Spring 5-2-2020

Application of Condition-Based Maintenance in Health Care: A Concept Analysis

Lindsey J. Ryan PhD, RN, ACNS-BC, NE-BC
Sharp Grossmont Hospital, Lindsey.Ryan@sharp.com

MPS	Journal	MSP No.	Dispatch: April 18, 2020	CE:
	NUF	12456	No. of Pages: 8	PE: Varsha Uniyal

DOI: 10.1111/nuf.12456

CONCEPT ANALYSIS

NURSING FORUM AN INDEPENDENT VOICE FOR NURSING WILEY

Application of condition-based maintenance in health care: A concept analysis

Lindsey J. Ryan PhD, RN, ACNS-BC, NE-BC

Medical Intensive Care Unit, Sharp Grossmont Hospital, La Mesa, California

Correspondence
Lindsey J. Ryan, PhD, RN, ACNS-BC, NE-BC, Medical Intensive Care Unit, Sharp Grossmont Hospital, 5555 Grossmont Center Dr, La Mesa, CA.
Email: Lindsey.Ryan@sharp.com

Abstract

Chronic illness burdens individuals, organizations and society, costing the US $3.5 trillion annually. Transposed from the engineering industry, condition-based maintenance is a novel concept that holds great promise for alleviating this burden by enhancing current health care delivery methods. Aims of this concept analysis include, (a) develop an operational definition for the term condition-based maintenance and (b) discuss the applicability and effectiveness of condition-based maintenance as applied to health care. A search of engineering and health care literature was completed. The search term "condition-based maintenance" was entered into the PubMed, Wiley Interscience Journals, CINAHL, Journals@Ovid, ProQuest Nursing & Allied Health Source, and Emerald databases. A review of the literature was completed to identify the qualities of condition-based maintenance. Utilizing the Walker and Avant method, antecedents, characteristics, and consequences were identified. A conceptual model of condition-based maintenance was developed encompassing two antecedents, four characteristics, and three consequences. Furthermore, a theoretical definition of condition-based maintenance was derived. Focus on the positive effects of proactively monitoring symptoms among chronically-ill persons is needed. Condition-based maintenance advances the National Institute of Nursing Research's focus on symptom science through the development of personalized strategies to treat and prevent the adverse symptoms of illness.

KEYWORDS

concept analysis, condition-based maintenance, predictive models, readmission, symptom science

In 2013, more than 4% of patients (3.9 million) discharged from a hospital were readmitted, costing the health care sector $52 billion dollars.[1] The US Patient Protection and Affordable Care Act has forced hospitals to re-examine health care delivery with the initiation of the Hospital Readmission Reduction Program), which ties patient outcomes to reimbursement for care provided. In November 2012, the Centers for Medicare & Medicaid Services began to reduce reimbursement payments to hospitals with high readmission rates.[2]

In 2013, the National Institute of Nursing Research[3] charged a group of symptom science experts with identifying potential research questions that could be used to advance nursing science. Experts discussed the importance of identifying biological indicators, understanding the behaviors of symptoms, finding symptom precursors, and creating management algorithms. In addition, experts strongly recommended the leveraging of technologies to improve symptom management and change the chronic illness trajectory through innovative care delivery models. When deriving a concept for analysis related to the topics of symptom science and hospital readmissions, concepts and models were examined from a wide range of industries that dealt with the general idea of

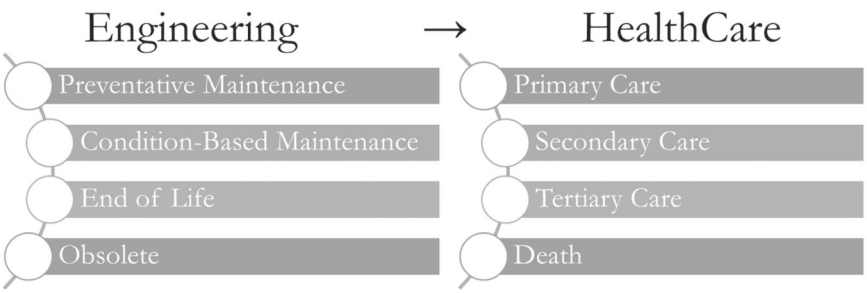

FIGURE 1 Concept derivation from the engineering industry to health care

"maintenance" and "failure" within their field. Articles within engineering were overwhelmingly filled with various maintenance models (Figure 1). These models were examined and the lifespan of equipment and related maintenance was closely reviewed and compared with the health care delivery model.

