Graph-Based Framework for Evaluating the Feasibility of Transition to Maintainomics

Bo Xing

Abstract Maintenance is a powerful support function for ensuring equipment productivity, availability and safety. Nowadays, growing concern for timeliness, accuracy and the ability to offer tracking information led to the augmentation of e-technologies' applications within maintenance management, i.e., e-maintenance. However, like any other information and communication (ICT)-based operation, massive data sets (i.e., big data) are generated from videos, audios, images, search queries, historic records, sensors, etc. Inevitably, e-maintenance needs to consider how to extract useful value from those raw and/or fused data as an important aspect before it can be adopted in any industry. This book chapter presents an overview of the e-maintenance data challenge. The main contribution of the article is the application of graph-theoretic approach (GTA) to the problem of finding an improved insight in the factors that determine the feasibility of maintainomics, i.e., data-centric maintenance. With such a concept, the maintenance-services can be upgraded from the low level of operations to the higher levels of planning and decision making.

Keywords e-Maintenance · Maintainomics · Graph-theoretic approach (GTA) · Feasibility index of transition (FIT) · Power plant · Innovative computational intelligence

B. Xing (✉)
Center for Asset Integrity Management (C-AIM), Department of Mechanical and Aeronautical Engineering, Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Pretoria, South Africa
e-mail: bxing2009@gmail.com

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1 Introduction

From a country's perspective, critical infrastructures may include such as banks, railways, and power supplies. Each of these infrastructures is so "large" and therefore can also be called as system of system since any one of them is a collection of task-oriented or dedicated sub-systems. All these sub-systems are organized in a manner that their resources and capabilities are pooled together to form a new and more complicated main system. Taking the electricity generation industry as an example, on one hand, the healthy condition of the national grid play a key part in keeping a country functioning properly; on the other hand, every involved power plant (more formally, sub-system) is composed of a large amount of equipments in which each individual machine acts an important role in helping the company to retain competitive in the market. As we can see, no matter how "big" or how "small" (relatively of course) a system is, maintaining its functional status is a maintenance engineer's major task. Looking at the power plant case again, traditionally, there are a number of ways in which power plant assets (e.g., transformers, turbines, and pipelines) fail and eventually get replaced. "Fail and fix" is often a practiced strategy to cope with this situation. However, as the competition in the global market increases, the accumulated breakdowns occurred in one single power plant may finally generate a fatal impact on the whole power supply system's performance. Under these circumstances, there is a need to consider all aspects of a sub-system performance, such as improving equipment reliability and availability, reducing unplanned outages, and predicting the remaining life of key system components. In this regard, a critical issue turns into selecting proper information processing and communicating tools to support the inspection and maintenance management. That means, for any an organization, maintenance interventions have to migrate from their traditional reactive approach, namely, "fail and fix", to a more advanced proactive approach, i.e., "predict and prevent" [1].

One possible direction which may spawn new ways to manage maintenance activities is the adoption and the usage of pervasive digital communications, e.g., mobile devices, remote sensing, online condition monitoring, etc. Accordingly, a new maintenance strategy (i.e., maintainomics) can be envisaged in which maintenance tasks are managed electronically by analyzing various real-time data [2]. For instance, Ref. [3] presented an integrated approach towards e-maintenance of engineering assets that based on radio frequency identification (RFID) technology. In a similar vein, the authors of [4] focused on the research of intelligent maintenance decision-making tools (i.e., Watchdog Agent™) which is used for multi-sensor assessment and prediction of a machine's or process's performance. Although maintainomics is desirable from many perspectives, all those digital bits that have been gathered are at the same time possible undesired and hazardous, just because more data (i.e., big data) does not necessarily mean better insights, in some cases, it even may result in confusion or disaster. Consequently, it is important to think strategically about how to adapt maintainomics to meet new maintenance demands. To address this issue, a graph-theoretic approach (GTA) is used to identify dominant factors that determining the feasibility of such transformation in the era of big data.

The remainder of this chapter is organized as follows. Subsequent to the introduction in Sect. 1, the background of maintenance, e-maintenance, big data, and maintainomics are briefed in Sect. 2. Then, the problem statement is presented in Sect. 3. The proposed methodologies are then detailed in Sect. 4. Next, Sects. 5 and 6 conduct an experimental study to demonstrate the feasibility of our proposed approaches. The future research directions are highlighted in Sect. 7. Finally, the conclusions drawn in Sect. 8 close this chapter.

2 Background

2.1 What is Maintenance?

Maintenance is normally seen as one of the few opportunities to reduce the cost of production, because it is the second highest operation costs in some industries [5]. Briefly, the heart of maintenance processes is condition monitoring that includes data acquisition, processing, analysis, interpretation, and extracting useful information from it. Traditionally, the maintenance actions are performed only when there is evidence of abnormal behaviors of a physical asset [6]. At the same time, researchers and/or scientists have relied upon monitoring programs just using invasive sampling at discrete periods, good experts, and/or handbooks. Limitations associated such programs (e.g., good experts are rare, sample acquisition takes long time, and uncertainty embedded for tedious sample analysis) result in high risk of equipment failures and therefore the company's top-line revenue plummets. In addition, the previous condition monitoring focuses only on monitoring and diagnostics, ignore prediction and prognosis [7]. As a result, to perform predictive-prognostic maintenance, it is evident that a proactive as well as reactive e-maintenance support system is required.

2.2 What is e-Maintenance?

Nowadays, the dependence on remotely sensed information can be found in many crucial areas of human endeavor such as meteorology, security services, banking systems, supply chains, and scientific researches. In asset management area, several authors pointed out that information and communication technologies (ICT) can be adopted as a tool to support in terms of quality data acquisition, real-time monitoring, and recording of divergences from standard acquisition [3]. In the literature (e.g., [5, 8–13]), this concept is defined as e-maintenance or tele-maintenance.

For instance, a new e-maintenance system has been studied in [14] which is based on the use of Internet and tether-free (i.e., wireless, Web, etc.) communication technologies. Later, Ref. [15] focused on the implementation of Web-based techniques to support e-maintenance services. In a similar vein, the authors of [16] proposed a framework by using RFID technology for real-time management of mobile assets. Also, worldwide case studies (e.g., automobile industry [17], power plant [18]) convinced that the implementation of ICT tools can improve products quality and reduce annual costs for maintenance.

In addition, as the maintenance itself is an extremely complex process and sometimes the inspections are difficult carried out by human operators even performed by dexterous technicians, the using of remotely controlled intelligent robots in an effort to accomplish the inspection or maintenance jobs faster and more reliable has increased greatly in the last few decades. For example, the authors of [19, 20] developed climbing robot for the structural inspection. An intelligent legged climbing robot is designed by [21] to perform the required inspection work in hazardous environments. Meanwhile, a large amount of pipeline inspection robots (i.e., in-pipe robots) have also been designed and fabricated. Generally speaking, the in-pipe robots can be classified into caterpillar [22], inchworm [23], walking [24], wheel [25], and pig types [26] depending on their travelling mechanisms. Interested readers please refer to [27, 28] for more detailed information regarding the intelligent robot assisted e-maintenance.

2.3 What is Big Data?

Recent advances in intelligence products, such as smart phones, and sensors and tracking devices, create tremendous amount of data (i.e., big data), which enable a researcher to extract the meaningful value much easier. According to a recent report compiled by McKinsey, the term "big data" refers to "datasets whose size is beyond the ability of typical database software tools to capture, store, manage, and analyses [29] ". For example, in genomic research, there are approximately 3 billion base pairs with a personal genome representing approximately 100 gigabytes of data [30]. In e-business, the datasets include social networks, purchase transaction records, blogs, mobile telephony, and digital entertainment. Also, from the maintenance engineers' point of view, the large historical records, the regular collected digital images, and the transactional information for operational reporting are also comprised of huge data. Other important aspect has been emphasized in addition to the volume is that big data may be unstructured, examples are text with social sentiments, audio and video, click streams, and website log files [31]. At the same time, big data is characterized by velocity, i.e., the rate of generation of data. For instance, to determine real-time roadway traffic conditions. As a result, the era of big data needs more interdisciplinary and multi-perspective research approaches that researchers have to create which were hard to implement before, such as new tools and solution approaches for data analytics [32], new paradigm for big data collection, storage, and processing [33], and privacy and security issues with big data [34].

2.4 What is Maintainomics?

As the maintenance environment more and more rely on the mobile devices and sensors, a serious question raises, namely, a huge amount of maintenance related data (big data in nature and is normally obtained by different kinds of automated sensors) are flooding in at rates never seen before. For instance, data from various control sensors for maintaining the different functions. Under these data over-loaded circumstances, different sources of data are collected, although a pretty good news compared with the traditional data scarce maintenance scenario, it is still necessary to sort out the required and useful data. In fact, the data in this type of "wide-area" sensing applications are no longer just focus on the equipment itself but can involve the analysis at scale of environment, legislation, and even workers' safety. In this study, the term "maintainomics" is utilized to denote the use of very large maintenance data content and the application of advanced core techniques (e.g., data mining, nature-inspired computational algorithms, Web and mobile technologies, new sensors, wireless communications, and different decision supporting systems) to improve the ways of organizations operating its maintenance management. For example, Ref. [35] proposed a conceptual model of a generic data acquisition system for improving maintenance management. Reference [36] broadly suggested that a common database can play an important role in reaching cost-effective improvements of maintenance performance, while Ref. [37] focused on the issue of maintenance-related data integration. Briefly, in the era of big data, maintainomics is an integration of traditional condition based maintenance, modern real-time online monitoring, and advanced intelligent technologies (see Fig. 1 for illustration). Notations ① $\sim$ ⑥ represent different sources of data collected during the process of e-maintenance which form a more complex scenario, i.e., maintainomics.

3 Problem Statement

Confronting with the emerging e-maintenance and the forthcoming maintainomics operating environment, it is necessary for every organization's strategic planners to make a decision about whether to perform such transformation for their own institution. Nevertheless, reaching a proper decision is often a complex process in practice, for instance, several authors (e.g., [38, 39]) believed in employing e-maintenance concept is not only based on the possibilities that new ICTs could offer but also need to integrate business performance such as operational, financial,

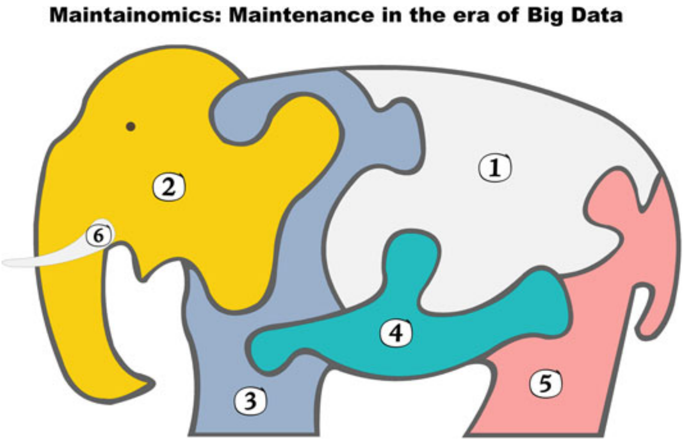

Fig. 1 Maintainomics: maintenance in the era of big data

human, and cultural factors. Consequently, a question raised by this study is how a company's "fitness" can be measured in terms of implementing maintainomics strategy. In other words, we need to come up a solution about how to perform a feasibility assessment for a particular firm regarding its suitability of aligning its present asset management policy with the maintainomics goal.

