

METHOD AND SYSTEM FOR REMAINING USEFUL LIFE PREDICTION OF A MULTI-COMPONENT OPERATIONAL SYSTEM

TECHNICAL FIELD

5 [0001] The present disclosure generally relates to a method and a system for remaining useful life prediction of a multi-component operational system.

BACKGROUND

[0002] Remaining useful life (RUL) of a system is the length of time a system likely
10 to operate before it requires a repair or replacement. RUL of a system is important to be accurately predicted in order to avoid catastrophic incident that may, for example, incur a huge amount of repairing cost, restoration cost, replacement cost and/or downtime of the system. One of the conventional techniques for estimating the system RUL is performed by inferring system RUL from the RUL of the important component
15 of a system. The health condition of an important component may be taken to reflect the overall health condition of the system. Therefore, if the health condition of an important component is degraded it can directly be concluded that the RUL of the system is the same with the RUL of this component. Thus, with this approach, the system RUL may have been concluded as the same value with the RUL of the important
20 component. In another approach, RUL of a system can be inferred from the shortest RUL among the RULs of all components. In this approach, the system estimates the RUL of several components in a system and determines the component having the minimum RUL value among all estimated component RULs to be the system RUL. For example, one technique employs RUL estimator of components of a system using long
25 short-term memory (LSTM) method. Then the system RUL was determined using the shortest component RUL. A need exists to provide an improved method and system for remaining useful life prediction of a multi-component operational system, that seek to overcome, or at least ameliorate, one or more of deficiencies in the conventional methods.

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SUMMARY

[0003] The present disclosure seeks to provide a technical solution to achieve a more accurate and optimal remaining useful life prediction of a multi-component operational system.

[0004] According to a first aspect of the present disclosure, there is provided a method of predicting remaining useful life of a multi-component operational system, using at least one processor, the method comprising:

5 obtaining component remaining useful life information associated to a plurality of components of the operational system, the component remaining useful life information indicates a remaining useful life corresponding to each component of the plurality of components;

10 obtaining component relationships information in relation to the operational system, the component relationships information indicates a relationship between a component and one or more other components of the multi-component operational system; and

determining the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information.

15 [0005] According to a second aspect of the present disclosure, there is provided a system for remaining useful life prediction of a multi-component operational system, the system comprising:

a memory; and

20 at least one processor communicatively coupled to the memory and configured to:

obtain component remaining useful life information associated to a plurality of components of the operational system, the component remaining useful life information indicates a remaining useful life corresponding to each component of the plurality of components;

25 obtain component relationships information in relation to the operational system, the component relationships information indicates a relationship between a component and one or more other components of the multi-component operational system; and

30 determine the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information.

[0006] According to a third aspect of the present disclosure, there is provided a computer program product, embodied in one or more non-transitory computer-readable storage mediums, comprising instructions executable by at least one processor to

perform a method of predicting remaining useful life of a multi-component operational system according to the first aspect.

BRIEF DESCRIPTION OF THE DRAWINGS

5 [0007] Embodiments of the present disclosure will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1 depicts a flow diagram of a method of predicting remaining useful life of a multi-component operational system, according to various embodiments of the
10 present disclosure;

FIG. 2 depicts a schematic block diagram of a system for remaining useful life prediction of a multi-component operational system, according to various embodiments of the present disclosure, such as corresponding to the method shown in FIG. 1;

FIG. 3 depicts a schematic block diagram of an exemplary computer system in
15 which a system for remaining useful life prediction of a multi-component operational system, according to various embodiments of the present disclosure, may be realized or implemented;

FIG. 4 depicts an exemplary diagram of an overall system implementation;

FIG. 5 shows an example flow diagram illustrating the exemplary steps of the
20 overall process of system RUL estimation system;

FIG. 6 is an example of flow diagram illustrating the exemplary steps of obtaining the component relationships map;

FIG. 7 shows a flowchart illustrating a process for the creation of component relationships map, according to various example embodiments of the present
25 disclosure;

FIG. 8 shows an example of the component relationships map;

FIG. 9 shows another example of the component relationships map implemented in a chiller system;

FIG. 10 shows an example of flow diagram illustrating a process of estimating
30 component RUL;

FIG. 11 is a flowchart illustrating a process for the creation of component RUL estimation function;

FIG. 12 shows an example of a data structure of input data;

FIG. 13 shows an example of estimating component RUL;

FIG. 14 shows an example of flow diagram illustrating the process of estimating system RUL;

FIGS. 15A-15B show an example of estimating system RUL in a chiller system;

FIGS. 16A-16B show another example of estimating system RUL in a chiller system;

FIG. 17 shows an example of flow diagram illustrating a process of a recommendation module;

FIGS. 18A-18B show exemplary scenarios in which the health condition of a component affects the health condition of other components which are correlated to the component;

FIG. 19 shows an exemplary scenario where inaccurate estimation of a system may affect the system operation; and

FIG. 20 shows an exemplary diagram illustrating estimation of system RUL.

DETAILED DESCRIPTION

[0008] A multi-component operational system, such as a chiller system in a non-limiting example, may be a complex system that includes a lot of sub-systems (or components). Each component interacts with one or more components in the system. The impact of the degradation of a component may affect the health condition of other component(s). The overall impact of all degraded components in the end may contribute to the system remaining useful life (RUL). As discussed above, in conventional techniques, the health condition of an important component may reflect the overall health condition of the system. Therefore, if the health condition of an important component is degraded it can directly be concluded that the RUL of the system is the same with the RUL of the degraded important component. However, according to various embodiments, because every component is inter-related (or correlated) to one another in the system, the effect of the degraded important component may affect the health condition(s) of other component(s) which in the end may be affecting the system RUL and may result in, for example, the shortened system RUL. Various embodiments of the present disclosure take into account that the impact of the degradation of a component may affect the health condition of other component(s) of the system, and that the overall impact of all degraded components may contribute to the system RUL.

[0009] Various embodiments of the present disclosure provide a method and system for remaining useful life prediction of a multi-component operational system.

FIG. 1 depicts a flow diagram of a method 100 of predicting remaining useful life of a multi-component operational system, using at least one processor. The method 100 comprises: obtaining, (at 102), component remaining useful life information associated to a plurality of components of the operational system, the component remaining useful life information indicates a remaining useful life corresponding to each component of the plurality of components; obtaining, (at 104), component relationships information in relation to the operational system, the component relationships information indicates a relationship between a component and one or more other components of the multi-component operational system; and determining, (at 106), the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information.