Condition-based maintenance traces back to the 1940's when the Rio Grande Railway Company crafted the model to detect coolant and fuel leaks in a diesel engine's lubricating oil. Due to the overwhelming success of the model, the US Army adopted and improved upon initial efforts which quickly grew in popularity during the 1950's, 1960's, and 1970's.[4] The condition-based maintenance model is simple and underpinned by the premise most equipment failures are preceded by certain signs, conditions, or indications.[5] Research shows condition-based maintenance improves equipment health management, lower life cycle costs, and prevents failures from occurring.[6] Application of equipment-related condition-based maintenance has been widely researched throughout various industries. However, the use of condition-based maintenance has not been explored in relation to health maintenance among humans. Application of the condition-based maintenance model may prove to have relevance in reducing hospital readmissions as it relates to the monitoring, identification, and treatment of specific disease processes before an individual experience a significant decline in health, warranting care.

1 | AIMS

The aims of this concept analysis paper are twofold. The first, to develop an operational definition of the term condition-based maintenance as applied to health care and second, to discuss the applicability and effectiveness of condition-based maintenance within health care.

2 | METHODS

The paper is presented in accordance with Walker and Avant's[7] eight-step concept analysis procedure: (a) selection of a concept, (b) determining the aim and purpose of the analysis, (c) identifying the uses of the concept, (d) defining the attributes of the concept, (e) constructing a model case example, (f) creating borderline, related and other case examples, (g) identifying the antecedents and consequences, and finally, (h) defining the empirical referents.[7]

The search term "condition-based maintenance" was entered into the PubMed, Wiley Interscience Journals, CINAHL, Journals@Ovid, ProQuest Nursing & Allied Health Source, and Emerald databases. Over 420 articles were identified from the initial search for the years 2010 to 2017 using the term condition-based maintenance. Limiters were applied which included full-text, peer-reviewed articles, available in English. The refining process narrowed the volume of pertinent literature to 54 articles, which were then retrieved and reviewed. Each article was reviewed for the definition, use, and key concepts of the term condition-based maintenance. Cited reference lists were also examined to identify any additional relevant literature resulting in six additional articles for a total of 60 articles reviewed. Of all the articles reviewed, 56 referenced the concept of condition-based maintenance and were used for further analysis.

3 | RESULTS

3.1 | Uses of the concept

While literature from the field of engineering prevails, condition-based maintenance can also be found in the automotive, aviation, defense, and manufacturing industries. Condition is a familiar term within health care literature, often referring to a patient's state of being. Condition is also frequently referenced within engineering and manufacturing industries to describe the state, or order, in which a piece of equipment exists.[8] In the field of sports medicine, the condition is used within the context of training or acclimatizing a person physically.[9] Lastly, in the field of law, the condition is viewed as the essence of a contract.[10] Recent literature explores the opportunities and barriers of adapting condition-based maintenance to other industries (eg, steel-making and chemical processing).[11,12] Although science has long held the notion of technology predicting patient outcomes, no published literature could be found applying the concept to the monitoring of human health conditions.[13] Condition-based maintenance has practical application within health care and could be applied to numerous conditions such as congestive heart failure, diabetes, chronic obstructive pulmonary disease, and chronic renal insufficiency.[14] To gain a firm understanding of condition-based maintenance, the definition of "condition," "based," and "maintenance" will be examined both independently and together.

