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Maintenance plays a key role in controlling manufacturing systems within normal operations. Consistent control within production requirements is difficult due to the complexity of manufacturing systems; that is, many components that are economically and structurally interdependent. Structural dependence between components implies that maintenance requires the disassembly of other, obstructing components. The disassembly may affect the failure rate of components and modify the maintenance plan. We proposed a maintenance optimisation model considering both economic and structural dependencies between components. The impact of structural dependence on the reliability of components was reviewed using a Proportional Hazard Model. The model implemented influencing factors such as component features, the system structure, and the production context. It supported a more accurate reliability assessment. We derived an adaptive maintenance strategy that integrated these dependencies and developed a cost-based optimisation model to determine a prudent maintenance plan. We conducted a case study on a spindle of a milling machine to prove feasibility and the model's ability to reliably assess and optimally maintain operations.

Maintenance, Optimisation, Disassembly

1. Introduction

Reliability is an important key performance indicator in manufacturing systems [1-3]. An accurate assessment of the system's reliability must prove functionality, efficiency, and safety. Reliability is also an appropriate decision indicator for production scheduling, spare parts management, and maintenance optimisation [4]. The reliability assessment becomes more complicated when the system is complex; that is, its many components are economically and structurally interdependent. Economic dependence means that joint (opportunistic) maintenance of several components can reduce cost. Structural dependence implies that component maintenance requires disassembly of obstructing components. Economic dependence was studied and successfully applied in maintenance optimisation [2,3]. Prior art rarely dealt with structural dependence in maintenance optimisation [3,5]. Most prior work assumed that disassembly would not impact component failure rates. This is not always true in practice.

Disassembly is categorised into three types: non-destructive, semi-destructive, and destructive disassembly [6]. Destructive disassembly deals with the partial or complete destruction of the obstructing components. The semi-destructive approach aims to destroy only connective components and leaving the main components with little or no damage. The non-destructive methods seek to leave components undamaged. These methods can cause undesired damage. The interaction between the faying surfaces of the components or between the components and the tool used to perform the disassembly may cause scratches, deformation, and more. [7]. Such damage increases the likelihood of failure, i.e., it reduces the reliability and operating performance of the affected components [8,9].

Component and system failure risk is underestimated if the impact of the disassembly operations on the failure rate of the components is ignored. An inaccurate reliability assessment and maintenance plan can then be expected. Our original approach starts with a model based on a connection matrix using the Proportional Hazard Model. It quantifies the impact of disassembly operations on the component failure rate. An opportunistic maintenance policy is then developed. It considers the impact of disassembly and the economic dependence between components, allowing a more realistic and efficient maintenance plan to develop, that is synchronised with the production plan.

We introduce the failure rate modelling integrating disassembly operations impact in section 2. Our opportunistic condition-based maintenance policy considering both economic and structural dependencies is discussed in section 3. Section 4 illustrates the application of the model and strategy proposed on the spindle of a milling machine. Conclusions and future work are presented in Section 5.

2. Failure rate modelling with impact of disassembly

2.1. System modelling and assumptions

A manufacturing system (i.e. machine tool) or sub-system (i.e. spindle) consists of n interdependent components connected in series, which are economically and structurally interdependent. Components form a hierarchical structure that is illustrated by a directed graph [10]. (Sub)system components experience hard failure. The degradation alone does not lead to component failure but likely factors into it. The failure rates of component i ($i = 1, 2 \ldots n$) can be described by a Weibull baseline Proportional Hazard Model:

$$h_i\big(t, Z_i(t)\big) = h_i^0(t)\varphi\big(Z_i(t)\big) \quad (1)$$

Where: $h_i^0(t) = \beta_i t^{\beta_i - 1}/(\lambda_i)^{\beta_i}$ is the Weibull baseline hazard rate with shape β_i and scale λ_i; $\varphi(Z_i(t)) = \varepsilon_i . Z_i(t)$, $Z_i(t)$ is a degradation signal and ε_i is regression coefficient quantifying the impact of degradation on the failure rate of component i. $Z_i(t)$ is assumed to follow a linear general path model, i.e., $Z_i(t) = \alpha_i + \mu_i t + \sigma_i B(t)$. In which, α_i, μ_i and σ_i are the initial degradation, degradation rate, and degradation volatility of component i, respectively, $B(t)$ is the standard Brownian motion. This model was extensively studied and successfully applied [11]. These parameters are either known or estimated based on historical data to model the impact of disassembly operations, reliability assessment, and maintenance optimisation.