[0010] Accordingly, the relationship of components may be taken into account in determining the RUL prediction of a multi-component operational system. The component relationships information indicates the relationships between components of the multi-component operational system. For example, the effect of degraded components to the system may be analyzed based on the component relationships information so that a comprehensive and accurate system RUL estimation (or prediction) may be achieved for a better decision on mitigation actions for the affected component(s) or system.

[0011] For example, the deterioration of a component (e.g., chilled water pump) may affect one or more other components, i.e., related components (e.g., compressor and power unit which may be related to the chilled water pump). It may cause the one or more related components to work harder than usual to compensate the operational system so that for example a system pre-setting can be met. These conditions may cause the RUL of the affected components, such as the deteriorated component and the one or more related components, to be shortened. In other words, the actual system RUL may not be the same with the RUL of one component even though the component is the most important or an important component of that system. For example, the health condition of a component may affect the health condition of other component(s) that in the end may affect the overall system RUL, e.g., the health condition of a component may shorten the system RUL because the accumulation effects of the degradation of all affected components. Therefore, the overall effects of components in the end will affect the RUL of the operational system, such as shorten the RUL of the operational system, or in other cases, lengthen the RUL of the operational system. In this regard, the RUL

of the operational system may be shorter than that estimated or predicted using conventional techniques. Therefore, various embodiments may take into account the overall impact of affected components, such as the deteriorated or degraded component and the one or more related components, to the system remaining useful life.

- 5 Accordingly, various embodiments take into account relationships among components in the estimation of system RUL and may advantageously achieve a higher accuracy of remaining useful life prediction of a multi-component operational system.

[0012] In relation to 102, in various embodiments, the method 100 further comprises obtaining operational data in relation to a plurality of system parameters
10 associated to the plurality of components of the operational system. The operational data may comprise measurement data or sensor data in relation to the plurality of systems parameters of the plurality of components obtained from one or more sensors associated to the components of the operational system. For example, one or more sensors may be installed at the respective components of the operational system. The
15 operational data may further comprise data obtained from a Building Energy Management System (BEMS) which may be collected in relation to the operational system.

[0013] In various embodiments, the above-mentioned obtaining remaining useful life information associated to a plurality of components of the operational system
20 comprises determining, for each component of the plurality of components, the remaining useful life corresponding to the component with respect to the operational data based on a component remaining useful life function.

[0014] In various embodiments, the above-mentioned obtaining component relationships information in relation to the operational system comprises determining
25 the component relationships information with respect to the operational data based on predefined key performance indicators.

[0015] In various embodiments, the component relationships information comprises, for each pair of correlated components of the plurality of components, correlation coefficients that represent the relationship between the pair of components.

30 [0016] In various embodiments, the above-mentioned determining the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information further comprises determining, for each component of the plurality of components, a significance value associated to the component, selecting a primary

component from the plurality of components based on respective significance value of the plurality of components, and determining the remaining useful life of the operational system based on the remaining useful life corresponding to the primary component selected and the remaining useful life corresponding to one or more components which are correlated to the primary component using a system remaining useful life estimation function. In various embodiments, the significance value associated to the component may be determined based on the remaining useful life corresponding to the component and the importance value associated to the component.

5 [0017] In various embodiments, the component relationships information comprises, for each pair of correlated components of the plurality of components, a first correlation coefficient indicating a degree to which a first component of the pair affects a second component of the pair, and a second correlation coefficient indicating a degree to which the second component of the pair affects the first component of the pair.

10 [0018] In various embodiments, the component relationships information in relation to the operational system further comprises, for each component of the plurality of components, an importance value associated to the component, the importance value indicating a degree to which the component contributes to a health condition of the operational system based on a correlation between the component and one or more other components.

15 [0019] In various embodiments, the system remaining useful life estimation function comprises, for each component of the one or more components which are correlated to the primary component selected, a weight corresponding to an effect of the remaining useful life corresponding to the component, the weight being based on the second correlation coefficient and the importance value associated to the component.

20 [0020] In various embodiments, the method 100 further comprises determining whether the remaining useful life of the operational system is below a threshold, in response to determining that the remaining useful life of the operational system is below the threshold, determining an optimization result based on an objective function to minimize cost of repair of components, cost of replacement of components or system and/or downtime of the system; and providing a recommendation based on the optimization result. Accordingly, various embodiments provide recommendation of an action that may be taken based on the result of system RUL estimation or prediction. Providing the recommendation may facilitate to maintain the system to operate as per

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normal as possible with the least effect on the system operation. Some actions may include but is not limited to repair component(s), replace component(s), or replace the overall system. Recommending appropriate action(s) may allow the action(s) to be taken, thus lengthening the life of the system and hence the overall system cost can be minimized.

[0021] FIG. 2 depicts a schematic block diagram of a system 200 for remaining useful life prediction of a multi-component operational system (which may be interchangeably referred to herein as a system RUL estimator), according to various embodiments of the present disclosure, such as corresponding to the method 100 of predicting remaining useful life of a multi-component operational system as described hereinbefore according to various embodiments of the present disclosure. The system 200 comprises a memory 202, and at least one processor 204 communicatively coupled to the memory 202 and configured to: obtain component remaining useful life information associated to a plurality of components of the operational system, the component remaining useful life information indicates a remaining useful life corresponding to each component of the plurality of components; obtain component relationships information in relation to the operational system, the component relationships information indicates a relationship between a component and one or more other components of the multi-component operational system; and determine the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information.

[0022] It will be appreciated by a person skilled in the art that the at least one processor 204 may be configured to perform the required functions or operations through set(s) of instructions (e.g., software modules) executable by the at least one processor 204 to perform the required functions or operations. Accordingly, as shown in FIG. 2, the system 200 may comprise a component remaining useful life information obtaining module (or a component remaining useful life information obtaining circuit) 206 configured to obtain component remaining useful life information associated to a plurality of components of the operational system; a component relationships information obtaining module (or a component relationships information obtaining circuit) 208 configured to obtain component relationships information in relation to the operational system, the component relationships information indicates a relationship between a component and one or more other components of the multi-component

operational system; and a system remaining useful life determining module (or a system remaining useful life determining circuit) 210 configured to determine the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information.