4 Proposed Methodology

Nowadays, a number of approaches have been suggested in the literature for the purpose of feasibility analysis. Amongst them, the graph theoretic approach (GTA) is often widely used to cope with multi-criteria decision making problems in both academic research and in industrial practice [40–43]. Inspired by the studies conducted by these scholars, the author of this work makes an attempt to apply a recently proposed GTA based methodology (known as feasibility index of transition, or FIT for short) to a selected industry in exploring its feasibility index during the course of transforming into maintainomics, i.e., data enriched e-maintenance. The following subsections give readers a brief overview regarding FIT and its main theoretical foundation, i.e., graph theory.

4.1 Background of Graph Theory

Graph theoretic approach (GTA) is a powerful decision making tool used to represent the relationships among different variables or subsystems based on the form of a digraph (directional graph) and matrix. Since 1736, GTA has been applied in a variety of fields, such as conceptual modelling [44], diagnosis [45], functional representation [46], and network analysis [47]. Basically, all graphs are composed exclusively of vertices (e.g., nodes, points) and edges (e.g., arcs, connections). To allow mathematical analysis, the interdependence on each other as well as their individual contribution to the system is assigned numerical values and an overall index is calculated. Interested readers are referred to [48–50] for more information regarding GTA.

4.2 Background of Feasibility Index of Transition

The feasibility index of transition (abbreviated as FIT) was coined by [51] for describing a chosen company's feasibility of moving forward to flexible manufacturing system (FMS). In order to analyze the trade-offs between various organizations for the adoption of FMS, certain enablers (or resources) should be chosen. In addition, the heritability of available enablers and the quantity of interactions among them may be directional independent or dependent. Built on this concept, a graph representation, illustrating the involved enablers and their potential interaction, was proposed in [51]. If interactions are found to be non-directional dependent, an undirected graph is thus used; on the opposite case, a digraph depiction is then employed.

For example, in their work [51], six groups of enablers (i.e., behavior enablers, non-behavioral enablers, financial enablers, methodologies, operational enablers, and human and cultural enablers) and their corresponding components were first identified and later used to examine the likelihood of transforming a traditional manufacturing environment into more advanced FMS. By simply calculating an index (i.e., FIT) value, one can easily find out to what degree a chosen target "fits" a company's situation. Mathematically, this process can be expressed via Eq. (1) [51]:

$$\text{FIT for ``FMS''} = f(\text{Enablers}) \tag{1}$$

where "FMS" stands for the goal that a manufacturing company wants to achieve.

A more general form of such equation can thus be further written as Eq. (2):

$$\text{FIT for ``Targeted Scenario''} = f(\text{Enablers}) \tag{2}$$

where "Targeted Scenario" represents a generic situation that an organization plans to orient itself to.

To check an organization's "fitness" in transformation, the graph theoretical based approach (utilized in [51]) is composed of four steps, namely, digraph visualization, matrix expression, permanent function establishing, and FIT value scale creating. The following subsections will provide a description of each step's detailed task.

4.2.1 Visualizing Enablers' Correlation via Digraph

In order to visualize the correlation between different enablers, a digraph (i.e., directed graph) is introduced at this stage as shown in Eq. (3) (adapted from [51]):

$$\begin{aligned} G &= (E, e) \\ E &= \{E_1, E_2, \ldots, E_P\} \\ e &= \{e_1, e_2, \ldots, e_P\} \end{aligned} \tag{3}$$

where G refers to a digraph which consists of two sets of items, namely, vertices (denoted by E), and edges (represented by e). In general, each edge (i.e., e_{ij}) can be identified via an ordered pair of vertices, (i.e., (E_i, E_j). The vertices (E_i and E_j) associated with the corresponding edge (e_{ij}) are thus called the end vertices or the nodes of e_{ij}. Please note, a self-loop occurs when a particular edge has the self-same vertex acting as its both nodes.

In [51], a node (E_i) stands for the ith enabler and the interdependence between enablers is pictured by different connecting directed edges. The number of nodes [i.e., the subscript P in Eq. (3)] is equal to the total number of enabler categories. In other words, P is a scenario-dependent parameter which was set to 6 (matching the total enabler categories' amount) in [51]. Accordingly, if a node E_i impresses a certain degree of influence against another node E_j, a directed line (represented by an arrow →) is drawn (from node E_i to E_j) to form edge e_{ij}. An illustration of this visualization process can be found below where an FMS enabler digraph (consisting of six enabler categories) is depicted [51].

As shown in Fig. 2, directional edges are found existing between E_1 and E_2, E_3, E_4, E_5, and E_6, respectively, which means that all other five enabler categories are swayed by node E_1 (i.e., behavioral enabler category) to some extent. For other edges, the same rule applies as well.

As one can see, this quickly drawn digraph can assist the decision makers in visualizing and analyzing the proposed transformation plan from a holistic perspective. Nevertheless, with the ever increasing number of nodes and their associated interrelationship degree, the digraph becomes more and more complex which will in turn decrease its readability. To cope with issue, a matrix form expression is further discussed as below.

4.2.2 Interpreting Enablers' Digraph Through Matrix

A matrix is a handy and powerful way of representing a digraph that is more processable by a computer. Suppose there is a digraph with P enablers, a matrix $\mathbf{F} = [e_{ij}]$ is thus can be used to represent such digraph as expressed in Eq. (4) [51]:

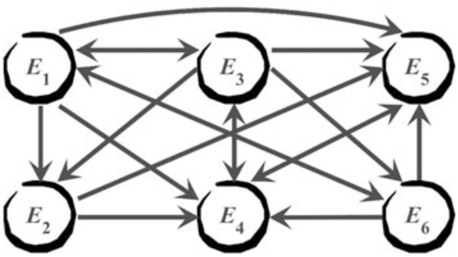

Fig. 2 FMS enabler categories' digraph

$$\mathbf{F} = \begin{matrix} \text{Enabler Categories} \\ E_1 \\ E_2 \\ E_3 \\ \vdots \\ \vdots \\ E_P \end{matrix} \begin{matrix} \begin{matrix} E_1 & E_2 & E_3 & \cdots & \cdots & E_P \end{matrix} \\ \begin{pmatrix} E_1 & e_{12} & e_{13} & \cdots & \cdots & e_{1P} \\ e_{21} & E_2 & e_{23} & \cdots & \cdots & e_{2P} \\ e_{31} & e_{32} & E_3 & \cdots & \cdots & e_{3P} \\ \vdots & \vdots & \vdots & \ddots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ e_{P1} & e_{P2} & e_{P3} & \cdots & \cdots & E_P \end{pmatrix} \end{matrix} \tag{4}$$

where e_{ij} indicates the interaction between the ith and jth enablers. Built on these principles, an demonstrating matrix expression derived from [51] is shown in Eq. (5):

$$\mathbf{F}^* = \begin{matrix} \text{Enabler Categories} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \end{matrix} \begin{matrix} \begin{matrix} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{matrix} \\ \begin{pmatrix} E_1 & e_{12} & e_{13} & e_{14} & e_{15} & e_{16} \\ 0 & E_2 & 0 & e_{24} & e_{25} & 0 \\ e_{31} & e_{32} & E_3 & e_{34} & e_{35} & e_{36} \\ 0 & 0 & e_{43} & E_4 & e_{45} & 0 \\ 0 & 0 & 0 & e_{54} & E_5 & 0 \\ e_{61} & 0 & 0 & e_{64} & e_{65} & E_6 \end{pmatrix} \end{matrix} \tag{5}$$

where the contributions of six enabler categories in transforming the traditional manufacturing system into FMS are represented via the diagonal elements of the matrix $\mathbf{F}^*$, i.e., E_1, E_2, E_3, E_4, E_5, and E_6, respectively. The interdependence of enablers E_i and E_j is denoted by the connecting edge e_{ij}. Please note that $e_{ij} \neq e_{ji}$ since the enablers are directed, and $e_{ii} = 0$ because there is no self-loop existing (in other words, the interaction between an enabler and itself does not exist).

Although the understandability of a matrix expression is better than digraph's from the machine perspective, both representations' uniqueness is inherent low which means they suffer high alterability by simply modifying the labels of their nodes. Under these circumstances, a subsequent fix solution is to establish a permanent function as discussed in subsection below.

4.2.3 Establishing the Matrix's Permanent Function Expression

For the purpose of developing a unique representation that is independent of labeling, a permanent function based on previously established variable matrix was proposed by the author of [51] at this stage. As mentioned in [51], the permanent function (i.e., $f^{\mathbf{F}^*}_{permanent}$) is a standard matrix function and plays a starring role in combinatorial mathematics.