The reliability of component i is defined as the probability that component i is still in functioning state at time t. It can be formulated as follows [9]:

$$R_i(t) = \exp\left[-\int_0^t h_i(s, Z_i(s))ds\right] \quad (2)$$

2.2. Disassembly operations and their impact

Disassembly operations are a process to separate one or several components from the system for offline maintenance [8,11]. In manufacturing systems, components are inter-connected via connectors. The disassembly operation of a component is defined as a process to disconnect connections in sequence to remove the component from the system and later reassemble the component after maintenance. The connection matrix, $G_c = [r_{ij}]$, is used to represent the system's structure, whereas, r_{ij} indicates whether there is a connection between the two components i and j. The value of the element r_{ij} is "1" if a connection exists, and otherwise "0".

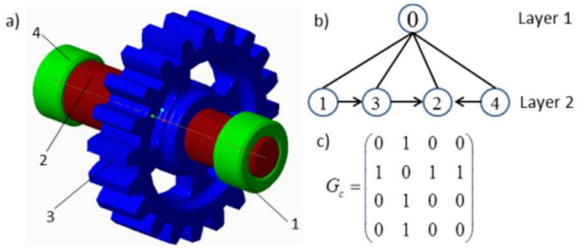

Fig. 1. (a)-a gearbox system (b)- its directed graph, and (c)-the corresponding connection matrix.

Figure 1 shows a simple gearbox system with its connection matrix and directed graph. Node 0 represents the whole system, and the numbered nodes (1, 2, 3, and 4) represent the components. The line that connects the node in the upper layers and the node in the lower layer indicates that disassembly of the lower layer node needs disassembly of the upper node first. The arrow between the nodes of the same layer represents the disassembly sequence between the nodes. We assumed that disassembling the connection (i,j) between the two components i and j results in an amount of damage δ_{ij} on the degradation level of the component i (δ_{ji} denotes the damage on component j) to model the impact of that disassembly. δ_{ij} depends on the following factors:

- The **strength** of the connection between the two components, i.e., the more difficult it is to break the connection, the higher is the degree of impact on the component's degradation level. The connection matrix is herein extended to represent the strength of the connection, $G_c^{extent} = [S_{ij}]$. $S_{ij} \geq 0$ is the strength of the connection between the two components i and j. S_{ij} is deterministic and can be acquired during the design stage.
- The **properties** of the component, i.e., the damage on components made of stronger materials is lower than that of components made of weaker materials.
- The **method/process** used to perform the disassembly. For example, using a mechanical process to dismount bearings impacts damage more than a hydraulic process [7]. The expertise of technicians also influences the impact of the disassembly, δ_{ij}. The adjustment factor θ_{ij} is used to reflect the technician's degree of expertise to perform the disassembly of the connection (i,j). θ_{ij} is likely random and can be described by a normal distribution with mean $\mu_{\theta_{ij}}$ and standard deviation $\sigma_{\theta_{ij}}$. The expected value $\mu_{\theta_{ij}}$ reflects the impact of the disassembly performance of the connection (i,j). The uncertainty endowed with maintenance technician quality is characterised by the corresponding standard deviation $\sigma_{\theta_{ij}}$.

δ_{ij} is expressed in Eq. (3).

$$\delta_{ij} = S_{ij}.\theta_{ij}/k_i \quad (3)$$

Where, $k_i \geq 0$ is a factor related to the properties of the component i and is estimated from previous data, life testing, etc.

δ_{ij} follows a normal distribution with mean $\mu_{\delta_{ij}} = S_{ij}.\mu_{\theta_{ij}}/k_i$ and variant $\sigma_{\delta_{ij}} = (S_{ij}/k_i)^2\sigma_{\theta_{ij}}$. We assumed that $\sigma_{\theta_{ij}}$ is rather small so that the probability for $\delta_{ij} < 0$ is likely zero. This assumption is valid when only qualified technicians are assigned to carry out complex disassembly operations.