5 [0023] It will be appreciated by a person skilled in the art that the above-mentioned modules are not necessarily separate modules, and one or more modules may be realized by or implemented as one functional module (e.g., a circuit or a software program) as desired or as appropriate without deviating from the scope of the present disclosure. For example, two or more of the component remaining useful life information obtaining module 206, the component relationships information obtaining module 208, and the system remaining useful life determining module 210 may be realized (e.g., compiled together) as one executable software program (e.g., software application or simply referred to as an “app”), which for example may be stored in the memory 202 and executable by the at least one processor 204 to perform the functions/operations as described herein according to various embodiments.

15 [0024] In various embodiments, the system 200 corresponds to the method 100 as described hereinbefore with reference to FIG. 1, therefore, various functions or operations configured to be performed by the at least one processor 204 may correspond to various steps of the method 100 described hereinbefore according to various embodiments, and thus need not be repeated with respect to the system 200 for clarity and conciseness. In other words, various embodiments described herein in context of the methods are analogously valid for the respective systems, and vice versa.

20 [0025] For example, in various embodiments, the memory 202 may have stored therein the component remaining useful life information obtaining module 206, the component relationships information obtaining module 208 and/or the system remaining useful life determining module 210, which respectively correspond to various steps of the method 100 as described hereinbefore according to various embodiments, which are executable by the at least one processor 204 to perform the corresponding functions/operations as described herein.

25 [0026] A computing system, a controller, a microcontroller or any other system providing a processing capability may be provided according to various embodiments in the present disclosure. Such a system may be taken to include one or more processors and one or more computer-readable storage mediums. For example, the system 200

described hereinbefore may include a processor (or controller) 204 and a computer-readable storage medium (or memory) 202 which are for example used in various processing carried out therein as described herein. A memory or computer-readable storage medium used in various embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

10 [0027] In various embodiments, a “circuit” may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a “circuit” may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g., a microprocessor (e.g., a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A “circuit” may also be a processor executing software, e.g., any kind of computer program, e.g., a computer program using a virtual machine code, e.g., Java. Any other kind of implementation of the respective functions which will be described in more detail below may also be understood as a “circuit” in accordance with various alternative embodiments. Similarly, a “module” may be a portion of a system according to various embodiments in the present disclosure and may encompass a “circuit” as above, or may be understood to be any kind of a logic-implementing entity therefrom.

25 [0028] Some portions of the present disclosure are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

30 [0029] Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, discussions utilizing terms

such as “obtaining”, “determining”, or the like, refer to the actions and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

[0030] The present specification also discloses a system (e.g., which may also be embodied as a device or an apparatus), such as the system 200, for performing the operations/functions of the methods described herein. Such a system may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or reconfigured by a computer program stored in the computer. The algorithms presented herein are not inherently related to any particular computer or other apparatus. Various general-purpose machines may be used with computer programs in accordance with the teachings herein. Alternatively, the construction of more specialized apparatus to perform the required method steps may be appropriate.

[0031] In addition, the present specification also at least implicitly discloses a computer program or software/functional module, in that it would be apparent to the person skilled in the art that the individual steps of the methods described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the spirit or scope of the disclosure. It will be appreciated by a person skilled in the art that various modules described herein (e.g., the component remaining useful life information obtaining module 206, the component relationships information obtaining module 208 and/or the system remaining useful life determining module 210) may be software module(s) realized by computer program(s) or set(s) of instructions executable by a computer processor to perform the required functions, or may be hardware module(s) being functional hardware unit(s) designed to perform the required functions. It will also be appreciated that a combination of hardware and software modules may be implemented.

[0032] Furthermore, one or more of the steps of a computer program/module or method described herein may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a general purpose computer. The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the steps of the methods described herein.

[0033] In various embodiments, there is provided a computer program product, embodied in one or more computer-readable storage mediums (non-transitory computer-readable storage medium), comprising instructions (e.g., the component remaining useful life information obtaining module 206, the component relationships information obtaining module 208 and/or the system remaining useful life determining module 210) executable by one or more computer processors to perform a method of predicting remaining useful life of a multi-component operational system as described hereinbefore with reference to FIG. 1. Accordingly, various computer programs or modules described herein may be stored in a computer program product receivable by a system therein, such as the system 200 as shown in FIG. 2, for execution by at least one processor 204 of the system 200 to perform the required or desired functions.

[0034] The software or functional modules described herein may also be implemented as hardware modules. More particularly, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the software or functional module(s) described herein can also be implemented as a combination of hardware and software modules.

[0035] In various embodiments, the system 200 may be realized by any computer system (e.g., desktop or portable computer system) including at least one processor and a memory, such as a computer system 300 as schematically shown in FIG. 3 as an example only and without limitation. Various methods/steps or functional modules (e.g., the component remaining useful life information obtaining module 206, the component relationships information obtaining module 208 and/or the system

remaining useful life determining module 210) may be implemented as software, such as a computer program being executed within the computer system 300, and instructing the computer system 300 (in particular, one or more processors therein) to conduct the methods/functions of various embodiments described herein. The computer system 300 may comprise a computer module 302, input modules, such as a keyboard 304 and a mouse 306, and a plurality of output devices such as a display 308, and a printer 310. The computer module 302 may be connected to a computer network 312 via a suitable transceiver device 314, to enable access to e.g., the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN). The computer module 302 in the example may include a processor 318 for executing various instructions, a Random Access Memory (RAM) 320 and a Read Only Memory (ROM) 322. The computer module 302 may also include a number of Input/Output (I/O) interfaces, for example I/O interface 324 to the display 308, and I/O interface 326 to the keyboard 304. The components of the computer module 302 typically communicate via an interconnected bus 328 and in a manner known to the person skilled in the relevant art.

[0036] It will be appreciated by a person skilled in the art that the terminology used herein is for the purpose of describing various embodiments only and is not intended to be limiting of the present disclosure. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0037] In order that the present disclosure may be readily understood and put into practical effect, various example embodiments of the present disclosure will be described hereinafter by way of examples only and not limitations. It will be appreciated by a person skilled in the art that the present disclosure may, however, be embodied in various different forms or configurations and should not be construed as limited to the example embodiments set forth hereinafter. Rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present disclosure to those skilled in the art.

[0038] Various example embodiments relate to remaining useful life prediction of a multi-component operational system. For the sake of simplicity and clarity and unless stated otherwise, various example embodiments will hereinafter be described with respect to the multi-component operational system being a chiller system. However, it will be appreciated by a person skilled in the art that the present disclosure is not limited to a chiller system and may be or include any operational systems having multiple components, which may have a useful life that may degrade over time.