Based on this concept, the permanent function of matrix $\mathbf{F}^*$ can be written as follows (adapted from [51]):

$$f^{\mathbf{F}^*}_{permanent} = item_1 + item_2 + item_3 + item_4 + item_5 + item_6 + item_7$$
$$\text{where}\begin{cases} item_1 = \prod_{i=1}^{6} E_i \\ item_2 = \prod_{i=1}^{6} e_{ii} \\ item_3 = \sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)E_kE_lE_mE_n \\ item_4 = \sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{ki} + e_{ik}e_{kj}e_{ji}\right)E_lE_mE_n \\ item_5 = \sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)\left(e_{kl}e_{lk}\right)E_mE_n + \\ \qquad \sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{kl}e_{li} + e_{il}e_{lk}e_{kj}e_{ji}\right)E_mE_n \\ item_6 = \sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)\left(e_{kl}e_{lm}e_{mk} + e_{km}e_{ml}e_{lk}\right)E_n + \\ \qquad \sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{kl}e_{lm}e_{mi} + e_{im}e_{ml}e_{lk}e_{kj}e_{ji}\right)E_n \\ item_7 = \sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)\left(e_{kl}e_{lm}e_{mn}e_{nk} + e_{kn}e_{nm}e_{ml}e_{lk}\right) + \\ \qquad \sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{ki}\right)\left(e_{lm}e_{mn}e_{nl}\right) + \\ \qquad \sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)\left(e_{kl}e_{lk}\right)\left(e_{mn}e_{nm}\right) + \\ \qquad \sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{kl}e_{lm}e_{mn}e_{ni} + e_{in}e_{nm}e_{ml}e_{lk}e_{kj}e_{ji}\right) \end{cases} \quad (6)$$

The detailed explanation regarding the main characteristics of these seven terms can be found below:

$item_1 = \prod_{i=1}^{6} E_i$	This item denotes the interactions of six main enabler categories, namely, from E_1 to E_6
$item_2 = \prod_{i=1}^{6} e_{ii}$	According to the original constraint setting (i.e., no self-loop found in the enablers digraph), the resultant of this item is null
$item_3 = \sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)E_kE_lE_mE_n$	Each component involved in this item stands for dual-element interdependency loop (denoted by $e_{ij}e_{ji}$) and the measure of the

	remaining four (in the context of FMS case) unconnected elements
$item_4 = \sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{ki} + e_{ik}e_{kj}e_{ji}\right)E_lE_mE_n$	In this term, a set of three-element interdependency loops (indicated by $e_{ij}e_{jk}e_{ki}$ and $e_{ik}e_{kj}e_{ji}$) and the measure of the remaining three (still in the context of FMS case) are represented by the components of the fourth item
$item_5$	This item is composed of two sub-items, i.e., $\sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)(e_{kl}e_{lk}) \quad E_mE_n$ and $\sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{kl}e_{li} + e_{il}e_{lk}e_{kj}e_{ji}\right)E_mE_n$. Two dual-element (represented by $e_{ij}e_{ji}$ and $e_{kl}e_{lk}$) interdependency loops and two FMS enabler categories (denoted by E_mE_n) are involved in the first sub-item; while the second sub-item consists of two four-element interdependency loops (i.e., $e_{ij}e_{jk}e_{kl}e_{li}$ and $e_{il}e_{lk}e_{kj}e_{ji}$) and two FMS enablers (i.e., E_mE_n)
$item_6$	There are also two sub-items contained in this item. The first sub-item (i.e., $\sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)(e_{kl}e_{lm}e_{mk} + e_{km}e_{ml}e_{lk})E_n$) is a product of three terms, namely, one dual-element interdependency loop (i.e., $e_{ij}e_{ji}$), two three-element interdependency loop (i.e., $e_{kl}e_{lm}e_{mk}$ and $e_{km}e_{ml}e_{lk}$), and one FMS enabler category (i.e., E_n). Following the alike fashion found in $item_5$, two terms (i.e., two five-element interdependency loops and one FMS enabler category) are multiplied to form $\sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{kl}e_{lm}e_{mi} + e_{im}e_{ml}e_{lk}e_{kj}e_{ji}\right)E_n$
$item_7$	Four sub-items are organized to configure the seventh item. A product of one dual-element interdependency loop (i.e., $e_{ij}e_{ji}$) and two four-element interdependency loop (i.e., $e_{kl}e_{lm}e_{mn}e_{nk}$ and $e_{kn}e_{nm}e_{ml}e_{lk}$) can be found in the first sub-item, i.e., $\sum_{i,j,k,l,m,n} \left(e_{ij}e_{ji}\right)(e_{kl}e_{lm}e_{mn}e_{nk} + e_{kn}e_{nm}e_{ml}e_{lk})$. Then two three-element interdependency loops are multiplied to form the second sub-item, i.e., $\sum_{i,j,k,l,m,n} \left(e_{ij}e_{jk}e_{ki}\right)(e_{lm}e_{mn}e_{nl})$. Next, a multiplication of three two-element interdependency

loops is performed to obtain the third sub-item, i.e., $\sum_{i,j,k,l,m,n} (e_{ij}e_{ji})(e_{kl}e_{lk})(e_{mn}e_{nm})$. Finally, two six-element interdependency loops (i.e., $e_{ij}e_{jk}e_{kl}e_{lm}e_{mn}e_{ni}$ and $e_{in}e_{nm}e_{ml}e_{lk}e_{kj}e_{ji}$) are included in the fourth sub-item of the seventh item

Once all 7 types of items have been successfully defined, one can simply substitute the element values of the earlier built FMS enablers' matrix (i.e., $\mathbf{F}^*$ in Sect. 4.2.2) for the just established permanent function, i.e., $f^{\mathbf{F}^*}_{permanent}$. After performing some basic algebraic and arithmetic operations, the final form of permanent function will turn into Eq. (7) as shown below (adapted from [51]):

$$
\begin{aligned}
f^{F^*}_{permanent} = {} & E_1E_2E_3E_4E_5E_6 \\
& + [(e_{13}e_{31})E_2E_4E_5E_6 + (e_{45}e_{54})E_1E_2E_3E_6 + (e_{16}e_{61})E_2E_3E_4E_5 \\
& + (e_{34}e_{43})E_1E_2E_5E_6] + [(e_{13}e_{36}e_{61})E_2E_4E_5 + (e_{35}e_{54}e_{43})E_1E_2E_6 \\
& + (e_{24}e_{43}e_{32})E_1E_5E_6 + (e_{36}e_{64}e_{43})E_1E_2E_5 + (e_{31}e_{14}e_{43})E_2E_5E_6] \\
& + [(e_{13}e_{31})(e_{45}e_{54})E_2E_6 + (e_{45}e_{54})(e_{16}e_{61})E_2E_3 + (e_{25}e_{54}e_{43}e_{32})E_1E_6 \\
& + (e_{36}e_{65}e_{54}e_{43})E_1E_2 + (e_{31}e_{15}e_{54}e_{43})E_2E_6] \\
& + [(e_{31}e_{16}e_{65}e_{54}e_{43})E_2 + (e_{61}e_{16})(e_{24}e_{43}e_{32})E_5] + [(e_{61}e_{16})(e_{25}e_{54}e_{43}e_{32})]
\end{aligned}
\quad (7)
$$

4.2.4 Creating FIT Value Scale

In general, FIT can be regarded as an indicator of the smoothness degree when an organization transforming itself from one state (normally in near out-of-date condition) to another state (preferably in an up-to-date situation). Mathematically, FIT can be described through Eq. (8) (adapted from [51]):

$$
\mathrm{FIT} = f^{\mathbf{F}^*}_{permanent} = \text{Permanent function of enablers' matrix} \quad (8)
$$

By computing the value of FIT, the feasibility of initiating the targeted transformation for any given company can thus be quantified. Since no negative term is included in Eq. (6) (see Sect. 4.2.3), we can conclude that the larger input numerical values of E_i and e_{ij} will always lead to an overall higher output value of FIT. In order to calculate the expected FIT value, the acquisition of the values of E_i and e_{ij} via the following ways is a must.

E_i's value Each enabler category's value is decided through treating each E_i as a subsystem and applying the GTA method to it accordingly. E_i's value is normally determined through analyzing the available system data and relative personnel opinions in an case study organization. In the

	case of where obtaining a quantitative value is not practicable, a ranked value judgment based on a scale of 1–10 is employed as a trade-off. Nevertheless, no matter which case comes in, the finally value of E_i is largely influenced by the acquirability of each individual building block's (i.e., e_{ij}) value
e_{ij}'s value	Under each enabler category, there are various influencing constitutes (i.e., e_{ij}). As suggested by the author of [51], a scale of 1–5 can be assigned to each e_{ij} individually for overcoming the directly immeasurable issue

To summarize, the FIT value can be gained as follows: First, identifying various influencing constitutes under each enabler category. Then, visualizing the number of constitutes and their corresponding correlation via a digraph. Once the digraph is drawn up, the next step is to interpret it with the help of matrix expression. Finally, after all preparations are done, the permanent function is obtainable and the FIT value can therefore be calculated.

4.2.5 Comparison

By identifying suitable enablers, we can see that FIT is a very helpful measurement in assisting us with the feasibility assessment of different organizations in terms of transforming themselves to a new business operating scenario. As shown in Eq. (FIT $= f^{\mathbf{F}^*}_{permanent}$ = Permanent function of enablers' matrix), the value of permanent function (with respect to the enablers' matrix) determines the final FIT value. In other words, for any selected firms (say two for comparison purpose), their similarity degree is high (from the "suitability to transformation" viewpoint) if their digraphs are selfsame; similarly, their digraphs will be identical if the corresponding enablers' matrices are alike. Therefore, in order to perform the applicable conversion feasibility analysis, the establishment of the corresponding permanent function is a key. Built on these deductions, the identification set for an firm can be express via Eq. (9) [51]:

$$/Z_1/Z_2/Z_3/Z_4/Z_{51} + Z_{52}/Z_{61} + Z_{62}/ \tag{9}$$

As we have learned that each obtained permanent function is composed of a set of items (seven of them for FMS case), and each individual item also consists of a couple of sub-items, the identification set shown in Eq. (9) for FMS case is understandable in which the value of the ith item is denoted by Z_i, and Z_{ij} stands for the value of the jth sub-item embraced in the ith item. By substituting the values of E_i and e_{ij} for the corresponding item and sub-item found in the permanent function, the values of Z_i and Z_{ij} can be acquired. In the case of sub-item does not exist, then let Z_{ij} equal to Z_i, i.e., $Z_{ij} = Z_i$.

In practice, for any two organizations, it is fair to say that the main enabler categories and the various involved empowering elements under each category for transforming into the desired target is rare same. Accordingly, the comparison of two companies can be conducted by assessing the relevant similarity or dissimilarity coefficient. Such coefficient is normally based on the numerical values of the items/sub-items found in an permanent function. The range of similarity/dissimilarity coefficient falls within [0, 1], i.e., the value of similarity coefficient factor is set as 1 while 0 is assigned to dissimilarity coefficient factor if two firms share a high degree of similarity (or low degree of dissimilarity) during the course of the targeted transformation; in a similar vein, the similarity and dissimilarity coefficient factor is set as 0 and 1, respectively, in the case of two firms show a high degree of dissimilarity (or low degree of similarity) within the planned conversion phase. As such, the dissimilarity coefficient for any two comparable firms was proposed in the form of Eq. (10) [51]:

$$\begin{aligned} Coefficient_{dissimilarity} &= \left(\frac{1}{U}\right)\sum_{i,j}\lambda_{ij} \\ U = \text{maximum of } &\left[\sum_{i,j}\left|Z_{ij}\right| \text{ and } \sum_{i,j}\left|Z'_{ij}\right|\right]. \end{aligned} \tag{10}$$

where Z_{ij} and Z'_{ij} represents the values of the terms involved in the chosen two comparable organizations, and the value of λ_{ij} is defined as $\lambda_{ij} = \left|Z_{ij} - Z'_{ij}\right|$. As shown in Eq. (10), only the absolute difference between the values of terms is considered. Meanwhile, the similarity coefficient can also be computed via Eq. (11) [51]:

$$Coefficient_{similarity} = 1 - Coefficient_{dissimilarity} \tag{11}$$

By introducing Eqs. (10) and (11), the main advantage of feasibility assessment can thus be quantified. Through the comparison of the relevant values (e.g., Z_{ij}, Z'_{ij}, $Coefficient_{dissimilarity}$, and $Coefficient_{similarity}$), the strengths and weaknesses of a particular participated organized can thus be identified and the possibility of corresponding improvement can also be evaluated.