The connections of other components on the disassembly path of the maintained components are also disconnected due to the structural dependence. The disassembly path for each component is assumed to be predefined due to technical constraints. The disassembly path of component h is represented by its disassembly matrix, $I^h = [I_{ij}^h]$, where, $I_{ij}^h = 1$ if connection between the two components (i and j) is on the disassembly path of component h; $I_{ij}^h = 0$ otherwise. The impact of disassembly of component h on the degradation level of component i can then be expressed as:

$$H_{ih} = \sum_{j=1}^{n} \delta_{ij}.I_{ij}^h \quad (4)$$

Intersections exist among the disassembly paths of different components during the maintenance on a group G^k of components. The disassembly path of the group G^k should be defined as: $I^{G^k} = I^j \cup I^l \cup \ldots \cup I^v, (j,l,\ldots v \in G^k)$. The impact of disassembly of group G^k on component i is then:

$$H_{iG^k} = \sum_{j=1}^{n} \delta_{ij}.I_{ij}^{G^k} \quad (5)$$

2.3. Failure rate modelling with disassembly impact

Each component is subjected to both continuous degradation over time (own degradation) and the damage caused by disassembly operations. The total degradation signal of component i can then be expressed as:

$$Z_{Hi}(t) = Z_i(t) + \sum_{k=0}^{N(t)} H_{iG^k} \quad (6)$$

Where $N(t)$ is the number of maintenance events. The failure rate of the component i can be rewritten as:

$$h_i(t, Z_{Hi}(t)) = h_i^0(t)\left[\varepsilon_i.Z_i(t) + \sum_{k=0}^{N(t)} H_{iG^k}\right] \quad (7)$$

Figure 2 (b) illustrates the correlation of the evolution of degradation signal and failure rate of system's components in a 3-unit system, with the directed graph of the system shown in Figure 2 (a). The directed graph underlines that component 1 and component 2 are restricted by each other, and the disassembly of one component always means the disassembly of the other, while component 3 is structurally independent of the two other components. At time t_1, component 1 is replaced. The degradation signal of component 2 jumps by an amount of δ_{21} due to the impact of the disassembly operation. The increase of degradation signal results in the increase of failure rate of component 2. Since components 3 is structurally independent from the two other components, the disassembly operations of the latter components do not affect the failure rate of component 3 and vice versa.

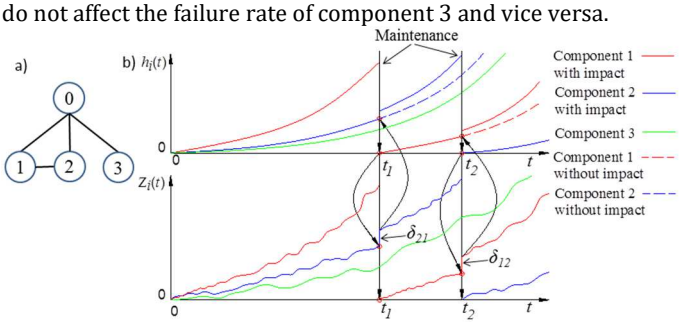

Fig. 2. (a)-directed graph and (b)-illustration of the evolution of degradation signal and failure rate of the system's components.

The impact modelling of disassembly operations allows investigating its effect on system reliability and maintenance optimisation.

3. Maintenance policy

A condition-based maintenance policy (CBM) is herein implemented; both economic and structural dependencies between components are considered.

3.1. Description of the proposed maintenance policy

The system's components shall be inspected at regular intervals $T_k=k.\tau$ (k=1, 2…) with the inter-inspection interval τ that is a decision variable which needs to be optimised. At every inspection, the degradation level of each operating component is measured. Each inspection incurs a cost c^I. Component failure is self-evident. The maintenance decisions are:

- If component i failed between (T_{k-1}, T_k), corrective maintenance (CM) is performed on component i at time T_k.
- If at time T_k, component i is still operating, both preventive maintenance and opportunistic maintenance rules are applied based on the predicted reliability of the components. More precisely:
  - *Preventive maintenance (PM) rule*: if the reliability of the component at the next inspection (T_{k+1}), denoted as $R_i(T_{k+1}|T_k)$, is less than the fixed preventive maintenance threshold, $R_i(T_{k+1}|T_k)<R_p$ (R_p is also a decision variable to be optimised), the component is preventively replaced at T_k.
  - *Opportunistic maintenance (OM) rule*: if CM and/or PM are implemented on a group G^k ($G^k\neq\emptyset$), component j, $j\notin G^k$ is opportunistically maintained together with group G^k if $R_j(T_{k+1}|T_k, G^k) < R_o$, $(R_p \le R_o < 1)$, R_o is also a decision variable to be optimised.