3.1.1 | Condition

The Middle English noun "condition" is derived from the 14th century Old French term "condicion," which is a derivative from the Latin word *"condicio,"* meaning "terms of agreement." In Merriam-Webster "condition" is defined as[15]:

- "a usually defective state of health,"
- "a way of living or existing,"
- "the state in which something exists: the physical state of something,"
- "the physical or mental state of a person or animal,"
- "a premise upon which the fulfillment of an agreement depends."

3.1.2 | Based

According to the Merriam-Webster dictionary, the word "based" was first known to be used in the 13th century.[16] The adjective is Middle English, originally derived from the Greek term *"bainein"* meaning "to go." Definitions of the word "based" include[16]:

- "the bottom or lowest part of something: the part on which something rests or is supported,"
- "something (such as a group of people or things) that provides support for a place, business, etc,"
- "a main ingredient to which other things are added to make something,"
- "the fundamental part of something,"
- "something on which something else is established."

3.1.3 | Maintenance

Maintenance (noun), dates back to the mid-14th century from an Old French term *"maintenir"* meaning "action of providing a person with the necessities of life."[17] Definitions for the modern term include:

- "the combination of all technical and associated administrative actions intended to retain a system in a state in which it can perform its required function,"[18]
- "all technical and managerial actions taken during usage period to maintain or restore the required functionality of a product or an asset."[19]

3.1.4 | Condition-based maintenance

Condition-based maintenance, also known at the time as predictive maintenance, was first introduced by the Rio Grande Railway Company in the late 1940s.[4] Over time slight variations of the definition have evolved and can be found throughout the literature:

- "a set of maintenance actions based on real-time or near real-time assessment of equipment condition, which is obtained from embedded sensors and/or external tests and measurements taken by portable equipment,"[20]
- "a decision-making strategy where the decision to perform maintenance is reached by observing the condition of the system and/or its components,"[21]
- "monitoring one or more indicators of asset condition that can be used to give warning of asset deterioration sufficiently in advance of failure so that there remains time to take preventive action,"[22]
- "a maintenance policy which do maintenance actions before product failures happen, by assessing product condition including operating environments, and predicting the risk of product failures in a real-time way, based on gathered product data."[19]

For the purposes of this paper, condition-based maintenance is defined as an efficient, proactive process utilizing monitoring methods to predict, identify, and repair health-related problems precisely, before an individual becoming burdened with illness necessitating hospitalization.

3.2 | Defining attributes

Walker and Avant[7] describe attributes as the characteristics most often related to the concept, differentiating the concept from other associated concepts. Through the exploration of identified attributes, condition-based maintenance can then be distinguished from other types of maintenance. Four primary attributes were identified following a review of the literature: predictive, proactive, precise, and efficient (Table 1).

3.2.1 | Predictive

Literature containing the use of "predictive" in relation to condition-based maintenance defines the term in an analytical, prognostic fashion. Through the application of condition-based maintenance, the end-user, or clinician, can gather monitored data, analyze the findings, and in turn, predict future failures or life expectancy.[26,34] Within health care, predictive models have been used for disease management considering they stratify risk and increase the optimization of clinical resource utilization. Several condition-based maintenance algorithms, or decision support systems, exist today which guide the end-user, or provider, in identifying appropriate responses related to data findings.[25] With the ability to make informed decisions, interventions then, are only provided if deemed necessary to prevent failures, or deterioration, from occurring. [29,31]

3.2.2 | Proactive

In a technologically savvy world, there are many opportunities to use or develop a proactive solution to identified problems. With the