4.2.6 Summary

Through Sects. 4.2.1 to 4.2.5, a GTA based approach for evaluating an organization's "fitness" degree towards a desired transformation are particularized. To summarize, the major stages embraced in this methodology are outlined as follows:

- Pinpoint the suitable enabler categories.
- Visualize the enabler categories' digraph.

- Allocate the necessary empowering elements under each category.
- Build up an empowering elements' digraph with respect to each enabler category.
- Establish the variable permanent matrix.
- Compute the permanent function at each sub-system level.
- Develop the scenario dependent matrix for enabler categories' digraph.
- Figure the permanent function of the previous stage obtained matrix.
- Sort the different companies in ascending/descending order. The company with the highest FIT value enjoys the best opportunity of fulfilling the examined transformation.
- Acquire the identification set for each considered organization via Eq. (9).
- Compare the relevant similarity/dissimilarity coefficient between two organizations based on Eqs. (10) and (11).
- Diarize the obtained results for future or further analysis.

5 Experimental Study Stage-1: Classifying Enabler Category and Identifying Empowering Element

Once the theoretical foundation of the present study has been finely established, an instant work would be verifying whether the proposed FIT measurement can be successfully applied to our focal question. In order to achieve this goal, a set of enabler categories and their involving empowering elements are first identified via a thorough literature review and an intensive communications with our industrial partner. Following a similar manner discovered in [51], a further grouping operation is performed on the classified enabler categories and the identified empowering elements (see Table 1) so that their permanent function value is more computable.

5.1 Behavioral Enabler Category (E_1)

This enabler class relates to the top management who is responsible for the implementation of maintainomics in an organization. In general term, this is often referred to as the strategic planning process which embraces the establishment of a company's main goals and objectives, and the allocation of required resources to achieve them [111]. In practice, top management often takes charge of such process, although resources, products, consumers, and competitors are among various factors that are inspected during the process of strategic planning.

According to [112], there is a growing imperative for companies to be able to mine and process big data in order to improve competitiveness. As a result, these enablers are the first step to identify and remove adoption barriers. For example,

Table 1 Power plant maintainomics enabler categories and the involving empowering elements

Set no.	Enabler category	Empowering element	References
Set 1	Behavioral	1. Top management commitment	[2, 52, 53]
		2. Clear vision	[54, 55]
		3. Comprehension on communication revolution	[56]
		4. Stay competitive	[52]
		5. Team spirit and motivation	[57]
		6. Attainability of trained employee	[58–60]
Set 2	Non-behavioral	1. Availability of data collection, storage, and analytic choices	[9, 61–64]
		2. Availability of good e-maintenance architecture and platform	[9, 14, 37, 39, 65–68]
		3. Availability of usable asset self-identification	[3, 13, 60]
		4. Availability of good suppliers	[2]
Set 3	Financial	1. Funding direct from companies	[59, 69]
		2. Funding from private sectors	[11, 59, 69]
		3. Funding from government	[55, 60, 69, 70]
		4. Funding from international cooperation	[11, 69, 71]
		5. Financial incentives	[13]
Set 4	Methodological	1. Effective data mining technologies	[72–74]
		2. Online conditional monitoring	[75]
		3. Effective use of data collection standards	[76],[55]
		4. Unmanned inspection	[77–81]

(continued)

Table 1 (continued)

Set no.	Enabler category	Empowering element	References
Set 5	Operational	1. Power plant maintenance scheduling (PPMS) optimize techniques	[82–85]
		2. Autonomous and/or remote machine condition inspection	[86–90]
		3. Advanced machine learning and computational intelligence techniques for processing big data	[91, 92]
		4. Open-source technologies (e.g., Hadoop) and parallel programming model (e.g., MapReduce)	[93–98]
		5. Advanced sensor technology, e.g., RFID	[3, 99–102]
		6. Proper decision making regarding the machine condition	[103–107]
Set 6	Human and cultural	1. Data-centric enterprise organizational culture	[31, 59, 70]
		2. People and skills challenges	[59, 60]
		3. Capability of making better decisions	[108]
		4. Maintenance culture	[109]
		5. Culture clash between traditional business analysts, statisticians, data-application developers, and others	[110]

McKinsey Institute pointed out in a report [53] that if top managers can rethink the role of information in business and invest in better systems (or personnel) to dissect and interpret big data, they ought to gain customer insights, effect more accurate budgeting and better performance management. In a similar vein, [52] suggested that success in the data-driven economy (e.g., e-maintenance) need to access and analyze endless insights on their business. Trouble is, there is huge gaps exist between what organizations want to have and what they are able to do. As advocated in [55] that one of important things is to make sure you have clear vision on the definition being used by your organization, because big data is not just a single set of data, it is able to connect different sets of data together and therefore to create even more sets of information. In addition, several authors (e.g., [58, 59]) concluded that to educate themselves (e.g., plant executives, maintenance managers, and work planners) on how to manipulate and analyze data can help the organizations to make effective decisions. Also, to change attitudes toward the practicality of working with large data stores [57] and to comprehend communication revolution [56] (e.g., a surge in machine-to-machine communications, increased interaction via mobile devices, and massive using of tracking systems) are important, because most companies' internal IT functions aren't up to the job.

5.2 Non-behavioral Enabler Category (E_2)

This enabler group refers to those theoretical foundations that are necessary for supporting e-maintenance deployment and data analysis. Main characteristic of maintainomics is that maintenance information and access to related services can become ubiquitous and transparently available across the maintenance operations chain. For this purpose, researchers increasingly deal with a variety of research fields ranging from operation & maintenance engineering, to software engineering, information and communication systems, and business management [2]. For example, several comprehensive architectural frameworks for e-maintenance have been proposed, such as [14, 37, 65]. In addition, from a technological point of view, maintainomics is made-up from one or several networks with servers (e.g., Intra-Net), wireless technologies (e.g., ZigBee), databases (e.g., open systems architecture for condition based maintenance (OSA-CBM)), semantic data modelling (e.g., MapReduce programming model), smart sensors [e.g., micro electro mechanical systems (MEMS)], personnel mobility supporting (e.g., tablets), and many more. Also, within maintainomics, asset self-identification [e.g., radio frequency identification (RFID)] is a key factor [60]. Furthermore, suppliers are the key non-behavioral enabler as well, because they can develop, evolve, and maintain products and services [2].

5.3 Financial Enabler Category (E_3)

This enabler set deals with the economic aspects of maintainomics. Collecting maintenance data, analyzing, using and integrating them within different organizations, requires financial supporting. Indeed, the era of big data reshapes the innovation processes from companies to private sectors, government and international cooperation. For example, the PROTEUS project is a collaborative initiative for implementation of web-based e-maintenance centers in Europe [71]. The Dynamite project which is founded by EU as well focused on a set of methodologies and tools to support the e-maintenance processes, such as smart tags, common database schemas, and financial cost-efficiency assessment [60]. In 2012, the White house launched a $200 million initiative and pointed out that the big data research can help government eases their tasks somehow and thus reducing the problems faced [70]. In order to view the different information types on the same computer terminal, the machinery information management open system alliance (MIMOSA) worked closely with the international standards organization (ISO) for machine condition assessment [60]. Also, several private sectors (e.g., healthcare, manufacturing, and consumer products) worked towards big data research [59, 69]. On the other hand, data itself offers opportunities for the companies. According to [13], an increasing number of companies recognize that e-maintenance can be seen as a business opportunity rather than a cost center.

5.4 Methodological Enabler Category (E_4)

This enabler classification concerns about the physical requirements for the efficient collection of maintenance related data, and the use of various approaches for the efficient data analysis. Different kinds of smart data acquisition devices are commercial available in the market. By investing heavily, most of them are purchasable. Nevertheless, to reach the full potential of maintainomics, a careful selection of suitable equipments and the proper use of data analyzing techniques are two things that we need to think twice before taking action. Looking at computational intelligence (CI), a powerful tool for data mining, as a branch of artificial intelligence, the development of CI enjoys a tremendous prosperity during the past two decades [92]. By mimicking some nature sourced principles, CI algorithms can offer us the capability of digging out the hidden patterns and/or correlations from a biggish data set. The potential of big data cannot be interpreted in a meaningful way without the help of novel computational data mining algorithms.

5.5 Operational Enabler Category (E_5)

This enabler category is related to the question of how to deal with the challenges of very large datasets in order to improve asset reliability and reduce maintenance outages? Several authors (e.g., [9, 13, 60, 113]) pointed out that colleting, storing, and retrieving all maintenance data (e.g., vibration analysis, non-destructive testing results, and digital images) is critical to resolving an unplanned equipment failure. As a result, more companies are rethinking their planning, operations and IT functions to improve their maintenance processes through large data sets. This requires more efficient scheduling optimization techniques, autonomous and/or remote online monitoring systems (e.g., [87]), new open-source technologies (e.g., non-relational databases, distributed processing framework, and parallel programming model), mature wireless sensor tools (e.g., RFID), and proper decision making regarding the machine condition to work together. For example, different optimization methods (e.g., ant colony optimization [82], artificial bee colony [114], dynamic programming, [115] genetic algorithm [116], simulated annealing [117], and hybrid approaches [118]) have been proposed in the literature to solve maintenance scheduling problem of power systems. Ref. [102] pointed out that smart wireless technology can help operators to identify failed steam traps and leaks as early as possible. In addition, thanks to the new open-source technologies (such as Hadoop), the operators' ability to process large datasets has been significantly improved.