The proposed maintenance policy is illustrated in Figure 3.

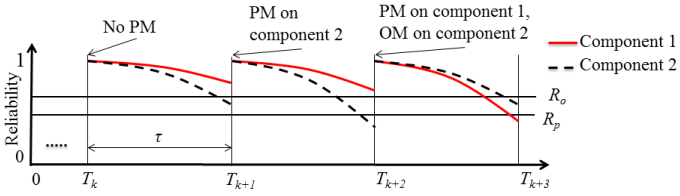

Fig. 3. Illustration of the maintenance policy

3.2. Reliability (Lifetime) prediction with disassembly impact

If at inspection event T_k, the component i is still functioning, the reliability of component i at the next inspection, $T_{k+1} = T_k + \tau$, will be [9]:

$$R_i(T_{k+1}|T_k) = \exp\left[-\varepsilon_i \int_{t_i^k}^{t_i^{k+1}} h_i^0(s).Z_i(s)ds\right] \quad (8)$$

If a group G^k is maintained at T_k, the reliability of component j is calculated with considering the impact of disassembly of the group G^k (see Eq. (7) and Eq. (8)).

$$R_j(T_{k+1}|T_k, G^k) = \exp\left[-\varepsilon_j \int_{t_j^k}^{t_j^k+\tau} h_j^0(s)\left(Z_j(s) + H_{jG^k}\right)ds\right] \quad (9)$$

3.3. Cost structure and maintenance optimisation

The PM cost for component i can be expressed as:

$$C_i^p = c^{ps} + c_i^p + c_i^{pd} \quad (10)$$

where c^{ps} is the set-up cost for PM and can be shared if several components are maintained together (it represents the economic dependence between components [2]); c_i^p is the specific PM cost of component i; $c_i^{pd} = \left(\tau_i^r+\tau_i^d\right).c^{pd}$ is the maintenance downtime cost with the PM downtime cost rate; c^{pd}, τ_i^r, and τ_i^d are the replacement and disassembly duration of components i. The disassembly duration of component i is calculated based on its disassembly path:

$$\tau_i^d = \frac{1}{2}\sum_{u=1}^{n}\sum_{v=1}^{n}\tau_{uv}.I_{uv}^i \quad (11)$$

Where, τ_{uv} is the disassembly duration of the connection (u, v). Similarly, disassembly duration of a group of components G^k is:

$$\tau_{G^k}^d = \frac{1}{2}\sum_{u=1}^{n}\sum_{v=1}^{n}\tau_{uv}.I_{uv}^{G^k} \quad (12)$$

The maintenance duration of the group G^k is:

$$\tau^{G^k} = \tau_{G^k}^d + \sum_{i\in G^k}\tau_i^r \quad (13)$$

This duration is significantly reduced by a multi-maintenance team [2]. After failure, when a CM is implicated on component i, it incurs a CM cost:

$$C_i^c = c^{cs} + c_i^c + c_i^{cd} \quad (14)$$

Where, c^{cs}, c_i^c and $c_i^{cd} = \left(\tau_i^r+\tau_i^d\right)c^{cd}$, are the corrective setup cost, specific cost and downtime cost, respectively.