TABLE 1 Attributes of condition-based maintenance

Sources	Number of attributes	Predictive	Proactive	Precise	Efficient
Abdul Rahman et al[23]	1 of 4	+			
Abou-El-Seoud and Matsui (2014)	3 of 4	+	+		+
Abou-El-Seoud et al. (2012)	3 of 4	+		+	+
Ahmad et al[24]	2 of 4	+			+
Altosole et al. (2014)	3 of 4	+		+	+
Baglee et al. (2016)	3 of 4	+	+		+
Baraldi et al. (2013)	1 of 4			+	
Bousdekis et al[25]	4 of 4	+	+	+	+
Byon[26]	2 of 4			+	+
Byon et al. (2011)	1 of 4	+			
Corodón et al. (2011)	1 of 4	+			
de Jonge et al[27]		+		+	
Dong et al. (2013)	2 of 4	+		+	
Eker and Camci (2013)	2 of 4	+			+
Feng et al[14]	1 of 4	+			
Grasso et al. (2014)	2 of 4	+			+
Greenough et al[22]	1 of 4				+
Guan et al. (2013)	2 of 4	+			+
Guo et al. (2016)	2 of 4	+			+
Huang[28]	1 of 4	+			
Hussain (2015)	2 of 4			+	+
Jayaswal et al. (2013)	3 of 4	+		+	+
Jiang et al[29]	3 of 4	+		+	+
Kamei et al[11]	1 of 4	+			
Khodabakhshian[30]	3 of 4	+	+		+
Kisić et al[31]	3 of 4	+		+	+
Last et al. (2011)	2 of 4	+			+
Lee and Ni (2015)	4 of 4	+	+	+	+
Lee et al[32]	1 of 4				+
Lee et al. (2015)	2 of 4	+			+
Li et al. (2014)	3 of 4	+	+		+
Li et al. (2015)	1 of 4				+
Liu et al. (2012)	1 of 4			+	
Lubini and Fuamba (2011)	3 of 4	+		+	+
Meyer and Adams (2013)	1 of 4	+			
Naderkhani and Makis (2015)	2 of 4		+		+
Pack (2014)	3 of 4	+	+		+
Prajapati and Ganesan (2013)	3 of 4	+		+	+
Rasaienia et al. (2013)	2 of 4	+		+	
Safari et al. (2010)	2 of 4			+	+

TABLE 1 (Continued)

Sources	Number of attributes	Predictive	Proactive	Precise	Efficient
Shin and Jun[19]	4 of 4	+	+	+	+
Shinkai et al. (2013)	1 of 4				+
Tarefder et al. (2013)	1 of 4	+			
Terpening et al. (2016)	3 of 4	+		+	+
Thompson (2010)	2 of 4	+		+	
Van and Bérenguer (2012)	2 of 4	+			+
Van Dam and Bond (2015)	2 of 4	+	+		
Wang et al (2014)	1 of 4		+		
Wu et al. (2013)	2 of 4	+			+
Xia et al. (2011)	2 of 4	+			+
Xiang and Coit (2014)	2 of 4	+			+
Xu et al[33]	1 of 4	+			
Yakub et al. (2012)	2 of 4	+		+	
Zhang et al. (2010)	4 of 4	+	+	+	+
Zhou et al[34]	2 of 4	+			+
Zhu et al[12]	1 of 4		+		

case of condition-based maintenance, having a monitoring process in place allows the end-user to not only predict but also proactively repair deteriorating systems before they advance to a state of failure.[23,25] For example, if predictive measures indicated an individual with congestive heart failure was deteriorating based on increased weight and shortness of breath, a provider could proactively intervene, preventing unnecessary stress for the individual and a potential visit to the emergency department.

3.2.3 | Precise

The success of condition-based maintenance lies in the ability of the concept to be precise in predicting deterioration. Just as an engineer intimately understands how a specific piece of equipment works, a provider should also have a complete understanding of the patient clinically to accurately set up predictive measures and precisely treat them should deterioration occur.[27]

3.2.4 | Efficient

The use of condition-based information has less associated costs than other concepts, which do not monitor deterioration.[27] In contrast to planned maintenance models, where maintenance is performed based upon predefined scheduled intervals, condition-based maintenance is performed only when deterioration is detected.[30] Condition-based maintenance lengthens the span of time between repairs, or office visits, cutting down on unnecessary maintenance activities that cost time, money, and manpower. Currently, health care in the United States most closely resembles the structure of a planned maintenance model, where patients are scheduled for predetermined office visits, despite an acute need for such. From infancy through adulthood, preventative care recommendations are made outlining when patients should see their provider, as well as when tests and procedures are to be performed. While these recommendations are largely evidence-based, the goal of catching disease through predetermined screening activities may be costlier in cases where only a very small fraction of the population would have become ill in the absence of preventive measures.

