# Perspectives on the Future of Maintenance Engineering Education

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**Abstract.** In this article, we aim to remedy the effects of skill-biased technological change within maintenance engineering and enable productivity gains from novel digital technologies such as Artificial Intelligence. We do this by outlining the critical role of education and the need for renewal and increased access to higher education within maintenance, followed by reviewing the literature on maintenance engineering education over the past two decades (2000-2020). In our systematic literature review, we identify nine key themes that have occupied maintenance researchers in their educational efforts, e.g. design and development of curricula, programs, and courses; identification of competence requirements and learning characteristics; and new educational formats such as gamification and innovative laboratory sessions using novel digital technologies. Following our review, we propose research- and policy-oriented recommendations for the future of maintenance engineering education.

**Keywords:** Maintenance, Engineering, Education, Digitization, Manufacturing

## 1 Introduction

The role of maintenance functions within manufacturing plants has changed significantly over the past decades; from undesired cost centers to enablers of resilient and sustainable production systems. This evolution is fueled by rapid technological change. Today, novel digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Additive Manufacturing (AM) are increasingly introduced to the production process (what to maintain) as well as the maintenance process (how to maintain) [1].

However, economic theories of technological change predict that harnessing the value of novel technologies requires complementary intangible investments. That is, before the promises of astonishing new technologies such as AI can blossom, firms must make large, time-consuming, and often neglected investments in complementary intangibles [2]. In the economics of digitization, this logic is often expressed as a bottleneck proposition: digital abundance leads to bottlenecks whenever essential complements cannot be digitized. No matter how much other inputs are increased, the absence of any essential complement will act as the weakest link and constrain growth. The digital winners will therefore be those with as many of the right complements in place as possible [3].

One essential complement to novel digital technologies that cannot be digitized is human skills [2]. This implies that if maintenance workers do not acquire the essential skills to execute new tasks and more complex versions of existing tasks enabled by novel digital technologies, no productivity gains will materialize. To relieve this skills bottleneck, one obvious part of the solution is education. The implicit solution framework is a race between technology and education: growth in demand from more-educated maintenance workers from skill-biased technological change versus growth in supply of more-educated maintenance workers from schooling [4].

Higher education (i.e. universities) plays a key role in this framework, where the need is two-fold: (1) *renew higher education* and (2) *increase access to higher education*. These two needs focusses on producing the right kind of maintenance workers that are complemented rather than substituted by novel digital technologies. However, this is already an uphill battle as it starts from low levels of education among maintenance workers and limited access to higher education [5]. But with the right roadmap for accelerating and renewing higher education in maintenance engineering, universities can increase the preparedness among manufacturing firms in realizing the benefits of novel digital technologies.

The aim of this paper is to stimulate this development of higher education, and we therefore review the existing literature on maintenance engineering education from the past two decades. We contribute to the maintenance discipline by providing an overview of research on maintenance engineering education as well as identifying the key themes that have occupied researchers in their educational efforts. Specifically, we present descriptive findings from a total of 25 articles and uncover nine key themes that reflect the body of knowledge provided by the literature sample. Based on the insights from the review, we propose several recommendations for the future of maintenance engineering education that encompasses both research and policy.

## 2 Review methodology

Existing research on maintenance engineering education is scarce. For example, Kans and Metso [6] claim that their structured literature review only revealed four relevant articles between 1997-2011. We therefore designed a Systematic Literature Review (SLR) process focusing on uncovering a wider net of plausibly relevant articles, intending to achieve a broad and representative but not necessarily comprehensive set of articles. The SLR process was designed as a four-step approach (Define, Retrieve, Select, Synthesize), with each step explained in the following sections.

**Step 1: Define.** In the first step, we defined the required characteristics of literature to be included in our review [7]. We specified a set of inclusion/exclusion criteria [8] within four main categories. (1) *Unit of analysis* was specified to be at the level of an article. (2) *Sources of data* were specified as either journal, conference, book chapter, or thesis, and we accepted any type of study (e.g. conceptual, empirical, review). This allowed us to capture a wide net of potentially relevant articles. Note however that since we focus on scientific literature, our review does not cover sources of data such as public reports or official standards (e.g. CEN - EN 15628). We defined the time window of the review as 2000-2020 since the early 2000s are recognized as the starting point for accelerated interest in digitization within maintenance. (3) *Theoretical domain* was specified as production maintenance, i.e. maintenance of production equipment within the manufacturing industry. (4) *Study context* was specified as higher education where the intended delivering body of education is universities, but the intended target audience could be either university students or industry professionals. Since we focus on higher education, we refer to maintenance as an engineering discipline; typically covered by programs such as mechanical or automation engineering and focused on knowledge situated in the professional practice of maintenance. Still, as a professional practice, maintenance also includes non-engineering topics (e.g. management).