5.6 Human and Cultural Enabler Category (E_6)

The last category focuses on the "soft" factors that affect the adoption of maintainomics. Nowadays, scholars convinced that companies who gain deeper insights into the data can gain superior value in a competitive marketplace. In addition, they agreed that the technology issues are not the biggest barrier [59]. Instead, the majority initiatives have failed to deliver expected results due to those initiatives have ignored the human and cultural side of organizations. For example, recent economist intelligence unit report pointed out that people and skills challenges, process and organizational structure considerations, and cultural changes are the key factors associated with successfully implementing big data initiatives [59]. In a similar vein, report [108] emphasized that democratization of data-driven decision-making, making cross-functional teams big data strategy architects, and leveraging key data and departments are largely aspirational. Another sub-enabler affecting the rapidly of adoption of maintainomics in organization is maintenance culture, with the idea that creation of new maintenance practices. For example, ref. [109] reviewed the maintenance culture in Nigeria and highlighted that poor maintenance culture (e.g., unplanned maintenance services, poor user habits, and lack of awareness) affects the productivity of Nigeria power generation stations.

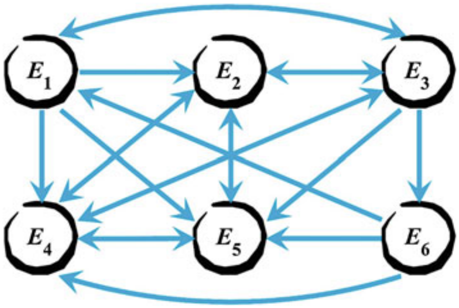

Fig. 3 Maintainomics scenario digraph representation

Finally, the different culture between developers, traditional business analysts, and systems administrators is also a crucial factor that affect the adoption of maintainomics.

5.7 Maintainomics Scenario Digraph Representation

According to the six main enabler categories and their associated interdependency, a maintainomics digraph can be drawn as depicted in Fig. 3:

Based on the derived maintainomics enabler categories' diagraph, the system level maintainomics matrix [see Sect. 4.2.2 for more details about its original form, i.e., Eq. (4)] can be re-written as Eq. (12):

$$\mathbf{F} = \begin{matrix} \text{Enabler} \\ \text{Categories} \\ E_1 \\ E_2 \\ E_3 \\ \vdots \\ \vdots \\ E_P \end{matrix} \begin{matrix} \begin{matrix} E_1 & E_2 & E_3 & \cdots & \cdots & E_P \end{matrix} \\ \begin{pmatrix} E_1 & e_{12} & e_{13} & \cdots & \cdots & e_{1P} \\ e_{21} & E_2 & e_{23} & \cdots & \cdots & e_{2P} \\ e_{31} & e_{32} & E_3 & \cdots & \cdots & e_{3P} \\ \vdots & \vdots & \vdots & \ddots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ e_{P1} & e_{P2} & e_{P3} & \cdots & \cdots & E_P \end{pmatrix} \end{matrix}$$
$$\Downarrow$$
$$\mathbf{F}^* = \begin{matrix} \text{Enabler} \\ \text{Categories} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \end{matrix} \begin{matrix} \begin{matrix} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{matrix} \\ \begin{pmatrix} E_1 & e_{12} & e_{13} & e_{14} & e_{15} & 0 \\ 0 & E_2 & e_{23} & e_{24} & e_{25} & 0 \\ e_{31} & e_{32} & E_3 & e_{34} & e_{35} & e_{36} \\ 0 & e_{42} & e_{43} & E_4 & e_{45} & 0 \\ 0 & e_{52} & 0 & e_{54} & E_5 & 0 \\ e_{61} & 0 & 0 & e_{64} & e_{65} & E_6 \end{pmatrix} \end{matrix} \quad (12)$$

6 Experimental Study Stage-2: FIT Value Calculation for Quantification Purpose

Obtaining a holistic digraph serves as a starting point for calculating the required FIT value that matches our maintainomics scenario. Apart from this, the following tasks also need to be performed.

Based on the identified empowering element under each enabler category, a set of digraphs are developed (as illustrated in Fig. 4a–f). Unlike the global digraph delineated in Fig. 3, the nodes in this local digraph stand for the empowering elements, while the edges are used to indicate their mutual relationship.

As shown in Fig. 4, according to the introduced measure scale, i.e., 1–10 for inheritance and 1–5 for interdependence, each enabler category's matrix and the corresponding permanent function value can also be obtained. A detailed breakdown of such computing process is demonstrated through $\mathbf{F}_1^*$ and $f_{permanent}^{\mathbf{F}_1^*}$.

Accordingly, the system level maintainomics matrix can be further re-written like Eq. (13) [see Sect. 5.7 for its intermediate form, i.e., Eq. (12)].

$$\mathbf{F}^* = \begin{array}{c} \text{Enabler Categories} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \end{array} \begin{array}{c} \begin{array}{cccccc} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{array} \\ \begin{pmatrix} E_1 & e_{12} & e_{13} & e_{14} & e_{15} & 0 \\ 0 & E_2 & e_{23} & e_{24} & e_{25} & 0 \\ e_{31} & e_{32} & E_3 & e_{34} & e_{35} & e_{36} \\ 0 & e_{42} & e_{43} & E_4 & e_{45} & 0 \\ 0 & e_{52} & 0 & e_{54} & E_5 & 0 \\ e_{61} & 0 & 0 & e_{64} & e_{65} & E_6 \end{pmatrix} \end{array}$$

$$\Downarrow$$

$$\mathbf{F}^* = \begin{array}{c} \text{Enabler Categories} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \end{array} \begin{array}{c} \begin{array}{cccccc} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{array} \\ \begin{pmatrix} 165038 & 2 & 2 & 4 & 3 & 0 \\ 0 & 3500 & 4 & 4 & 3 & 0 \\ 1 & 2 & 10167 & 4 & 3 & 3 \\ 0 & 4 & 4 & 3855 & 4 & 0 \\ 0 & 3 & 0 & 3 & 14690 & 0 \\ 3 & 0 & 0 & 2 & 3 & 26426 \end{pmatrix} \end{array} . \quad (13)$$

where the values of diagonal entries are replaced by just acquired sub-systems' permanent function values, namely, $E_1 = f_{permanent}^{\mathbf{F}_1^*} = 165038$, $E_2 = f_{permanent}^{\mathbf{F}_2^*} = 3500$, $E_3 = f_{permanent}^{\mathbf{F}_3^*} = 10167$, $E_4 = f_{permanent}^{\mathbf{F}_4^*} = 3855$, $E_5 = f_{permanent}^{\mathbf{F}_6^*} = 14690$, and $E_6 = f_{permanent}^{\mathbf{F}_6^*} = 26426$, while the corresponding scale value (1–5) are used to substitute the values of e_{ij}.

At this stage, the system level permanent function value, i.e., $f_{permanent}^{\mathbf{F}^*}$, is calculable which is found to be equal to 9.32018×10^{25}. Accordingly, the proposed

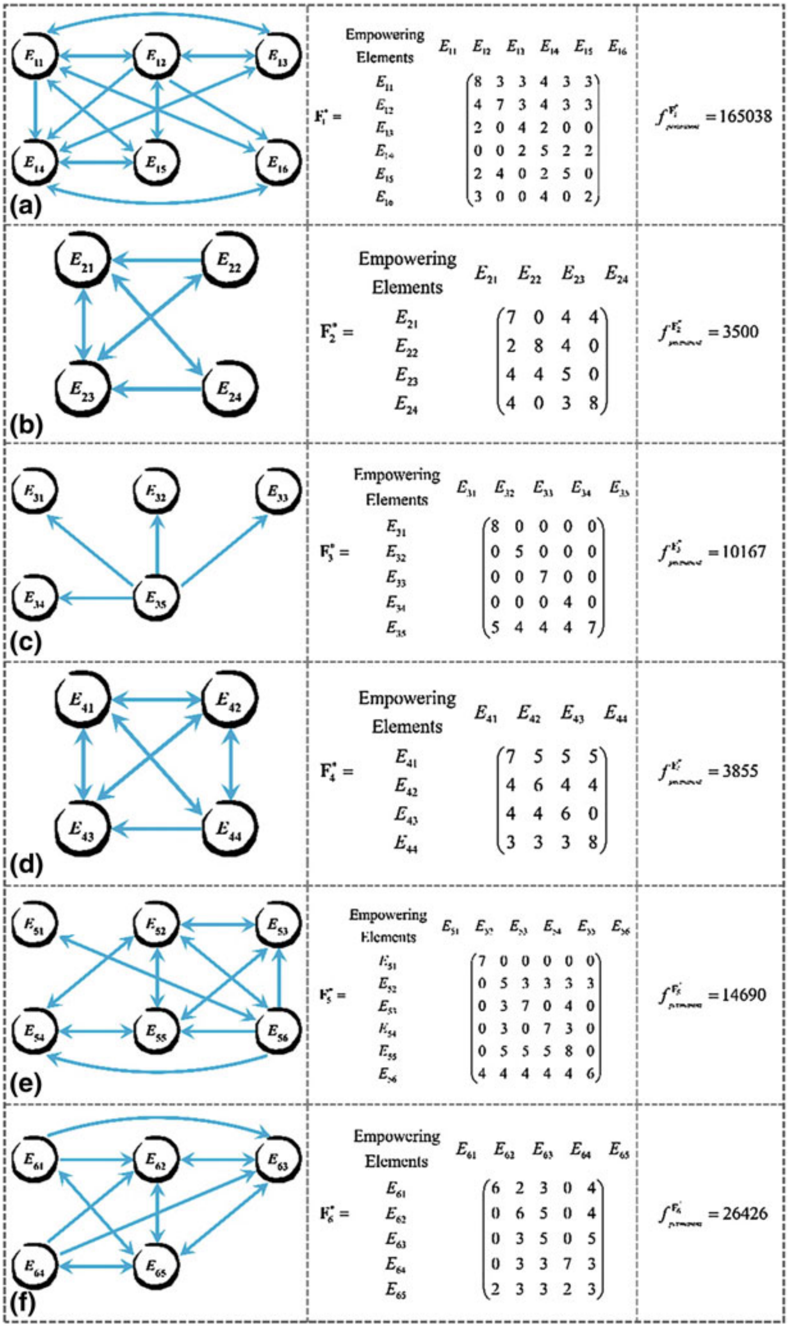

Fig. 4 Digraph representation for empowering elements

FIT measurement mathematically characterizes the feasibility of the chosen case in converting itself to the maintainomics scenario.

7 Experimental Study Stage-3: FIT Value Calculation for Comparison Purpose

In order to illustrate the usefulness of the proposed FIT measurement, a comparison study between two power plants is further introduced in this section in which the comparison approach is based on the methodology detailed in Sect. 4.2.5, while the selected power plant cases are briefed as follows:

- Power plant 1—fossil power plant: it is well known that fossil fuel-fired power plants are the main sources of power generating. Traditionally, power companies put "fail and fix" strategy into maintenance practices. However, as the pressure of rapid development around the globe, there is a need to continuously reduce unscheduled downtime and unexpected breakdowns.
- Power plant 2—wind power plant: several authors (e.g., [119–122]) convinced that wind power plants brings huge benefits for electricity generation due to they are clean, inexhaustible, and reduce the noise and visual disturbance to people. However, the wind industry is facing challenges with high installation and maintenance costs, and potentially longer time out of operation at failures [123, 124].