[0039] System RUL is important to be accurately estimated. Inaccurate system RUL estimation may cause inappropriate timely actions, unexpected system shutdowns and/or unplanned system downtime, and hence may increase the overall cost of the system.

[0040] Various example embodiments provide a method to estimate the system RUL utilizing component relationships map (corresponding to the “component relationships information” as described hereinbefore according to various embodiments). According to various example embodiments, the component relationships map may be a diagram that shows all components of the system together with the lines that connect one component to other components that represent the relationships among them. There may be a constant number in the relationship line that imply the correlation coefficient between one component and another component. According to various example embodiments, there may be importance values that represent the significance of the component in contributing to the system health condition that in the end affects the system RUL. Importance value of a component may be calculated using correlation coefficients in the relationship lines that go out from this component. Procedures to estimate the system RUL may start with estimation of components RUL, followed by estimation of the system RUL.

[0041] According to various example embodiments, optimal recommendation(s) may be provided according to the result of the system RUL estimation, whether to repair or replace a component, some components or a system based on the operating cost, repairing cost, restoration cost, replacement cost and/or downtime of the system. The obtained system RUL may be checked to determine whether or not the system RUL is below a predefined system RUL threshold. If the system RUL is below the predefined system RUL threshold, according to various example embodiments, an optimization problem pertaining to recommendation(s) may be executed to be solved. The

recommendation(s) may include repair component(s), replace component(s), or replace the overall system, that may be given to the system user.

[0042] Accordingly, various example embodiments may achieve a more accurate and optimal system RUL estimator that estimates system RUL by utilizing component relationships map and suggests optimal recommendation(s) related to the result of system RUL estimation.

[0043] For example, an RUL estimator (or predictor) of a chiller system that is configured to estimate RUL for a system by utilizing component relationships map may be provided. Accordingly, the effect of degraded component(s) to the system can be analysed based on component relationships map so that comprehensive and accurate system RUL estimation (or prediction) can be achieved for a better decision on what should be done to the affected component(s) or system. Various example embodiments suggest appropriate action(s) as recommendation in order to maintain the system to operate as per normal as possible with the least effect on the system operation. According to various example embodiments, the RUL estimator is configured to produce optimal recommendation(s) whether to repair or replace a component, some components or the system based on the operating cost, repairing cost, restoration cost, replacement cost and/or downtime of the system. Various example embodiments may be employed as user friendly application that provides insightful recommendation(s) that may facilitate ease of the operators' job and results in the most cost-effective mitigation action(s).

[0044] The method and system for remaining useful life prediction of a multi-component operational system will now be described below with respect to a chiller system according to various example embodiments. According to various example embodiments, the component relationships map may be a chiller relationships map which is a diagram that shows all components of the system together with the lines that connect one component to other components that represent the relationships among them (e.g., corresponding to the "relationship between a component and one or more other components of the multi-component operational system" as described hereinbefore according to various embodiments). By utilizing the chiller relationships map, the effect of the degraded health condition of a component to other components may be easily captured, and hence the system RUL may be more accurately estimated.

[0045] FIG. 4 depicts an exemplary diagram of an overall system implementation 400. The system implementation includes chiller system 410, system RUL estimation

- system 420, building management system (BMS) 430, and a communication network 440. The chiller system 410 includes the chiller components, e.g., compressor, condenser, evaporator, etc., with sensors installed to capture the chiller system key performance indicators (KPIs) (corresponding to the “operational data in relation to a plurality of system parameters associated to the plurality of components of the operational system” as described hereinbefore according to various embodiments). BMS 430 is a system to monitor and control the mechanical and electrical equipment of a building that include chiller system, power system, lighting system, water system, gas system, fire system, and security system. The input of system RUL estimation system 420 may come directly from the chiller system 410 and/or from BMS 430. In some systems, BMS 430 may not be required in order to estimate system RUL. The communication network 440 connects all system components in the overall system and it may support various connectivity, such as Ethernet, Wi-Fi, and/or Zigbee with various protocols, such as BACnet, TCP/UDP, CAN.
- 15 **[0046]** FIG. 5 shows an example flow diagram illustrating the exemplary steps of the overall process of system RUL estimation system 420. At 502, relevant input data may be obtained. The input data may include the operational data in relation to the plurality of system parameters associated to the plurality of components of the operational system. In non-limiting examples, the input data may further include
- 20 occupancy data, weather data, etc. At 504, RUL of component(s) may be estimated. At 506, component relationships map may be obtained. At 508, system RUL may be estimated by using the input of component relationships map and RUL(s) of component(s). After system RUL has been estimated, at 510, a determination may be made as to whether the system RUL is below a threshold. If the system RUL is not
- 25 below the threshold, the process returns to step 502. Otherwise, if the system RUL is below the threshold, at 512, a recommendation module may be run. At 514, recommendation(s) may be produced or provided. After providing recommendation(s), the process returns to step 502. The system RUL estimation system always keeps running to estimate system RUL continuously.
- 30 **[0047]** FIG. 6 is an example of flow diagram illustrating the exemplary steps of obtaining the component relationships map 506 (corresponding to the “obtaining component relationships information in relation to the operational system” as described hereinbefore according to various embodiments). At 602, the existence of component relationships map in a database system may be determined. At 604, a determination

may be made as to whether the component relationships map is available or not. If the component relationships map is not available in the database system, at 606, the component relationships map may be created. At 608, the created component relationships map may be applied for system RUL estimation. Otherwise, if the component relationships map is available, at 608, this component relationships map may be applied for system RUL estimation.

[0048] FIG. 7 shows a flowchart illustrating a process 606 for the creation of component relationships map. At 702, predefined chiller key performance indicators (KPIs) (corresponding to the “predefined key performance indicators” as described hereinbefore according to various embodiments) may be collected from database. At 704, the chiller KPIs data (corresponding to the “operational data in relation to a plurality of system parameters associated to the plurality of components of the operational system” as described hereinbefore according to various embodiments) may be obtained from sensors. At 706, the correlation coefficients of chiller components may be calculated based on the chiller data. The calculation of correlation coefficients may be carried out using several methods, e.g. Pearson correlation method, Kendall rank correlation method, Spearman correlation method, the Point-Biserial correlation method, etc. At 708, the component relationships map may be created based on the calculated correlation coefficients. At 710, the created component relationships map may be stored in storage (e.g., database).

