability*, MMR2017, July 2017, Grenoble, France.

[3] J. S. Srai, M. Kumar, G. Graham, W. Phillips, J. Tooze, S. Ford and B. Ravi. Distributed manufacturing: scope, challenges and opportunities. *International Journal of Production Research*, 54(23), 6917-6935, 2016.

[4] L. Dieulle, C. Brenguer ,A. Grall, M. Roussignol. Sequential condition-based maintenance scheduling for a deteriorating system. *European Journal of operational research*, 150(2), 451-461, 2003.

[5] R. P. Nicolai, R. Dekker. Optimal maintenance of multi-component systems: a review. *In Complex system maintenance handbook*, 263-286. Springer, London, 2008.

[6] M. C. O. Keizer, S. D. P. Flapper and R. H. Teunter. Condition-based maintenance policies for systems with multiple dependent components: A review. *European Journal of Operational Research*, 261(2), 405-420, 2017.

[7] R. Dekker, R.E. Wildeman and F. A. Frank A van der Duyn Schouten. A review of multi-component maintenance models with economic dependence.*Mathematical Methods of Operations Research*, 45, 411-435, 1997.

[8] Y. Zhou, Z. Zhang, T. R. Lin, L. Ma. Maintenance optimisation of a multi-state series-parallel system considering economic dependence and state-dependent inspection intervals. *Reliability Engineering and System Safety*, 111, 248-259, 2013.

[9] L. Liu, M. Yu, Y. Ma, Y. Tu. Economic and economic-statistical designs of an X control chart for two-unit series systems with condition-based maintenance. *European Journal of Operational Research*, 226(3), 491-499, 2013.

[10] H.C Vu, P. Do, A. Barros and C. Bérenguer. Maintenance planning and dynamic grouping for multi-component systems with positive and negative economic dependencies. *IMA Journal of Management Mathematics*, 26(2), 145-170, 2014.

[11] Z. Hameed and J. Vatn. Role of grouping in the development of an overall maintenance optimization framework for offshore wind turbines. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 226(6),584-601, 2012.

[12] M. Stalhane, H. Vefsnmo, E. E. Halvorsen-Weare, L. M. Hvattum and L. M. Nonås. Vessel fleet optimization for maintenance operations at offshore wind farms under uncertainty. *Energy Procedia*, 94, 357-366, 2016.

[13] C. A. Irawan, D. Ouelhadj, D. Jones, M. Stålhane and I. B. Sperstad. Optimisation of maintenance routing and scheduling for offshore wind farms. *European Journal of Operational Research*, 256(1), 76-89, 2017.

[14] R. Wildeman, R. Dekker and A. Smit. A dynamic policy for grouping maintenance activities. *European Journal of Operational Research*, 99(3), 530-551, 1997.

[15] H.C. Vu, P. Do, A. Barros and C. Bérenguer. Maintenance grouping strategy for multi-component systems with dynamic contexts. *Reliability Engineering and System Safety*, 132, 233-249, 2014.

[16] J. Díaz-Ramírez, J.I. Huertas, and F. Trigos. Aircraft maintenance, routing, and crew scheduling planning for airlines with a single fleet and a single maintenance and crew base. *Computers and Industrial Engineering*, 75, 68-78, 2014.

[17] N.A. Al-Thani, M.B. Ahmed and M. Haouari. A model and optimization-based heuristic for the operational aircraft maintenance routing problem. *Transportation Research Part C: Emerging Technologies*, 72, 29-44, 2016.

[18] D. T. Phan and Y. Zhu. Multi-stage optimization for periodic inspection planning of geo-distributed infrastructure systems. *European Journal of Operational Research*, 245(3), 797-804, 2015.

[19] A. Goel and F. Meisel. Workforce routing and scheduling for electricity network maintenance with downtime minimization. *European Journal of Operational Research*, 231(1), 210-228, 2013.

[20] H. Tang, E. Miller-Hooks and R. Tomastik. Scheduling technicians for planned maintenance of geographically distributed equipment. *Transportation Research Part E: Logistics and Transportation Review*, 43(5), 591-609, 2007.

[21] F. Camci. Maintenance scheduling of geographically distributed assets with prognostics information. *European Journal of Operational Research*, 245(2), 506-516, 2015.

[22] E. López-Santana, R. Akhavan-Tabatabaei, L. Dieulle, N. Labadie and A. L. Medaglia. On the combined maintenance and routing optimization problem. *Reliability Engineering and System Safety*, 145, 199-214, 2016.

[23] C. P. Bajaj. Some constrained shortest-route problems. *Mathematical Methods of Operations Research*, 15(1), 287-301, 1971.

[24] H. C. Joksch. The shortest route problem with constraints. *Journal of Mathematical analysis and applications*, 14(2), 191-197, 1996.

[25] K. Bouvard, S. Artus, C. Bérenguer and V. Cocquempot. Condition-based dynamic maintenance operations planning and grouping. Application to commercial heavy vehicles. *Reliability Engineering and System Safety*, 96(6), 601-610, 2011.

[26] P. Do, A. Barros and C. Bérenguer. Dynamic grouping maintenance strategy with time limited opportunities. *Reliability Engineering and System Safety*, 120, 51-59, 2013.