The required values for power plant 1 (PP_1) are already known through Sects. 5 and 6. Following the similar procedure, the values for power plant 2 (PP_2) are also obtainable. All values are listed below:

- PP_1: $E_1^{PP_1} = 165038$, $E_2^{PP_1} = 3500$, $E_3^{PP_1} = 10167$, $E_4^{PP_1} = 3855$, $E_5^{PP_1} = 14690$, $E_6^{PP_1} = 26426$, $e_{12}^{PP_1} = 2$, $e_{13}^{PP_1} = 2$, $e_{14}^{PP_1} = 4$, $e_{15}^{PP_1} = 3$, $e_{23}^{PP_1} = 4$, $e_{24}^{PP_1} = 4$, $e_{25}^{PP_1} = 3$, $e_{31}^{PP_1} = 1$, $e_{32}^{PP_1} = 2$, $e_{34}^{PP_1} = 4$, $e_{35}^{PP_1} = 3$, $e_{36}^{PP_1} = 3$, $e_{42}^{PP_1} = 4$, $e_{43}^{PP_1} = 4$, $e_{45}^{PP_1} = 4$, $e_{52}^{PP_1} = 3$, $e_{54}^{PP_1} = 3$, $e_{61}^{PP_1} = 3$, $e_{64}^{PP_1} = 2$, $e_{65}^{PP_1} = 3$,

$$\mathbf{F}^*_{PP_1} = \begin{array}{c} \text{Enabler Categories} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \end{array} \begin{array}{c} \begin{array}{cccccc} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \end{array} \\ \begin{pmatrix} 165038 & 2 & 2 & 4 & 3 & 0 \\ 0 & 3500 & 4 & 4 & 3 & 0 \\ 1 & 2 & 10167 & 4 & 3 & 3 \\ 0 & 4 & 4 & 3855 & 4 & 0 \\ 0 & 3 & 0 & 3 & 14690 & 0 \\ 3 & 0 & 0 & 2 & 3 & 26426 \end{pmatrix} \end{array},$$

and $f_{permanent}^{\mathbf{F}^*_{PP_1}} = 9.32018 \times 10^{25}$.

- PP_2: $E_1^{PP_2} = 6863$, $E_2^{PP_2} = 1899$, $E_3^{PP_2} = 89689$, $E_4^{PP_2} = 5897$, $E_5^{PP_2} = 198996$, $E_6^{PP_2} = 9879$, $e_{12}^{PP_2} = 3$, $e_{13}^{PP_2} = 2$, $e_{14}^{PP_2} = 4$, $e_{15}^{PP_2} = 3$, $e_{16}^{PP_2} = 5$, $e_{24}^{PP_2} = 2$,

$e_{25}^{PP_2} = 4,\quad e_{31}^{PP_2} = 2,\quad e_{32}^{PP_2} = 2,\quad e_{34}^{PP_2} = 4,\quad e_{35}^{PP_2} = 2,\quad e_{36}^{PP_2} = 2,\quad e_{43}^{PP_2} = 3,$
$e_{45}^{PP_2} = 4,\quad e_{54}^{PP_2} = 5,\quad e_{61}^{PP_2} = 4,\quad e_{64}^{PP_2} = 4,\quad e_{65}^{PP_2} = 3,$

$$\mathbf{F}^*_{PP_2} = \begin{array}{c} \text{Enabler} \\ \text{Categories} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \end{array} \begin{array}{c} \quad E_1 \quad E_2 \quad E_3 \quad E_4 \quad E_5 \quad E_6 \\ \begin{pmatrix} 6863 & 3 & 2 & 4 & 3 & 5 \\ 0 & 1899 & 0 & 2 & 4 & 0 \\ 1 & 2 & 89689 & 4 & 2 & 2 \\ 0 & 0 & 3 & 5897 & 4 & 0 \\ 0 & 0 & 0 & 5 & 198996 & 0 \\ 4 & 0 & 0 & 4 & 3 & 9879 \end{pmatrix} \end{array}, \text{ and}$$

$f_{permanent}^{\mathbf{F}^*_{PP_2}} = 1.628 \times 10^{25}.$

According to Eq. (10) (see Sect. 4.2.5), $U =$ maximum of $\left[\sum_{i,j} |Z_{ij}|\right.$ and $\left.\sum_{i,j} |Z'_{ij}|\right] = f_{permanent}^{\mathbf{F}^*_{PP_1}} = 9.32018 \times 10^{25}$, and $\sum_{i,j} \lambda_{ij} = \sum_{i,j} |Z_{ij} - Z'_{ij}| = 7.69218 \times 10^{25}$, the dissimilarity coefficient $Coefficient_{dissimilarity}$ and the similarity coefficient $Coefficient_{similarity}$ equals to 0.78 and 0.22, respectively.

The results of this work indicate that the dissimilarity degree between PP_1 and PP_2 is high. In addition to this, although the overall permanent function value of PP_2 is lower than its competitor PP_1, PP_2 enjoys a high permanent function value for its methodological and operational enabler categories. On the contrary, PP_1 possesses a higher permanent function value for its behavioral enabler category which in turn implies the suitability for transition to maintainomics is largely influenced by the this enabler category and its associated empowering elements.

8 Future Work

In this chapter, a GTA-based FIT assessment methodology has been successfully applied to our focal problem, i.e., maintainomics transformation. Although the present work offers some novel contributions to both big data and maintenance literature, there is still room for further improvement. One immediately future research direction would be introducing fuzzy graph model. It is quite well acknowledged that graphs are simple models that are easy to use for representing interrelationships between objects in which objects are denoted by vertices, while the correlations are indicated by edges. Nevertheless, in spite of its convenience, when it comes to the situation of vagueness contained in the objects' description, or found in the relationships, or in both, traditional GTA often performs poorly [125]. The numerical values assigned to E_i and e_{ij}, respectively, in this study are crisp and deterministic in nature. With the ever increasing complexity of many modern systems (e.g., maintainomics case), the uncertainty gradually plays a pivotal role in any attempts of trying to optimize and maximize the overall system model's usefulness. Under such circumstances, the introduction and application of fuzzy relations to maintainomics FIT evaluation becomes necessary and important. Once the feasibility of the maintainomics is confirmed, another future research direction will be bringing more CI methods into e-maintenance operational level for dealing with big data analytics.

9 Conclusion

Thanks to the use of sensors in maintenance (e.g., online monitoring, smart meters, etc.), the rate of growth of generated sensory data far outstrips human capacity to consume it. As a result, enterprises increasingly meet the challenges imposed by how to convert myriads of available raw data to high-level actionable information. This book chapter studies such emerging phenomena and builds a set of enablers to address those issues. The end-product of this chapter is maintainomics, a new concept that facilitates the entry of e-maintenance to any enterprises by evaluating a permanent feasibility function obtained from an enablers' digraph. The experimental studies demonstrated the suitability of our proposed methodology.

References

1. Muller, A., Suhner, M.-C., Iung, B.: Maintenance alternative integration to prognosis process engineering. J. Qual. Maint. Eng. **13**, 198–211 (2007)
2. Kajko-Mattsson, M., Karim, R., Mirjamdotter, A.: Essential components of e-maintenance. Int. J. Perform. Eng. **7**, 555–571 (2011)
3. Haider, A., Koronios, A.: e-prognostics: a step towards e-maintenance of engineering assets. J. Theor. Appl. Electron. Commer. Res. **1**, 42–55 (2006)
4. Lee, J., Ni, J., Djurdjanovic, D., Qiu, H., Liao, H.: Intelligent prognostics tools and e-maintenance. Comput. Ind. **57**, 476–489 (2006)
5. Campos, J.: Development in the application of ICT in condition monitoring and maintenance. Comput. Ind. **60**, 1–20 (2009)
6. Jardine, A.K.S., Lin, D., Banjevic, D.: A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech. Syst. Signal Process. **20**, 1483–1510 (2006)
7. Niu, G., Yang, B.-S., Pecht, M.: Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance. Reliab. Eng. Syst. Saf. **95**, 786–796 (2010)
8. Iung, B.: From remote maintenance to MAS-based e-maintenance of an industrial process. J. Intell. Manuf. **14**, 59–82 (2003)
9. Levrat, E., Iung, B., Marquez, A.C.: e-maintenance: a review and conceptual framework. Prod. Plann. Control **19**, 408–429 (2008)
10. Muller, A., Marquez, A.C., Iung, B.: On the concept of e-maintenance: review and current research. Reliab. Eng. Syst. Saf. **93**, 1165–1187 (2008)
11. Karim, R., Candell, O., Söderholm, P.: e-maintenance and information logistics: aspects of content format. J. Qual. Maint. Eng. **15**, 308–324 (2009)