3.3 | Constructed cases

3.3.1 | Model case

Mrs. Jones is an 81-year-old female who had an aortic valve repair 6 days ago. Today's labs revealed hemoglobin and hematocrit of 11 of 29, respectively and her cardiac echogram ejection fraction was 36%, previously 32% during surgery. Mrs. Jones was started on 20 mg furosemide daily and weekly erythropoietin injections (*predictive*). As she prepared for discharge she received verbal instructions from both her primary nurse and cardiac surgeon. In addition to the printed discharge materials, Mrs. Jones was also provided a SpO2 monitor (*monitor and analyze deterioration data*) and explicit instructions for use with successful return demonstration (*proactive*). Four days after Mrs. Jones has been discharged home from the hospital she notices a weight gain of five pounds and her SpO2 monitor is

reading 94%, down from her usual 98% (*abnormal data values*). Throughout the day, Mrs. Jones' legs feel noticeable "heavier" and she experiences difficulty catching her breath when walking. Mrs. Jones calls her primary care provider. The physician asks specific questions related to her cardiac function then instructs Mrs. Jones to take an additional 20 mg of furosemide each day and calls in a prescription for an angiotensin-converting enzyme inhibitor (*precise & efficient*). The following morning Mrs. Jones notes a weight loss of two pounds and a decrease in her shortness of breath and leg swelling. Mrs. Jones is able to reduce her clinic visits and stay out of the hospital due to the at-home monitoring process set in place (*increased safety*, *decrease burden and costs*). Mrs. Jones' health is stable and she is able to enjoy life with her family and friends (*life extension*).

This scenario is a model case because it includes all four critical attributes and exemplifies the identified definition of condition-based monitoring. The provider predicts the patient may have complications following surgery based on objective data gathered in the hospital. This prompts the provider to proactively set up a process in which the patient can be monitored for signs of deterioration long before a crisis occurs. When the patient begins deteriorating the provider asks precise questions and responds with a treatment that is both precise and efficient to meet the needs of the patient. Overall, this process is efficient; it was handled quickly over the phone and kept the patient from deteriorating further and needing an appointment, or worse, rehospitalized.

3.3.2 | Borderline case

Claire suffers from chronic hypertension and expended the last of her antihypertensive medication this morning. Claire placed a call to her primary care provider and left a voicemail requesting a renewal of her prescription (*precise*). Mid-morning her primary care provider calls in the prescription to Claire's identified pharmacy on file. The primary care provider then calls Claire to close the loop and notify her the prescription has been placed (*efficient*).

In this borderline case, only two of the four attributes are represented. Claire has a chronic condition which she is being treated for and could have predicted her need for additional medication. Indeed, Claire could have proactively reached out to her primary care provider before she ran out to prevent a potential health crisis.

3.3.3 | Contrary case

Jed wakes up feeling tired and notices mild shortness of breath throughout the day. The following day Jed notices a marked increase in his shortness of breath, he is pale and complains of his heart racing. Jed's wife drives him to the local emergency department where he is admitted. After multiple tests and procedures, Jed is diagnosed with congestive heart failure exacerbation.

This is a contrary case as it does not contain any of the attributes associated with the concept itself. Jed became acutely ill which he could not predict or proactively treat. Due to the various symptoms, he was experiencing the emergency department providers ordered multiples tests and procedures related to their constructed dual diagnoses. This episode of health care delivery, while appropriate, was neither precise nor efficient. Condition-based maintenance could have prevented the extent of the exacerbation, including a visit to the emergency department, through proactive monitoring of precise symptoms. If a monitored, electronic database to record pertinent data such as daily weights and oxygenation levels were available, it could have predicted Jed's deterioration and signaled a need for early intervention.