[0049] FIG. 8 shows an example of the component relationships map. According to various example embodiments, the component relationships map shows all components of the system together with the lines that connect one component to other components that represent the relationships among them (e.g., corresponding to the “relationship between a component and one or more other components of the multi-component operational system” described hereinbefore according to various embodiments). For example, with respect to component 1, the component relationships map indicates a relationship between component 1 and component 2, between component 1 and component 3, and between component 1 and component 4, as illustrated by the lines (or arrows) between these components in FIG. 8. There are constant number in the relationship line that imply the correlation coefficient between one component and another component. The correlation coefficients may be denoted as follows.

$A = a_{12}, a_{21}, a_{13}, a_{31}, \dots, a_{n6}$ represent correlation coefficients among components. The values of A may be between -1 to 1.

The component relationships map comprises, for each pair of correlated components of the plurality of operational components, a first correlation coefficient indicating a degree to which a first component of the pair affects a second component of the pair, and a second correlation coefficient indicating a degree to which the second component of the pair affects the first component of the pair. For example, as illustrated for the pair of correlated components 1 and 2, a first correlation coefficient a_{12} may indicate a degree to which a first component of the pair (e.g., component 1) affects a second component of the pair (e.g., component 2), and a second correlation coefficient a_{21} may indicate a degree to which the second component of the pair affects the first component of the pair.

[0050] The component relationships map may include importance values that represent the significance of the component in contributing to the system health condition that in the end affects the system RUL. The importance values of the components may be denoted as follows.

$I = i_1, i_2, i_3, \dots, i_n$ represent important values of components. The values of I may be between 0 to 1.

[0051] The importance value of a component may be calculated using correlation coefficients in the relationship lines that go out (e.g., the first correlation coefficients) from this component. The values of I may be obtained by averaging the absolute correlation coefficients that are going out from a component. For example, the importance value of component 4 802 may be calculated as follows:

$$i_4 = \frac{|a_{41} + a_{42} + a_{45} + a_{46}|}{4}$$

[0052] FIG. 9 shows another example of the component relationships map implemented in the chiller system. The coefficient number in between two components represents the correlation between one component and another component. The values can be from -1 to 1. The positive values mean components have proportional relationship, and vice versa, the negative values mean components have inverse proportional relationship. The magnitude of the coefficient represents how strong or weak is the correlation between the two components. For example, power unit has correlation to compressor with the coefficient of 0.95. This means the power unit has

strong proportional relationship with the compressor. In other words, if the power unit degrades it will then cause the compressor to degrade.

[0053] The number next to the component refers to the importance value of the component that shows how big is the influence of this component to affect other connected components which in the end contributes to the system health condition. The values may be in the range from 0 to 1. The value of 0 (zero) means that the component has no weight that contributes to the system health condition, whereas the value of 1 (one) means that the component has a significant weight that contributes to the system health condition. In this example, the power unit has the biggest importance value to chiller system, e.g., 0.9, since the breakdown of the power unit will significantly affect other components and in the end will affect the overall chiller system.

[0054] FIG. 10 shows an example of flow diagram illustrating a process 504 of estimating component RUL. At 1002, one component may be selected to estimate the RUL of the component. At 1004, a determination may be made as to whether the component RUL estimation function of this component is available. Each component may have its respective component RUL estimation function. If the component RUL estimation function corresponding to the selected component is not available, at 1006, all input data related to this component may be obtained. At 1008, a determination may be made as to whether the input data is sufficient to create the function. If the input data is not sufficient, at 1010, a predefined default component RUL estimation function may be obtained which can be collected from the knowledge of system expert accumulated for period of time. Otherwise, if the input data is sufficient, at 1012, a component RUL estimation function may be created. The process continues to step 1014. Referring back to the determination at 1004, if the component RUL estimation function corresponding to the selected component is available, at 1014, the component RUL estimation function may be retrieved. At 1016, the RUL of component may be estimated with the given function. At 1018, the component RUL may be stored in database. At 1020, a determination may be made as to whether all components' RULs have been estimated. If all components' RULs have not been estimated, the process returns to 1002 and continues to estimate the RUL of other components. Otherwise, the process ends.

[0055] FIG. 11 is a flowchart illustrating a process 1012 for the creation of component RUL estimation function. At 1102, the measurement data and the operated lifetime data of the (selected) component may be obtained. For example, the measurement data may be in any form of physical quantity, such as but not limited to,

electricity voltage, electricity current, vibration, light intensity, etc. The operated lifetime may be the lifetime from the beginning of operation until the current condition (the component is still in operation). FIG. 12 shows an example of the data structure of the input data. It contains sequential number (or entries) of measurement logging 1202, timestamp of measurement 1204, component identifier (ID) 1206, measurement values 1208 and operated lifetime 1210. Referring back to FIG. 11, at 1104, component RUL estimation function may be created using analytical method, such as regression method, artificial neural network method, deep learning method, etc. The system, using the data that have been obtained, such as the historical data of measurement and component time of failure, and using methods, which may include but is not limited to similarity model, degradation model and survival model, may translate the measurement value or data to health condition indicator value. For example, to translate the measurement data to health condition indicator value, a relationship model between the historical data of measurement and the component time of failure may be trained. The component time of failure may be calculated from the beginning of operation until the time when the component fails. In an embodiment, the health condition indicator value may be inversely proportional to a component usage time measurement or parameter. The component usage time may be the same with the operated lifetime data. As time goes by, the physical quantity of a component may change, e.g. it decreases by time. Therefore, the historical data of the measurement and component lifetime may be obtained and used to train a function/model. The health condition indicator value represents the health condition/performance of a component. The values may be in the range of 0 to 1. For example, a new working component may have a health condition indicator value of 1 or near 1, whereas a component that has broken down or cannot be operated anymore (component with zero, 0, RUL), may have the health condition indicator value of 0. Using the data that have been obtained, derived or determined, i.e. the health condition indicator value, together with component usage time, a graph between health condition indicator value/performance and usage time of a component can be trained to be a function/model. Said differently, a relationship model between the health condition indicator and component usage time may be trained. The training may produce a curve 1310 of health condition indicator value vs component usage time, as illustrated in FIG. 13. This function/model in the end can be used to estimate the RUL of component based on a current health condition of the component. At 1106, the created component RUL estimation function may be stored in database.