12. Karim, R., Söderholm, P., Candell, O.: Development of ICT-based maintenance support services. J. Qual. Maint. Eng. **15**, 127–150 (2009)
13. Jantunen, E., Emmanouilidis, C., Arnaiz, A., Gilabert, E.: e-maintenance: trends, challenges and opportunities for modern industry. In: Proceedings of the 18th IFAC World Congress, pp. 453-458. Milano, Italy, 28 Aug–02 Sept 2011
14. Han, T., Yang, B.-S.: Development of an e-maintenance system integrating advanced techniques. Comput. Ind. **57**, 569–580 (2006)
15. Choi, J.-B., Yeum, S.-W., Ko, H.-O., Kim, Y.-J., Kim, H.-K., Choi, Y.-H., et al.: Development of a web-based aging monitoring system for an integrity evaluation of the major components in a nuclear power plant. Int. J. Press. Vessels Pip. **87**, 33–40 (2010)
16. Vo, C.C., Chilamkurti, N., Loke, S.W., Torabi, T.: Radio-Mama_an RFID based business process framework for asset management. J. Netw. Comput. Appl. **34**, 990–997 (2011)
17. Miertschin, K.W., Forrest, B.D.: Analysis of Tobyhanna army depot's radio frequency identification (RFID) pilot program: RFID as an asset management tool. Master thesis, Naval Postgraduate School, Monterey, CA, USA, 2005
18. Mahakul, T.K., Baboo, S., Patnaik, S.: Implementation of enterprise asset management using IT tools: a case study of IB thermal power station. J. Inf. Technol. Manage. **XVI**, 39–67 (2005)
19. Briones, L., Bustamante, P., Serna, M.A.: Robicen: a wall-climbing pneumatic robot for inspection in nuclear power plants. Robot. Comput. Integr. Manuf. **11**, 287–292 (1994)
20. Balaguer, C., Gimenez, A., Jardon, A.: Climbing robots' mobility for inspection and maintenance of 3D complex environments. Auton. Robots **18**, 157–169 (2005)
21. Luk, B.L., Cooke, D.S., Galt, S., Collie, A.A., Chen, S.: Intelligent legged climbing service robot for remote maintenance applications in hazardous environments. Robot. Auton. Syst. **53**, 142–152 (2005)
22. Wang, W., Wang, K., Zhang, H.: Crawling gait realization of the mini-modular climbing caterpillar robot. Prog. Nat. Sci. **19**, 1821–1829 (2009)
23. Lim, J., Park, H., An, J., Hong, Y.-S., Kim, B., Yi, B.-J.: One pneumatic line based inchworm-like micro robot for half-inch pipe inspection. Mechatronics **18**, 315–322 (2008)
24. Neubauer, W.: A spider-like robot that climbs vertically in ducts or pipes. In: Presented at the Proceedings of IEEE/RSJ International Conference on Intelligent Robotics and Systems, pp. 1178-1185, 1994
25. Prasad, E.N., Kannan, M., Azarudeen, A., Karuppasamy, N.: Defect identification in pipe lines using pipe inspection robot. Int. J. Mech. Eng. Robot. Res. **1**, 20–31 (2012)
26. Hu, Z., Appleton, E.: Dynamic characteristics of a novel self-drive pipeline pig. IEEE Trans. Rob. **21**, 781–789 (2005)
27. Schmidt, D., Berns, K.: Climbing robots for maintenance and inspections of vertical structures—a survey of design aspects and technologies. Robot. Auton. Syst. **61**, 1288–1305 (2013)
28. Roslin, N.S., Anuar, A., Jalal, M.F.A., Sahari, K.S.M.: A review: hybrid locomotion of in-pipe inspection robot. Proc. Eng. **41**, 1456–1462 (2012)
29. Manyika, J., Chui, M., Brown, B., Bughin, J., Dobbs, R., Roxburgh, C., et al.: Big Data: The Next Frontier for Innovation, Competition, and Productivity. McKinsey Global Institute, Washington (2011)
30. O'Driscoll, A., Daugelaite, J., Sleator, R.D.: 'Big data', Hadoop and cloud computing in genomics. J. Biomed. Inform. **46**, 774–781 (2013)
31. Chang, R.M., Kauffman, R.J., Kwon, Y.: Understanding the paradigm shift to computational social science in the presence of big data. Decis. Support Syst. **63**, 67–80 (2014)
32. Wu, X., Zhu, X., Wu, G.-Q., Ding, W.: Data mining with big data. IEEE Trans. Knowl. Data Eng. **26**, 97–107 (2014)
33. Dai, J., Huang, J., Huang, S., Liu, Y., Sun, Y.: The Hadoop stack: new paradigm for big data storage and processing. Int. Technol. J. **16**, 92–110 (2012)
34. Sagiroglu, S., Sinanc, D.: Big data: a review. In: Presented at the 2013 International Conference on Collaboration Technologies and Systems (CTS), pp. 42-47, 2013

35. Nieva, T., Wegmann, A.: A conceptual model for remote data acquisition systems. Comput. Ind. **47**, 215–237 (2002)
36. Kans, M., Ingwald, A.: Common database for cost-effective improvement of maintenance performance. Int. J. Prod. Econ. **113**, 734–747 (2008)
37. Pistofidis, P., Emmanouilidis, C., Koulamas, C., Karampatzakis, D., Papathanassiou, N.: A layered e-maintenance architecture power by smart wireless monitoring components. In: Proceedings of the 2012 International Conference on Industrial Technology (ICIT), pp. 1-6, 2012
38. Iung, B., Marquez, A.C.: Special issue on e-maintenance. Comput. Ind. **57**, 473–475 (2006)
39. Iung, B., Levrat, E., Marquez, A.C., Erbe, H.: Conceptual framework for e-maintenance: illustration by e-maintenance technologies and platforms. Ann. Rev. Control **33**, 220–229 (2009)
40. Yao, Y.: A spectrum decision support system for cognitive radio networks. Licentiate Thesis, School of Computing, Blekinge Institute of Technology, Karlskrona, Sweden, 2012
41. Marais, K.B., Saleh, J.H.: Beyond its cost, the value of maintenance: an analytical framework for capturing its net present value. Reliab. Eng. Syst. Saf. **94**, 644–657 (2009)
42. Kalafatas, G.: A graph theoretic modeling framework for generalized transportation systems with congestion phenomena. PhD thesis, Purdue University, West Lafayette, Indiana, 2010
43. Thakkar, J., Kanda, A., Deshmukh, S.G.: Evaluation of buyer-supplier relationships using an integrated mathematical approach of interpretive structural modeling (ISM) and graph theoretic matrix: the case study of Indian automotive SMEs. J. Manuf. Technol. Manage. **19**, 92–124 (2008)
44. Franceschet, M., Gubiani, D., Montanari, A., Piazza, C.: A graph-theoretic approach to map conceptual designs to XML schemas. ACM Trans Database Syst **38**, 6:1–6:44 (2013)
45. Sabharwal, S., Garg, S.: Determining cost effectiveness index of remanufacturing: a graph theoretic approach. Int. J. Prod. Econ. **144**, 521–532 (2013)
46. Hou, F., Shen, W.-M.: Graph-based optimal reconfiguration planning for self-reconfigurable robots. Robot. Auton. Syst. **62**, 1047–1059 (2014)
47. Pishvaee, M.S., Rabbani, M.: A graph theoretic-based heuristic algorithm for responsive supply chain network design with direct and indirect shipment. Adv. Eng. Softw. **42**, 57–63 (2011)
48. Even, S., Even, G.: Graph Algorithms, 2nd edn. Cambridge University Press, New York (2012). ISBN 978-0-521-51718-8
49. Mesbahi, M., Egerstedt, M.: Graph Theoretic Methods in Multiagent Networks. Princeton University Press, Princeton (2010). ISBN 978-0-691-14061-2
50. Kreyszig, E., Kreyszig, H., Norminton, E.J.: Advanced Engineering Mathematics, 10th edn. Wiley, Hoboken (2011). ISBN 978-0-470-45836-5
51. Raj, T., Shankar, R., Suhaib, M.: GTA-based framework for evaluating the feasibility of transition to FMS. J. Manuf. Technol. Manage. **21**, 160–187 (2010)
52. Johnson, J.E.: Big data + big analytics = big opportunity. Financ. Executive **28**, 50–53 (2012)
53. Brynjolffson, E., Hammerbacher, J., Stevens, B.: Competing Through Data: Three Experts Offer Their Game Plans. McKinsey Global Institute, Washington (2011)
54. Buhl, H.U., Röglinger, M., Moser, F., Heidemann, J.: Big data: a fashionable topic with(out) sustainable relevance for research and practice? Bus. Inf. Syst. Eng. **2**, 65–69 (2013)
55. Jackson, R.A.: Big data big risk. Internal Auditor **70**, 34–38 (2013)
56. Big data needn't be a big headache: how to tackle mind-blowing amounts of information. Strateg. Dir. **28**, 22–24 (2012)
57. Alstyne, M.V., Brynjolfsson, E., Madnick, S.: Why not one big database: principles for data ownership. Decis. Support Syst. **15**, 267–284 (1995)
58. Chen, H., Chiang, R.H.L., Storey, V.C.: Business intelligence and analytics: from big data to big impact. MIS Q. **36**, 1165–1188 (2012)

59. Watson, J.: Big Data and Consumer Products Companies: People, Processes and Culture Barriers. The Economist Intelligence Unit Limited, London, New York, Hong Kong, Geneva (2013)
60. Emmanouilidis, C., Jantunen, E., Gilabert, E., Arnaiz, A., Starr, A.: e-maintenance update: the road to success for modern industry. In: Proceedings of the 24th International Congress on Condition Monitoring and Diagnostics Engineering Management, pp. 1–10. Stavanger, Norway, ISBN 0-9541307-2-3, 2011
61. Computer_Weekly. (2013) Big data storage choices. Computer Weekly 1–3
62. Huang, Y.-S., Duy, D., Fang, C.-C.: Efficient maintenance of basic statistical functions in data warehouses. Decis. Support Syst. **57**, 94–104 (2014)
63. Xu, X.-B., Yang, Z.-Q., Xiu, J.-P., Liu, C.: A big data acquisition engine based on rule engine. J. China Univ. Posts Telecommun. **20**, 45–49 (2013)
64. Urbani, J., Kotoulas, S., Maassen, J., Harmelen, F.V., Bal, H.: WebPIE: a Web-scale parallel inference engine using MapReduce. Web Semant.: Sci. Serv. Agents World Wide Web **10**, 59–75 (2012)
65. Candell, O., Karim, R., Parida, A.: Development of information system for e-maintenance solutions within the aerospace industry. Int. J. Perform. Eng. **7**, 583–592 (2011)
66. Chebel-Morello, B., Medjaher, K., Arab, A.H., Bandou, F., Bouchaib, S., Zerhouni, N.: e-maintenance for photovoltaic power generation system. Energy Proc. **18**, 640–643 (2012)
67. Hung, M.-H., Chen, K.-Y., Ho, R.-W., Cheng, F.-T.: Development of an e-diagnostics/maintenance framework for semiconductor factories with security considerations. Adv. Eng. Inform. **17**, 165–178 (2003)
68. Yu, R., Iung, B., Panetto, H.: A multi-agents based e-maintenance system with case-based reasoning decision support. Eng. Appl. Artif. Intell. **16**, 321–333 (2003)
69. Katal, A., Wazid, M., Goudar, R.H.: Big data: issues, challenges, tools and good practices. In: Presented at the 2013 Sixth International Conference on Contemporary Computing (IC3), pp. 404–409, 2013
70. Gobble, M.M.: Big data: the next big thing in innovation. Res. Technol. Manage. **56**, 64–66 (2013)
71. Hausladen, I., Bechheim, C.: e-maintenance platform as a basis for business process integration. In: Proceedings of the 2nd IEEE International Conference on Industrial Informatics (INDIN), pp. 46–51, 2004
72. Crowe, J., Candlish, J.R.: Data analytics: the next big thing in information. Grey J. **9**, 157–159 (2013)
73. Lee, J., Lapira, E., Bagheri, B., Kao, H.-A.: Recent advances and trends in predictive manufacturing systems in big data environment. Manuf. Lett. **1**, 38–41 (2013)
74. Pedrycz, W.: Granular Computing: Analysis and Design of Intelligent Systems. CRC Press, Boca Raton (2013). ISBN 978-1439886816
75. Yam, R.C.M., Tse, P.W., Li, L., Tu, P.: Intelligent predictive decision support system for condition-based maintenance. Int. J. Adv. Manuf. Technol. **17**, 383–391 (2001)
76. Cumbley, R., Church, P.: Is "Big Data" creepy. Comput. Law Secur. Rep. **29**, 601–609 (2013)
77. Bloss, R.: By air, land and sea, the unmanned vehicles are coming. Ind. Robot **34**, 12–16 (2007)
78. Pagnano, A., Höpf, M., Teti, R.: A roadmap for automated power line inspection. Maintenance and repair. Proc. CIRP **12**, 234–239 (2013)
79. Jones, D.I., Earp, G.K.: Camera sightline pointing requirements for aerial inspection of overhead power lines. Electr. Power Syst. Res. **57**, 73–82 (2001)
80. Wan, S., Bian, X., Chen, L., Yu, D., Wang, L., Guan, Z.: Electrostatic discharge effect on safe distance determination for 500 kV ac power line's helicopter inspection. J. Electrostat. **71**, 778–780 (2013)
81. Jones, D.I., Whitworth, C.C., Earp, G.K., Duller, A.W.G.: A laboratory test-bed for an automated power line inspection system. Control Eng. Pract. **13**, 835–851 (2005)