3.4 | Antecedents

The conditions and events that precede a concept are labeled antecedents.[7] In relation to condition-based maintenance, two antecedents have been identified in the literature: (a) monitor and analyze deterioration data and (b) abnormal data values (Figure 2).[19,22]

A structure and process must be in place to monitor and analyze data to detect deterioration. Monitored data points can then be gathered and analyzed to better predict whether or not deterioration is detected. Deterioration is identified through abnormal values and predicts whether a maintenance intervention is required to proactively prevent an episode of failure, as well as an estimated life expectancy.[21]

3.5 | Consequences

Subsequent events that occur as a result of the concept are labeled as consequences.[7] Throughout the literature three positive

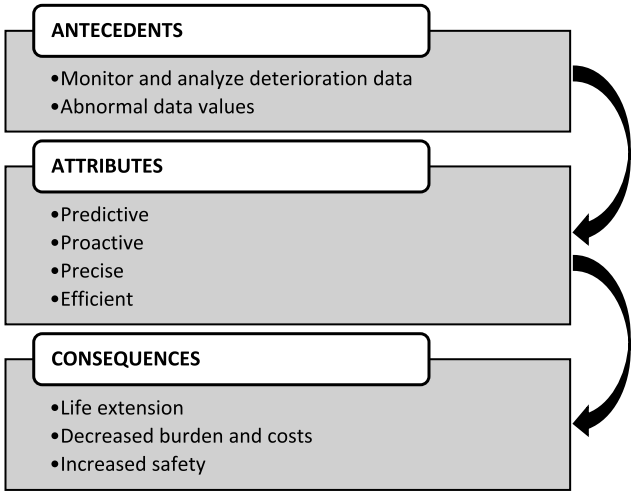

FIGURE 2 Antecedents, defining attributes, and consequences of condition-based maintenance

consequences were consistently identified as a result of condition-based maintenance: (a) life extension, (b) decreased burden & costs, and (c) increased safety.

Asset life may be extended with the use of condition-based maintenance concept because it essentially prevents failure from occurring. As a result, there is both better utilization of the asset's life and a reduction in maintenance cost.[27]

Application of condition-based maintenance leads to a decrease in burden and costs.[24] As data are gathered from the monitoring process, an early indication of deterioration can be identified and proactive, precise maintenance can then be performed. Safety is increased when an asset is identified as deteriorating and proactive, precise maintenance is performed to prevent failure.[30]

3.6 | Empirical referents

The attributes of condition-based maintenance—predictive, proactive, precise, and efficient—can be measured quantitatively. In reviewing the literature several instruments were identified, for example, the electronic vibration measurement instrument.[35] Unfortunately, all identified instruments are specific to the monitoring of equipment and are not transferrable to monitoring human conditions. Considering the attributes, along with the antecedents and consequences, there are a number of ways to create applicable instruments within the health care industry.

Instrument construction would need to be disease specific since the monitoring and analysis of deterioration data would be unique to the specific disease.

4 | DISCUSSION

This analysis underpins the importance of symptom science through the transposing and trialing of established monitoring methods to improve patient safety, increase lifespan, decrease burden and health care costs. This concept analysis is considered innovative, nonetheless, it is also abstract in nature. Without applicable empirical referents, further research is needed to identify if condition-based maintenance can be adapted to monitoring various human conditions effectively. Additional quantitative and qualitative research focusing on both disease-specific measurements and quality of life components could further develop the concept in becoming more concrete. Outcomes from this analysis may be useful in the development and testing of measurement instruments.

4.1 | Relevance to clinical practice

Condition-based maintenance advances the National Institute of Nursing Research[36] focus on "developing personalized strategies to treat and prevent the adverse symptoms of illness across diverse populations and settings." Clarifying the concept of condition-based maintenance may lead to improved assessment practices through early identification of symptom precursors, the optimization of symptom dynamics, and prevention of symptom relapse or clinical deterioration.