[0056] FIG. 13 shows an example of estimating component RUL. The component RUL estimator may obtain the function curve or graph 1310 (representing the relationship between the health condition indicator value and component usage time) from the stored/trained data. Based on the current input 1320, the system may estimate the component RUL 1330. For example, a current health condition indicator value of the component may be determined based on measurement data of the component. The health indicator value may be converted to component usage time using the curve 1310. In other words, the current component usage time may be determined based on the curve 1310 of health condition indicator value vs component usage time. The RUL of the component may be determined or calculated based on the usage time of the component.

[0057] FIG. 14 shows an example of flow diagram illustrating the process 508 of estimating system RUL. At 1402, all affected components' RULs may be obtained. The estimation of components' RULs may be carried out based on an ad-hoc basis according to the occurrence of failure in a certain component or predefined schedule basis. In the case of ad-hoc basis, the RUL of the affected component and RULs of other components related to the affected component may be calculated. In another case of schedule basis execution of system RUL estimation, all components' RULs may be calculated. At 1404, the correlation coefficients of the related components may be obtained from the component relationships map. At 1406, the correlation coefficients and importance values may be translated into weights in the system RUL estimation function. At 1408, the system RUL may be estimated. According to various example embodiments, to estimate the system RUL, the most significant component (e.g., corresponding to the "primary component" as described hereinbefore according to various embodiments) among all affected components may be determined. Calculating the significance values of the components may be carried out by dividing the component RULs with their importance values attached to them. For example, the most significant component (comp') may have the lowest significance value as mathematically expressed as follows.

$$comp' = \min(S)$$

$$S = \frac{RUL}{I}$$

where:

$S = [s_1, s_2, s_3, \dots, s_n]$ are the significance values of component 1, 2, 3, ..., n, respectively.

$I = [i_1, i_2, i_3, \dots, i_n]$ are the importance values of component 1, 2, 3, ..., n, respectively.

5 [0058] With the assistance of the component relationships map, the weight of the effect of each health condition may be determined.

[0059] Referring to FIG. 8, the system RUL may be determined by selecting the most significant component RUL, e.g., Component 1 and subtracting the RUL of the selected most significant component from RULs of other correlated components. The weight of each component RUL may be calculated from the multiplication product of the square of importance value (I) and the correlation coefficient (A). As illustrated in FIG. 8, Component 1 is correlated to Components 2, 3 and 4, hence the system RUL(y) may be calculated as follows:

$$y = RUL(Component\ 1) - i_2^2 * a_{21} * \frac{RUL(Component\ 1)^2}{RUL(Component\ 2)} - i_3^2 * a_{31} * \frac{RUL(Component\ 1)^2}{RUL(Component\ 3)} - i_4^2 * a_{41} * \frac{RUL(Component\ 1)^2}{RUL(Component\ 4)}$$

[0060] Referring back to FIG. 14, at 1410, the estimated (or predicted) system RUL may be stored in database.

[0061] FIGS. 15A-15B show an example of estimating system RUL in a chiller system. FIG. 15A shows the component relationships map of the chiller system. FIG. 15B shows example calculations of importance and significance values of components in the chiller system. From the calculation, it is known that the chilled water pump is the most significant component since it has the lowest significant value of 3.33 compared to other components. Therefore, the chiller system RUL (y) may be estimated as follows:

$$y = RUL(Chilled\ Water\ Pump) - 0.6^2 * 0.55 * \frac{RUL(Chilled\ Water\ Pump)^2}{RUL(Evaporator)} - 0.9^2 * 0.9 * \frac{RUL(Chilled\ Water\ Pump)^2}{RUL(Power\ Unit)}$$

$$y = 2 - 0.6^2 * 0.55 * \frac{2^2}{5.5} - 0.9^2 * 0.9 * \frac{2^2}{3.5} = 1.023\ year$$

[0062] FIGS. 16A-16B show another example of estimating system RUL in a chiller system where all components have the same importance values, e.g., 1. FIG. 16A shows the component relationships map of a chiller system. FIG. 16B shows some

calculations of importance and significance values of components in the chiller system. From the calculation, it is known that the chilled water pump is the most significant component since it has the lowest significance value of 2 compared to other components. Therefore, the chiller system RUL (y) may be estimated as follows:

$$\begin{aligned}
 5 \quad y &= RUL(\text{Chilled Water Pump}) - 1^2 * 0.55 * \frac{RUL(\text{Chilled Water Pump})^2}{RUL(\text{Evaporator})} - 1^2 * 0.9 \\
 &\quad * \frac{RUL(\text{Chilled Water Pump})^2}{RUL(\text{Power Unit})} \\
 y &= 2 - 1^2 * 0.55 * \frac{2^2}{5.5} - 1^2 * 0.9 * \frac{2^2}{3.5} = 0.571 \text{ year}
 \end{aligned}$$

[0063] FIG. 17 shows an example of flow diagram illustrating the process 512 of a recommendation module. At 1702, the system RUL may be obtained. At 1704, a determination may be made as to whether the system RUL is less than a threshold. If the system RUL is less than threshold, at 1706, an optimization problem may be solved and at 1708 an optimization result(s) may be obtained. Otherwise, if the system RUL is not less than the threshold, the process ends. The threshold, for example, may be a lifetime threshold predefined by the system, such as 50% of lifetime in a non-limiting example. However, user(s) may input their preference value through user configuration in the system.

[0064] According to various example embodiments, the objective function of the optimization is to minimize the cost of repair of component(s), replacement (component(s) or system) and the system downtime. The recommendation(s) may be given based on the result of optimization, e.g., to repair component(s), to replace component(s) or to replace the system. The objective of the optimization is to minimize the cost function, which in one of embodiment may be formulated as follows:

$$\begin{aligned}
 25 \quad \text{Min} \left[u \left(\sum_{k \in K} (v_k \cdot (RPR_k + DTrpr_k) + w_k \cdot (REP_k + DTrep_k)) \right) + z \cdot (REP_{sys} \right. \\
 \left. + DTrepsys) \right]
 \end{aligned}$$

Subject to:

$$\begin{aligned}
 u + z &= 1 \\
 v_k + w_k &= 1, & \forall k \\
 k &\in \{1, 2, 3, \dots, K\}, & \forall k
 \end{aligned}$$

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$$u \in \{0,1\}$$

$$v_k \in \{0,1\}, \quad \forall k$$

$$w_k \in \{0,1\}, \quad \forall k$$

$$z \in \{0,1\}$$

5 where

RPR_k is the repair cost of component k

$DTrpr_k$ is the penalized cost of down time because of the component k repair event