Three decision variables (τ, R_p, and R_o) need to be optimised. In maintenance optimisation framework, maintenance cost is usually used as the main criterion [2,3]. A maintenance cost model is herein developed named long-run maintenance cost rate model, and defined as:

$$C^{\infty}(\tau, R_p, R_o) = \lim_{t\to\infty}\frac{C^t(\tau,R_p,R_o)}{t-t_{down}} \quad (15)$$

Where, C^t (τ, R_p, R_o) and t_{down} are cumulative maintenance cost and downtime of the system within the period (0, t]. The long-run maintenance cost rate is rewritten with the renewal theory [12] as:

$$C^{t_{end}}(\tau, R_p, R_o) = \frac{\sum_{k=1}^{N}(C_I^k+C_m^k)}{t_{end}-t_{down}} \quad (16)$$

Where, $t_{end} = N.\tau$ is the length of the first life cycle of the system; N is the number of inspections in the first life cycle; $C_I^k = \sum_{i=1}^{n} c_i^I$ is the inspection cost; $t_{down} = \sum_{k=1}^{N}\tau^{G^k}$; and C_m^k is the maintenance cost at the k^{th} inspection. The optimal value of decision variables can be obtained by minimising the long-run maintenance cost rate.

4. Case study: spindle unit of a milling machine

It is now necessary to concretely illustrate the impact of disassembly operations on the system reliability and maintenance optimisation for a spindle unit of a milling machine [13,14]. The case was chosen as part of a collaboration with RENAULT on the maintenance of a 5-axis machine tool (but with anonymised data).

4.1. Description of the spindle unit

An internal motor driven spindle unit generally consists of six main components: spindle house, spindle shaft, front bearings, rear bearings, motor, and clamping unit [13] (Figure 4).

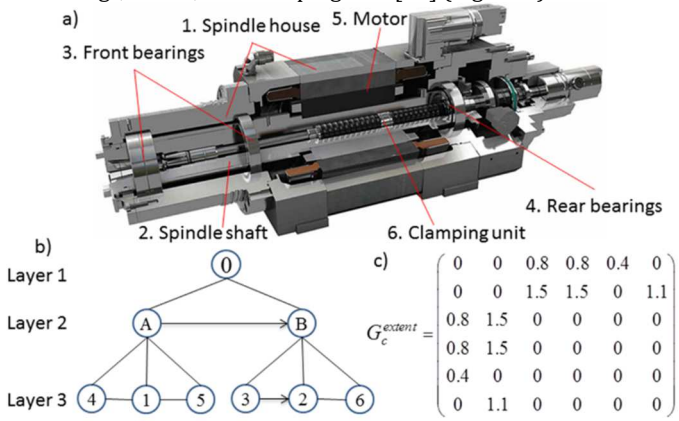

Fig. 4. a- A sketch of an internal motor spindle, b-its directed graph and c-its extent connection matrix.

The spindle unit is a structurally dependent system. The disassembly matrix of each component of the spindle is shown in Figure 5. The failure rate and degradation parameters of the components of the spindle unit are given in Table 1.

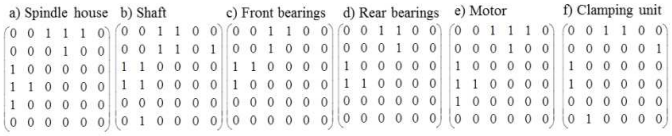

Fig. 5. Disassembly matrix of spindle components

Table 1. System parameters

Parameters / Components	β_i	λ_i (months)	ε_i	α_i	μ_i	σ_i	k_i
1. Spindle house	5	60	0.15	0	0.09	0.02	1.8
2. Spindle shaft	3	50	0.3	0	0.08	0.02	1.6
3. Front bearings	2	12	0.4	0	0.01	0.03	0.8
4. Rear bearings	2	12	0.4	0	0.01	0.03	0.8
5. Motor	4	60	0.3	0	0.08	0.02	2.5
6. Clamping unit	2	20	0.35	0	0.09	0.02	0.9

The maintenance costs are provided in Table 2. All cost parameters are given in arbitrary units (arbitrary cost unit (acu)).

Table 2. Maintenance cost parameters

Parameters / Components	c_i^p	c^{ps}	c^{pd}	c_i^c	c^{cs}	c^{cd}	c_i^l	τ_i^r (hour)
1. Spindle house	100	50	20	500	200	100	10	4
2. Spindle shaft	120			600			25	5
3. Front bearings	60			300			15	1
4. Rear bearings	60			300			15	1
5. Motor	120			600			20	4
6. Clamping unit	100			500			15	2

The disassembly duration (in hours) of each connection and the mean and variation of the adjustment factor are presented in Figure 6.