**Step 2: Retrieve.** The second step consisted of retrieving a baseline sample of potentially relevant literature [7]**.** As previous similar reviews only uncovered a small number of articles [6], we deployed a two-step procedure. Firstly, we used the following search string in the Scopus database: "(manufacturing OR production) AND maintenance AND engineering AND education". We delimited the search to only relevant disciplines, followed by downloading all articles that were deemed relevant based on title, abstract, and/or keywords. Secondly, we searched for additional articles through tracking references-of-references from the Scopus sample. We did this to avoid overlooking articles that were not indexed in Scopus or remained undetected by our search string. The baseline sample consisted of a total of 51 articles.

**Step 3: Select.** Using the baseline sample, the third step consisted of selecting pertinent literature by applying the inclusion/exclusion criteria [7]. Firstly, we reviewed the title, abstract, and keywords and classified each article as either "included" or "excluded". We erred in the direction of inclusion for articles that did not clearly meet our definitions of primary studies [8] but marked them as "borderline" cases. At this stage, 15 articles were excluded and 10 articles were marked as borderline. Thereafter, we read the full text of all included and borderline articles. Here we excluded the articles that did not fulfill all of our criteria. For example, we excluded articles that did not fulfill our theoretical domain (e.g. education of aerospace maintenance) or study context (e.g. firm-specific educational programs or a sole focus on on-job training). We also excluded implicit duplicates, i.e. articles by the same authors that covered the same content across multiple publication outlets. A total of 11 articles were excluded at this stage, resulting in a final sample of 25 articles.

**Step 4: Synthesize.** In the final step, we synthesized the literature [7] by means of two analyses. (1) *Descriptive analysis* focused on providing an overview of the 25 articles included in the review. We analyzed: year of publication, article type, country of affiliation, and target audience. The following classification of article type was used: C = Conference; J = Journal; B = Book chapter, T = Thesis (MSc or PhD). The target audience was classified as either U = University education, P = Professional education, or both (P & U). (2) *Thematic analysis* focused on uncovering the main themes within the body of knowledge provided by the literature sample. Based on reading the full text of all articles, we deployed an inductive and iterative coding approach to identify the themes [8]. The themes were finally used as a classification scheme for all articles, where one article could cover more than one theme.

## 3 Findings

We present our findings in two sections, reflecting the two types of analyses. The descriptive findings are presented first (Section 3.1), followed by the thematic findings (Section 3.2). The main thematic findings are summarized in Table 1.

### 3.1 Descriptive findings

Four main descriptive findings summarize the articles included in our review. Firstly, articles on maintenance engineering education have been published at a low but consistent pace over the past two decades; 25 articles across 20 years yield an average of 1,25 articles each year. Secondly, the vast majority of articles are published in conference proceedings (C, 72%). We only identified four journal articles (J, 16%) and the rest were book chapters or theses (B & T, 12%). Two of the journal articles are published in generic engineering educational journals and two are published in the same domain-specific journal: Journal of Quality in Maintenance Engineering. Thirdly, there is a focus on both target groups, reflected in that roughly half (U, 52%) of all articles focus on university education and the rest on either professional education or both (P, P & U, 48%). Fourthly, the majority of all articles are published by European authors (72%), especially from the Nordic countries (Sweden, Finland, Norway with 32%). The other countries of affiliation are the US, Australia, Greece, UK, Italy, Slovakia, Spain, Netherlands, Venezuela, Colombia, Ireland, Austria, and Bulgaria. However, it should be noted that our review did not include non-English articles (e.g. Chinese, Korean).

### 3.2 Thematic findings

The nine inductively generated themes are listed in Table 1 along with summaries of their thematic content and associated references. The intention is to summarize the body of knowledge provided by the literature for each theme, not to outline the substantive findings from each of the articles within each theme.

**Table 1.** Summary of thematic findings.

| Theme and definition | Thematic content | References |
|---|---|---|
| ***1. Review of educations:*** existing maintenance engineering educations (e.g. courses and programs). | Overview of existing (past or present) courses and programs in maintenance engineering education, e.g. describing and comparing courses nationally and globally. | [6, 9-11] |