REP_k is the replacement cost of component k

$DTrep_k$ is the penalized cost of down time because of the component k replacement

10 event

$REPs_{sys}$ is the replacement cost of the system

$DTreps_{sys}$ is the penalized cost of down time because of the system replacement event

15 u is the binary variable to determine whether the component(s) need to be repaired/replaced or not. The value of 1 means that the component(s) need to be repaired/replaced while the value of 0 means the component(s) do not need to be repaired/replaced

v_k is the binary variable to determine whether the component k need to be repaired or not. The value of 1 means that the component k needs to be repaired while the value of 0 means the component k does not need to be repaired

20 w_k is the binary variable to determine whether the component k need to be replaced or not. The value of 1 means that the component k needs to be replaced while the value of 0 means the component k does not need to be replaced

25 z is the binary variable to determine whether the system need to be replaced or not. The value of 1 means that the system needs to be replaced while the value of 0 means the system does not need to be replaced

[0065] The solution of the optimization problem will be the variables of u , v_k , w_k and z . The variables u and z are complementary, which means when there is a repair or replacement of component(s), the system will not be replaced, and vice versa, if the system is replaced there is no repair or replacement of a component required for the system. Similarly, the variables v_k and w_k are also complementary, which means when there is a repair of a component, there will be no replacement of that component, and vice versa, when there is a replacement of a component, there will be no repair of that

component. Based on these solution variables, the respective recommendation(s) are given whether to repair/replace component(s) or to replace the system.

[0066] FIGS. 18A-18B show exemplary scenarios in which the health condition of a component affects the health condition of other components which are correlated to the component. Referring to FIG. 18A, in this example, it is found that the health condition of chilled water pump is deteriorated which also means that the RUL of chilled water pump is decreasing. Using conventional techniques, the RUL of the chiller system may be concluded to be the same of the RUL of the chilled water pump component. However, according to various embodiments of the disclosure, it is noted that the deterioration of the chilled water pump component may affect other components (e.g., correlated components), such as the compressor and power unit components. It may cause the compressor and power unit components to work harder than usual to compensate the chiller system so that the chiller pre-setting can be met. These conditions may cause the RUL of the affected components to be shortened. Therefore, the overall effects of the components in the end will affect the actual RUL of the chiller system (denoted as RUL'). For example, in this case, the RUL' of the chiller system may be shorter than the RUL of the chiller system that is estimated using conventional techniques.

[0067] Referring to FIG. 18B, in this example, it is found that the health condition of a sensor is deteriorated which also means that the RUL of the sensor is decreasing. Using conventional techniques, the RUL of the chiller system may be concluded to be as the same of the sensor. However, according to various embodiments of the disclosure, it is noted the deterioration of the sensor may affect other components (e.g., correlated components), such as the condenser water pump and power unit components. The deterioration of the sensor may cause wrong measurement reading and it may cause the condenser water pump and power unit components to work less than usual to fix with the error measurement. These conditions may cause the RUL of the affected components to be lengthened. Therefore, the overall effects of components in the end will affect the actual RUL of the chiller system (denoted as RUL'). For example, in this case, the RUL' of the chiller system may be longer than the RUL of the chiller system that is estimated using conventional techniques.

[0068] FIG. 19 shows an exemplary scenario where inaccurate estimation of a system RUL may compromise the appropriate action(s) and execution time that need

to be taken related to the health condition of the system which in the end may affect the system operation and increase the overall cost.

[0069] FIG. 20 shows an exemplary diagram illustrating estimation of system RUL. For example, for the estimation of system RUL on an ad-hoc basis (e.g., according to the occurrence of failure in a certain component), the system may calculate the affected component and other components that are related to the affected component. The estimation of system RUL may be a function of all the affected components as follows:

$$y = f(RUL(component\ #1), RUL(component\ #2), \dots, RUL(component\ #(n - 1), RUL(component\ #n))$$

10 [0070] By implementing various example embodiments, such as the system RUL estimator, a more accurate system RUL may be determined by utilizing the component relationships map and based on the result of system RUL estimation, recommendation(s) may be given in order to maintain the system to operate as per normal as possible with the least effect on the system operation.

15 [0071] Accordingly, various example embodiments provide a method of system RUL estimation that is more accurate and optimal by utilizing component relationships map and suggests optimal recommendation(s) related to the result of system RUL estimation.

[0072] In other example embodiments, the operational system may relate to a district cooling system (DCS), i.e. centralized cooling system that provides cooling through chilled water to industrial, commercial and residential buildings through a closed-loop pipe distribution network. This system has similar configuration and characteristic with a building chiller system, but in a bigger scale. It may serve an area that may include several buildings. The DCS may include centralized chiller plant, closed-loop pipe distribution network and consumer substation (e.g. air handling units, heat exchangers and chilled water piping in the building). Since the DCS has similar configuration and characteristic with building chiller system, various example embodiments may be directly implemented to estimate DCS RUL more accurately by utilizing component relationships map and may give an optimal recommendation(s) to maintain the DCS to operate as per normal as possible with the least effect on the DCS operation.

[0073] In other example embodiments, the operational system may relate to a building microgrid system which comprises several components, such as solar photovoltaic (PV), battery storage system, diesel generator, gas engine, etc., to provide

power to the building. Various example embodiments may be used to estimate the RUL building microgrid system in which the system RUL estimator utilizes component relationships map of building microgrid. Various example embodiments estimates the system RUL and gives recommendation(s), i.e. repair component(s), replace component(s), or replace the overall system.

[0074] While embodiments of the disclosure have been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the scope of the disclosure as defined by the appended claims. The scope of the disclosure is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

What is claimed is:

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1. A method of predicting remaining useful life of a multi-component operational system, using at least one processor, the method comprising:

obtaining component remaining useful life information associated to a plurality of components of the operational system, the component remaining useful life information indicates a remaining useful life corresponding to each component of the plurality of components;

obtaining component relationships information in relation to the operational system, the component relationships information indicates a relationship between a component and one or more other components of the multi-component operational system; and

determining the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information,

wherein the method further comprises:

if the component relationships information is not available, creating the component relationships information, and

wherein the creating the component relationships information comprises:

collecting predefined KPIs (key performance indicators) of the operational system from a database system;

obtaining KPIs data of the operational system from sensors, wherein the KPIs data is operational data in relation to a plurality of system parameters associated to the plurality of components;

calculating correlation coefficients of the plurality of components based on the operational data; and

creating the component relationships information based on the correlation coefficients.