82. Foong, W.K.: Ant colony optimization for power plant maintenance scheduling. Unpublished doctoral thesis, School of Civil and Environmental Engineering, University of Adelaide, 2007
83. Foong, W.K., Maier, H.R., Simpson, A.R.: Power plant maintenance scheduling using ant colony optimization. In: Chan, F.T.S., Tiwari, M.K. (eds.) Swarm Intelligence, Focus on Ant and Particle Swarm Optimization. Chapter 6, pp. 289–320. InTech, Vienna (2007). ISBN 978-3-902613-09-7
84. Foong, W.K., Simpson, A.R., Maier, H.R., Stolp, S.: Ant colony optimization for power plant maintenance scheduling optimization—a five-station hydropower system. Ann. Oper. Res. **159**, 433–450 (2008)
85. Mohanta, D.K., Sadhu, P.K., Chakrabarti, R.: Deterministic and stochastic approach for safety and reliability optimization of captive power plant maintenance scheduling using GA/SA-based hybrid techniques. Reliab. Eng. Syst. Saf. **92**, 187–199 (2007)
86. Netland, Y., Skavhaug, A.: Two pilot experiments on the feasibility of telerobotic inspection of offshore wind turbines. Presented at the 2nd Mediterranean Conference on Embedded Computing (MECD—2013, ECyPS'2013), Budva, Montenegro, pp. 1–4, 2013
87. Pan, M.-C., Li, P.-C., Cheng, Y.-R.: Remote online machine condition monitoring system. Measurement **41**, 912–921 (2008)
88. Das, J.D., S. Chowdhuri, J. Bera, and G. Sarkar, "Remote monitoring of different electrical parameters of multi-machine system using PC," *Measurement,* vol. 45, pp. 118-125, 2012
89. Mendoza-Jasso, J., Ornelas-Vargas, G., Castañeda-Miranda, R., Ventura-Ramos, E., Zepeda-Garrido, A., Herrera-Ruiz, G.: FPGA-based real-time remote monitoring system. Comput. Electron. Agric. **49**, 272–286 (2005)
90. Jonsson, K., Holmström, J., Levén, P.: Organizational dimensions of e-maintenance: a multi-contextual perspective. Int. J. Syst. Assur. Eng. Manage. **1**, 210–218 (2010)
91. Witten, I.H., Frank, E., Hall, M.A.: Data mining: practical machine learning tools and techniques, 3rd edn. Morgan Kaufmann, Elsevier Inc., Burlington (2011)
92. Xing, B., Gao, W.-J.: Innovative computational intelligence: a rough guide to 134 clever algorithms. Springer International Publishing Switzerland, Cham, Heidelberg, New York, Dordrecht, London, ISBN 978-3-319-03403-4 (2014)
93. Dai, J., Huang, J., Huang, S., Liu, Y., Sun, Y.: The Hadoop stack: new paradigm for big data storage and processing. Int. Technol. J. **16**, 92–110 (2012)
94. Patel, A.B., Birla, M., Nair, U.: Addressing big data problem using Hadoop and map reduce. In: Proceedings of 2012 Nirma University International Conference on Engineering (NUiCONE), pp. 1–5, 06–08 Dec 2012
95. Qiu, Z., Lin, Z.-W., Ma, Y.: Research of Hadoop-based data flow management system. J. China Univ. Posts Telecommun. **18**, 164–168 (2011)
96. Edwards, M., Rambani, A., Zhu, Y., Musavi, M.: Design of Hadoop-based framework for analytics of large synchrophasor datasets. Procedia Computer Science **12**, 254–258 (2012)
97. ElSheikh, G., ElNainay, M.Y., ElShehaby, S., Abougabal, M.S.: SODIM: service oriented data integration based on MapReduce. Alexandria Eng. J. **52**, 313–318 (2013)
98. Kolberg, W., Marcos, P.D.B., Anjos, J.C.S., Miyazaki, A.K.S., Geyer, C.R., Arantes, L.B.: MRSG—a MapReduce simulator over SimGrid. Parallel Comput. **39**, 233–244 (2013)
99. Ko, C.-H.: RFID-based building maintenance system. Autom. Constr. **18**, 275–284 (2009)
100. Osman, M.S., Ram, B., Stanfield, P., Samanlioglu, F., Davis, L., Bhadury, J.: Radio frequency identification system optimisation models for lifecycle of a durable product. Int. J. Prod. Res. **48**, 2699–2721 (2010)
101. Xing, B., Gao, W.-J., Marwala, T.: The applications of computational intelligence in radio frequency identification research. In: IEEE International Conference on Systems, Man, and Cybernetics (IEEE SMC), pp. 2067–2072. Seoul, Korea, 14–17 Oct 2012
102. MacDonald, I.: Smart wireless provides a sound basis for improved performance. Mod. Power Syst. 20–22 (2012)

103. Herzog, M.A.: Machine and component residual life estimation through the application of neural networks. Master thesis, Department of Mechanical and Aeronautical Engineering, Faculty of Engineering, University of Pretoria, Pretoria, South Africa, 2006
104. Herzog, M.A., Marwala, T., Heyns, P.S.: Machine and component residual life estimation through the application of neural networks. Reliab. Eng. Syst. Saf. **94**, 479–489 (2009)
105. Marwala, T.: Fault identification using neural networks and vibration data. Unpublished doctoral thesis, St. John's College, University of Cambridge, 2000
106. Xing, B., Gao, W.-J.: Computational Intelligence in Remanufacturing. IGI Global, Hershey (2014). ISBN 978-1-4666-4908-8
107. Gao, W.-J., Xing, B., Marwala, T.: Teaching—learning-based optimization approach for enhancing remanufacturability pre-evaluation system's reliability. In: IEEE Symposium Series on Computational Intelligence (IEEE SSCI), pp. 235-239. Singapore, 15–19 Apr 2013
108. Whelan, C.: Big data and the democratisation of decisions. The Economist Intelligence Unit Limited, London, New York, Hong Kong, Geneva (2012)
109. Onohaebi, O.S., Lawai, V.O.: Poor maintenance culture; the bane to electric power generation in Nigeria. J. Econ. Eng. 28–33 (2010)
110. Manoochehri, M.: Data just right: introduction to large-scale data and analytics. Pearson Education Inc, Upper Saddle River (2014). ISBN 978-0-321-89865-4
111. Pride, W.M., Hughes, R.J., Kapoor, J.R.: Business, 12th edn. South-Western, Cengage Learning, Mason (2014). 2014
112. Brown, B., Chui, M., Manyika, J.: Are you ready for the era of 'big data'?. McKinsey Global Institute, New York (2011)
113. Al-Qahtani, M.S., Aramco, S.: Information and communication technology infrastructure in e-maintenance. In: Proceedings of the Fourth International Conference on Information, Process, and Knowledge Management, ISBN 978-1-61208-181-6, pp. 7–11, 2012
114. Anandhakumar, R., Subramanian, S., Ganesan, S.: Modified ABC algorithm for generator maintenance scheduling. Int. J. Comput. Electr. Eng. **3**, 812–819 (2011)
115. Moghaddam, K.S., Usher, J.S.: Preventive maintenance and replacement scheduling for repairable and maintainable systems using dynamic programming. Comput. Ind. Eng. **60**, 654–665 (2011)
116. Wang, Y., Handschin, E.: A new genetic algorithm for preventive unit maintenance scheduling of power systems. Electr. Power Energy Syst. **22**, 343–348 (2000)
117. Saraiva, J.T., Pereira, M.L., Mendes, V.T., Sousa, J.C.: A simulated annealing based approach to solve the generator maintenance scheduling problem. Electr. Power Syst. Res. **81**, 1283–1291 (2011)
118. Yare, Y., Venayagamoorthy, G.K.: Optimal maintenance scheduling of generators using multiple swarms-MDPSO framework. Eng. Appl. Artif. Intell. **23**, 895–910 (2010)
119. Breton, S.P., Moe, G.: Status, plans and technologies for offshore wind turbines in Europe and North America. Renew. Energy **34**, 646–654 (2009)
120. Akdag, S.A., Dinler, A.: A new method to estimate weibull parameters for wind energy applications. Energy Convers. Manag. **50**, 1761–1766 (2009)
121. Irfan, U., Qamar-uz-Zaman, C., Andrew, J.C.: An evaluation of wind energy potential at Kati Bandar, Pakistan. Renew. Sustain. Energy Rev. **14**, 856–861 (2010)
122. Esteban, M.D., Diez, J.J., Lpez, J.S., Negro, V.: Why offshore wind energy? Renew. Energy **36**, 444–450 (2011)
123. Nguyen, T.H., Prinz, A., Friisø, T., Nossum, R., Tyapin, I.: A framework for data integration of offshore wind farms. Renew. Energy **60**, 150–161 (2013)
124. Hameed, Z., Vatn, J., Heggset, J.: Challenges in the reliability and maintainability data collection for offshore wind turbines. Renew. Energy **36**, 2154–2165 (2011)
125. Sunitha, M.S.: Studies on fuzzy graphs. Doctoral thesis, Department of Mathematics, Faculty of Science, Cochin University of Science and Technology, Cochin, 2001