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|---|---|---|
| ***2. Competence requirements*:** knowledge, skills, abilities, and other characteristics of maintenance engineering professionals. | Competence requirements for professional maintenance engineers; individual skills, bundles of skills, and categorization of skills using educational frameworks (e.g. the CDIO syllabus). | [6, 10, 12-14] |
| ***3. Learner characteristics:*** personal, academic, social, and cognitive aspects that influence why, how, and what maintenance engineering students learn | Unique learning characteristics of maintenance engineering students that need to be considered in educational design, e.g. time and space constraints, prior knowledge and skills, and digital literacy of adult learners. | [10-12, 15-17] |
| ***4. Curricula design:*** topics and learning objectives relevant for inclusion in maintenance engineering education. | Curricula used in existing education or proposals of curricula for future education, e.g. curriculum based on EFNMS requirements and general guidelines for curriculum for modern engineering education. | [10, 13, 15-19] |
| ***5. Course and program design*:** design of individual courses and aggregate programs for maintenance engineering education. | Design and/or delivery of courses and programs for maintenance engineering education, e.g. MSc courses with a specified structure of content, teaching and learning activities, and assessment. | [10, 16, 20-22] |
| ***6. Laboratory sessions:*** learning environments where students can observe, practice, and experiment with maintenance topics, individually or in groups. | Laboratory sessions for maintenance engineering education, e.g. remote condition monitoring and maintenance laboratory, techniques for predictive maintenance, and sensor diagnostics. | [14, 23-25] |
| ***7. Online learning:*** maintenance engineering education delivered in online learning environments. | Online learning environments for maintenance education, e.g. e-Learning systems for vocational education, web-based modules for condition monitoring, and provision of online study materials for asynchronous learning. | [10, 15, 17, 18, 22, 26, 27] |
| ***8. Gamification:*** applications of elements of game playing in maintenance engineering education. | Learning environments that include game content and game play, e.g. teaching the pitfalls and ambiguities of OEE or strategic challenges with maintenance of rolling stock. | [28, 29] |
| ***9. AR and VR:*** applications of AR and VR systems in maintenance engineering education. | Experimental learning environments using AR and VR to enable interaction with real (or very close to real) situations in maintenance engineering, e.g. occupational hazards during maintenance execution. | [30, 31] |

In addition to uncovering and elaborating on the content of the nine themes (Table 1), we also observed five patterns across the themes. Firstly, most of the themes are covered in articles that span the entire review period, suggesting them to be relevant for maintenance engineering education. Also, each theme is covered by a minimum of two articles (i.e. at least 4% of the literature sample). Secondly, "Course program and design" seemed to be an important theme in the first decade, but not the second (6 articles up until 2010; zero articles after 2010). This might be indicative of the shorter life-cycle and rapid evolvement of modern maintenance engineering. Thirdly, and similarly, articles covering "Online learning" also received more emphasis in the first decade of our review (7 articles up until 2013; zero articles after 2013). However, online learning has recently increased in importance due to the COVID-19 pandemic, and we predict that this will soon be reflected in the publication landscape. Fourthly, more recent themes include "Gamification", "AR and VR", as well as "Laboratory sessions" using novel digital technologies (7 articles published since 2015). Fifth and finally, we observe that maintenance researchers have been occupied with presenting ideas, concepts, methods, and tools for how to *renew higher education*, but that there is no or at least very little attention or concrete proposals for how to *increase access to higher education*.

## 4 Conclusions and recommendations for the future

The ultimate goal is to produce the right kind of maintenance workers that are complemented rather than substituted by technology [2]. From our systematic literature review of 25 articles published between 2000-2020, we have identified nine key themes that have occupied maintenance researchers in their educational efforts. Based on the insights from our review, we propose a set of recommendations for the future in terms of two general research suggestions and two general policy suggestions.

**Research on skills**. Future maintenance workers need to interface with new technologies such as AI algorithms in novel decision-making processes. However, the potential productivity gains from such process improvement require that maintenance workers possess two forms of complementary skills: domain-specific skills (accumulated through prior learning within the maintenance domain) and vintage-specific skills (accumulated through familiarity of tasks with new technology) [32]. Still, we do not know exactly which skills that are complementarities and which are substitutes, and we do not know exactly how individual and/or bundles of skills interface differently with specific technologies. We therefore call for more research on skills.

**Research on education**. As we gain more knowledge into what skills that should be the locus of education, we still face the hurdle of implementation as we lack a body of knowledge on effective maintenance engineering education. Therefore, we call for more research on education - developing explanatory and predictive knowledge on what constitutes effective maintenance engineering education, as well as prescriptive knowledge on evidence-based design of maintenance engineering education.

**Renew education**. The race against technology will not be won simply by increasing educational spending whilst holding current educational practices constant, because traditional education is designed for producing traditional skills. Therefore, we call for renewing maintenance engineering education by identifying the right modern skillsets for maintenance workers, translating them into achievable learning objectives, and implementing them using teaching and learning methods that fit a digital age.

**Increase access to education**. Traditional maintenance engineering education has focused on specialized courses, programs, and degrees. Therefore, we call for increasing access to higher education by means of novel forms of individualized education (e.g. module-based online learning and open educational resources) as well as novel forms of interdisciplinary education (e.g. case-based analytics projects with teams of mechanical engineering students and data science students).

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