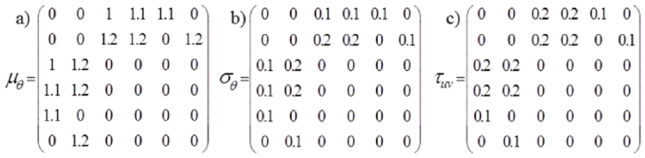

Fig. 6. (a)-mean and (b)-variation of adjustment factor for each connection, (c)-disassembly duration of each connection

4.2. Reliability assessment

With the inspection interval of τ=5, at the inspection T_k=30, the respective age of the components is $t_i^k = (30, 30, 10, 10, 30, 10)$ and the degradation level is $z_i^k = (3.2, 2.8, 1.1, 1.0, 2.2, 0.9)$. Suppose that components 3 and 4 (front and rear bearings) are replaced at T_k. Figure 7 shows the predicted reliability of the system at the next inspection T_{k+1}. It underlines that the disassembly operations associated with the maintenance of components 3 and 4 have a significant impact on system reliability.

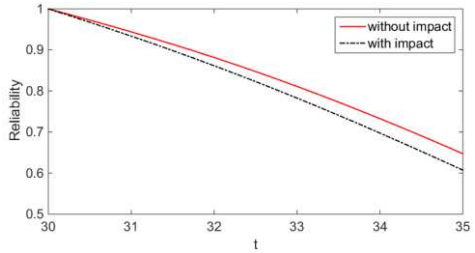

Fig. 7. System reliability with the disassembly impact

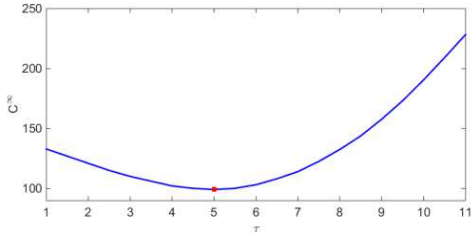

Fig. 8. Maintenance cost as a function of τ when R_p =0.65 and R_o=0.72

4.3. Optimal maintenance policy

CBM introduced in Section 3 is implemented on the spindle. Monte Carlo simulation is herein applied to find the optimal decision variables (τ, R_p, R_o). The long-run cost rate C^∞ (τ, R_p, R_o) is evaluated for different values of τ ($\tau > 0$), R_p ($0 < R_p < 1$), and R_o ($R_p \le R_o < 1$) using Eq. (15). The optimal values of the decision parameters are τ^* = 5.1 (months), R_p^* = 0.65, and R_o^* = 0.72 with the minimum cost rate C^∞ (τ^*, R_p^*, R_o^*) = **99.28** acu. Figure 8 shows the impact of the inspection interval τ on the cost rate when R_p = 0.65 and R_o = 0.72.

4.4. Impact of disassembly on the optimum maintenance policy

We assumed that the disassembly operations impact on the failure rate of the components is **ignored** to study the impact of disassembly operations on the optimum maintenance policy. It means that $H_{jG^k} = 0$ in the failure rate model presented in Eq. (6). In this case, the optimal decision parameters are τ^* = 5.6 (months), R_p^* = 0.67, and R_o^* = 0.75. Then the values of these decision variables are applied to the system **considering** disassembly impact. Consequently, the long-run maintenance cost rate is now **106.6** acu. This is significantly higher than the cost determined in section 4.3 (7.37% increase). The reason is that in section 4.3, the disassembly impact is integrated in the optimisation process to find the optimum maintenance policy, while this is not the case in section 4.4 (the impact is considered after calculation of the optimal parameters). It implies that not regarding structural dependence between components in finding the optimal decision variables can lead to a sub-optimal maintenance policy with potential impact on production time.

5. Conclusions

Our maintenance model quantifies the impact of disassembly operations on the failure rate of the components with structural dependence. Several factors that influence the impact of disassembly operations can be considered, such as component properties, strength of the connections between components and more. An opportunistic maintenance policy considering both the impact of disassembly and economic dependence is proposed. The case study focused on the maintenance of the spindle unit of a milling machine. It proved that the maintenance plan is suboptimal if the impact of disassembly operations is ignored. We validated the model with real machine tool data to extend our findings to other industrial systems.

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