2. The method according to claim 1, wherein the component relationships information comprises, for each pair of correlated components of the plurality of

components, the correlation coefficients that represent the relationship between the pair of components.

3. The method according to claim 1 or 2, wherein said determining the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information further comprises:

determining, for each component of the plurality of components, a significance value associated to the component;

selecting a primary component from the plurality of components based on respective significance values of the plurality of components; and

determining the remaining useful life of the operational system based on the remaining useful life corresponding to the primary component selected and the remaining useful life corresponding to one or more components which are correlated to the primary component using a system remaining useful life estimation function.

4. The method according to claim 3, wherein the component relationships information comprises, for each pair of correlated components of the plurality of components, a first correlation coefficient indicating a degree to which a first component of the pair affects a second component of the pair, and a second correlation coefficient indicating a degree to which the second component of the pair affects the first component of the pair.

5. The method according to claim 4, wherein the component relationships information in relation to the plurality of components of the operational system further comprises, for each component of the plurality of components, an importance value associated to the component, the importance value indicating a degree to which the component contributes to a health condition of the operational system based on a correlation between the component and one or more other components.

6. The method according to claim 5, wherein the system remaining useful life estimation function comprises, for each component of the one or more components which are correlated to the primary component selected, a weight corresponding to an effect of the remaining useful life corresponding to the component, the weight being

based on the second correlation coefficient and the importance value associated to the component.

7. The method according to any one of claims 1 to 6, further comprising:

5 determining whether the remaining useful life of the operational system is below a threshold;

in response to determining that the remaining useful life of the operational system is below a threshold, determining an optimization result based on an objective function to minimize cost of repair of components, cost of replacement of components
10 or system and/or downtime of the system; and

providing a recommendation based on the optimization result.

8. The method according to any one of claims 1 to 7:

further comprising obtaining the operational data in relation to the plurality of
15 system parameters associated to the plurality of components of the operational system; and

wherein said obtaining remaining useful life information associated to a plurality of components of the operational system comprises determining, for each component of the plurality of components, the remaining useful life corresponding to
20 the component with respect to the operational data based on a component remaining useful life function.

9. The method according to any one of claims 1 to 7 further comprising obtaining the operational data in relation to the plurality of system parameters associated to the
25 plurality of components of the operational system; and wherein said obtaining component relationships information in relation to the operational system comprises determining the component relationship information with respect to the operational data based on the predefined KPIs.

30 10. The method according to any one of claims 1 to 9, wherein the operational system comprises a chiller system.

11. A system for remaining useful life prediction of a multi-component operational system, the system comprising:

a memory; and

at least one processor communicatively coupled to the memory and configured to:

obtain component remaining useful life information associated to a plurality of components of the operational system, the component remaining useful life information indicates a remaining useful life corresponding to each component of the plurality of components;

obtain component relationships information in relation to the operational system, the component relationships information indicates a relationship between a component and one or more other components of the multi-component operational system; and

determine the remaining useful life of the operational system based on the component remaining useful life information associated to the plurality of components and the component relationships information,

wherein the at least one processor is further configured to:

if the component relationships information is not available, create the component relationships information, and

wherein, to create the component relationships information, the at least one processor is configured to:

collect predefined KPIs (key performance indicators) of the operational system from a database system;

obtain KPIs data of the operational system from sensors, wherein the KPIs data is operational data in relation to a plurality of system parameters associated to the plurality of components;

calculate correlation coefficients of the plurality of components based on the operational data; and

create the component relationships information based on the correlation coefficients.

12. The system according to claim 11, wherein the component relationships information comprises, for each pair of correlated components of the plurality of components, the correlation coefficients that represent the relationship between the pair of components.

13. The system according to claim 11 or 12, wherein said determine the remaining useful life of the operational system based on the component remaining useful life information associated to a plurality of components and the component relationships information further comprises:

5 determining, for each component of the plurality of components, a significance value associated to the component;

selecting a primary component from the plurality of components based on respective significance value of the plurality of components; and

10 determining the remaining useful life of the operational system based on the remaining useful life corresponding to the primary component selected and the remaining useful life corresponding to one or more components which are correlated to the primary component using a system remaining useful life estimation function.

14. The system according to claim 13, wherein the component relationships information comprises, for each pair of correlated components of the plurality of components, comprises a first correlation coefficient indicating a degree to which a first component of the pair affects a second component of the pair, and a second correlation coefficient indicating a degree to which the second component of the pair affects the first component of the pair.

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15. The system according to claim 14, wherein the component relationships information in relation to the plurality of components of the operational system further comprises, for each component of the plurality of components, an importance value associated to the component, the importance value indicating a degree to which the component contributes to a health condition of the operational system based on a correlation between the component and one or more other components.

25

16. The system according to claim 15, wherein the system remaining useful life estimation function comprises, for each component of the one or more components which are correlated to the primary component selected, a weight corresponding to an effect of the remaining useful life corresponding to the component, the weight being based on the second correlation coefficient and the importance value associated to the component.

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17. The system according to any one of claims 11 to 16, wherein the at least one processor is further configured to:

determine whether the remaining useful life of the operational system is below a threshold;

5 in response to determining that the remaining useful life of the operational system is below a threshold, determine an optimization result based on an objective function to minimize cost of repair of components, cost of replacement of components or system and/or downtime of the system; and

provide a recommendation based on the optimization result.

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18. The system according to any one of claims 11 to 17:

wherein the at least one processor is further configured to obtain the operational data in relation to the plurality of system parameters associated to the plurality of components of the operational system; and

15 wherein said obtain component remaining useful life information associated to a plurality of components of the operational system comprises determining, for each component of the plurality of components, the remaining useful life corresponding to the component with respect to the operational data based on a component remaining useful life function.

20

19. The system according to any one of claims 11 to 17, wherein the at least one processor is further configured to obtain the operational data in relation to the plurality of system parameters associated to the plurality of components of the operational system; and wherein said obtain component relationships information in relation to the
25 plurality of components of the operational system comprises determining the component relationship information with respect to the operational data based on the predefined KPIs.

30

20. A computer program product, embodied in one or more non-transitory computer-readable storage mediums, comprising instructions executable by at least one processor to perform a method of predicting remaining useful life of a multi-component operational system according to any one of claims 1 to 10.