Within this concept analysis, condition-based monitoring is explored and defined within the context of the health care industry to further advance symptom science efforts. An abundant amount of literature on condition-based monitoring exists; however, research focusing on the application of the concept within health care is limited. Through the identification of antecedents, attributes, and consequences, health care providers may begin to investigate the translation of this concept into clinical practice. Constructed cases demonstrating the presence and absence of the attributes are provided to enhance the understanding of condition-based monitoring as a concept. Empirical referents are proposed to enhance recognition of this abstract concept and measure defining attributes in the future.

ACKNOWLEDGMENTS

Support for this study was provided in part by the Robert Wood Johnson Foundation, Sharp HealthCare, and the University of San Diego. The views expressed here do not necessarily reflect the views of the Robert Wood Johnson Foundation, Sharp Healthcare, University of San Diego.

ORCID

Lindsey J. Ryan http://orcid.org/0000-0001-5724-4143

REFERENCES

1. Fingar K, Washington R. (2015). HCUP Statistical Brief #196: *Trends in Hospital Readmissions for Four High-Volume Conditions, 2009-2013*. http://www.hcup-us.ahrq.gov/reports/statbriefs/sb196-Readmissions-Trends-High-Volume-Conditions.pdf
2. Centers for Medicare & Medicaid Services. *Hospital Readmission Reduction Program (HRRP)*. 2016. https://www.cms.gov/medicare/medicare-fee-for-service-payment/acuteinpatientpps/readmissions-reduction-program.html
3. National Institute of Nursing Research. (2020). Symptom Science. https://www.ninr.nih.gov/newsandinformation/iq/symptom-science-workshop
4. Prajapati A, Bechtel J, Ganesan S. Condition based maintenance: a survey. *J Qual Mainten Eng*. 2012;18(4):384-400.
5. Bloch HP, Geitner FK. Practical Machinery Management for Process Plants. *Machinery Failure Analysis and Troubleshooting*. 2. Baytown, TX: Exxon Chemical Co; 1983.
6. Banks J. *An overview of condition based maintenance* [PDF document]. http://www.logisticsymposium.org/paperclip/speaker_management/14LA/presentation_file_distribution/358/8186d0e75243585e8e3bab96281ea9e1d0b2c646.pdf
7. Walker LO, Avant KC. *Strategies for Theory Construction in Nursing*. 5th ed. Upper Saddle River, NJ: Pearson Education Limited; 2011.
8. Cueman MK. US patent 6 765 993. 2004.
9. Cocke C, Dawes J, Orr R. The impact of two different conditioning programs on fitness characteristics of police academy cadets. *Asics Sports Medicine Conference*. 21-24 October 2015; Gold Coast, Australia.
10. Martin EA. (2009). A dictionary of law. OUP Oxford.
11. Kamei M, Takai O. Effect of sensor information accuracy on condition-based strategy of GIS/GCB maintenance. *Elec Eng Japan*. 2011;176(2):14-21.

12. Zhu Q, Peng H, van Houtum GJ. A condition-based maintenance policy for multi-component systems with a high maintenance setup cost. *Or Spectrum*. 2015;37(4):1007-1035.
13. Taylor CA, Draney MT, Ku JP, et al. Predictive medicine: computational techniques in therapeutic decision-making. *Comput Aided Surg*. 1999;4(5):231-247.
14. Feng Q, Rafiee K, Keedy E, Arab A, Coit DW, Song S. Reliability and condition-based maintenance for multi-stent systems with stochastic-dependent competing risk processes. *Int J Adv Manufact Technol*. 2015;80(9-12):2027-2040.
15. Merriam-Webster. Condition. 2015. http://www.merriam-webster.com/dictionary/condition
16. Merriam-Webster. Based. 2015. http://www.merriam-webster.com/dictionary/based
17. Merriam-Webster. Maintenance. 2015. http://www.merriam-webster.com/dictionary/maintenance
18. Zhang H, Kang R, Pecht M. A hybrid prognostics and health management approach for condition-based maintenance. *2009 IEEE International Conference on Industrial Engineering and Engineering Management*. December 2009; pp. 1165-1169.
19. Shin JH, Jun HB. On condition based maintenance policy. *J Comput Des Eng*. 2015;2(2):119-127.
20. Butcher SW. Assessment of condition-based maintenance in the department of defense. Logistics Management Institute, 2000. McLean, VA; p. 1-70.
21. Kothamasu R, Huang SH, VerDuin WH. System health monitoring and prognostics–a review of current paradigms and practices. *Handbook of Maintenance Management and Engineering*. London: Springer; 2009:337-362.
22. Greenough RM, Grubic T. Modelling condition-based maintenance to deliver a service to machine tool users. *Int J Adv Manufact Technol*. 2011;52(9-12):1117-1132.
23. Abdul Rahman AG, Noroozi S, Dupac M, Al-Attas SMSM, Vinney JE. A hybrid approach for nondestructive assessment and design optimisation and testing of in-service machinery. *Nondestr Test Eval*. 2013;28(1):44-57.
24. Ahmad R, Kamaruddin S. An overview of time-based and condition-based maintenance in industrial application. *Comput Ind Eng*. 2012;63(1):135-149.
25. Bousdekis A, Magoutas B, Apostolou D, Mentzas G. A proactive decision making framework for condition-based maintenance. *Ind Manag Data Syst*. 2015;115(7):1225-1250.
26. Byon E. Wind turbine operations and maintenance: a tractable approximation of dynamic decision making. *IIE Trans*. 2013;45(11):1188-1201.
27. de Jonge B, Teunter R, Tinga T. The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance. *Reliab Eng Syst Safe*. 2017;158:21-30.
28. Huang YH. Artificial neural network model of bridge deterioration. *J Perform Constr Facil*. 2010;24(6):597-602.
29. Jiang R, Kim MJ, Makis V. Maximum likelihood estimation for a hidden Semi-Markov model with multivariate observations. *Qual Reliab Eng Int*. 2012;28(7):783-791.
30. Khodabakhshian R. Maintenance management of tractors and agricultural machinery: preventive maintenance systems. *Agric Eng Int CIGR J*. 2013;15(4):147-159.
31. Kisić E, Đurović Ž, Kovačević B, Petrović V. Application of control charts and Hidden Markov models in condition-based maintenance at thermoelectric power plants. *Shock Vib*. 2015;2015:1-11.
32. Lee BJ, Kang CW, Kim SJ, Bae SJ. Optimal replacement strategy for stochastic deteriorating system with random wear limit under periodic inspections. *Int J Adv Manufact Technol*. 2014;71(1-4):219-231.
33. Xu P, Liu R, Sun Q, Wang F. A novel short-range prediction model for railway track irregularity. *Discrete Dyn Nat Soc*. 2012;2012:1-12.
34. Zhou Q, Son J, Zhou S, Mao X, Salman M. Remaining useful life prediction of individual units subject to hard failure. *IIE Trans*. 2014;46(10):1017-1030.
35. Mitchell JS. From vibration measurements to condition-based maintenance. *Sound Vib*. 2007;41(1):62.
36. National Institute of Nursing Research. Themes: Symptom Science. 2020. https://www.ninr.nih.gov/aboutninr/ninr-mission-and-strategic-plan/themes-symptom-science
37. Lee S, Ni J. Joint decision making for maintenance and production scheduling of production systems. *Int J Adv Manufact Technol*. 2013;66(5-8):1135-1146.

QS

How to cite this article: Ryan LJ. Application of condition-based maintenance in health care: A concept analysis. *Nursing Forum*. 2020;1–8. https://doi.org/10.1111/nuf.12456