A Literature Review of Evaluation Approaches for Cyber-Physical Production Systems

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Abstract: The role of Cyber-physical production systems (CPPSs) as Industry 4.0 enablers has raised the interest to upgrade legacy production systems. However, manufacturers face uncertainty when assessing if the transformation process is worth it. In this context, the aim of this study is to review the works in the existing literature that approach the evaluation of CPPSs in a context of production systems' transformation. To do so, we adopted a systematic literature review process that comprises the development of a framework of six review questions that help us to analyze and characterize the literature found. From the literature review, this paper presents a conceptual model that aims at establishing the basis for a complete approach for CPPS evaluation.

1 INTRODUCTION

Production systems have been the core of the manufacturing industry since the appearance of the steam machine that set off the first industrial revolution back in the 18th century. Later innovations like electricity, production lines and information technologies enabled a continuous evolution in industry. As of today, technological breakthroughs like cloud computing, data analytics, the Internet of things (IoT) and artificial intelligence (AI) have paved the way for the fourth industrial revolution, also known as Industry 4.0, in which the fusion of the physical and virtual worlds has been possible, in part, by Cyber-Physical Systems (CPS) (Kagermann et al., 2013). When a CPS is applied to production environments, we refer to it as a Cyber-Physical Production System (CPPS) (Wang et al., 2015). We conceive a CPPS according to the definition of X. Wu, (2022) as: "A combination of technological agents, IT agents and humans, collaborating within a synergistic production environment to carry out technical, decision-making, or cognitive tasks autonomously, using the best capabilities of each kind of agent involved".

Nowadays, the ever-increasing business demands like the need for customized products or the decrease in the product lifecycles (Neugebauer et al., 2016) drives the transition from legacy manufacturing systems to CPPSs as a main stake for manufacturers. However, such transition must be well-founded since it usually implies high upfront investments for organizations, development time and it is surrounded by considerable uncertainty (X. Wu, 2022). Therefore, the evaluation of the CPPSs to be implemented plays a crucial role in the transformation context to reduce uncertainty and mitigate risks. In this context, we formulate the following research question: "How do existing methods evaluate a CPPS along its lifecycle, especially during its design?". To answer this question, we perform a systematic literature review on the existing approaches to evaluate CPPSs to identify the gaps in this research subject.

This work is structured as follows: Section 2 presents a systematic literature review of the evaluation approaches for CPPSs. This leads us, in Section 3, to work out a conceptual model that allows to fulfill the gaps identified in the analysis of the literature review. Finally, Section 4 draws some conclusions and sets out a research agenda for the future.

2 STATE OF THE ART

The literature review followed in this work is based on the framework proposed by vom Brocke et al., (2009), which consists of five phases illustrated on Fig. 1. Likewise, each phase is explained below.

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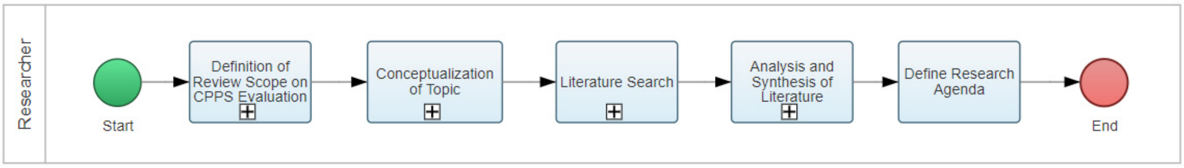

Figure 1: BPMN illustration of the systematic literature review process followed in this work.

2.1 Definition of Review Scope

The first phase comprises 6 stages, each one is intended to define one constituent characteristic of the review: focus, goal, organization, perspective, audience, and coverage. Our focus is the review of research outcomes on CPPSs evaluation. The goal is to describe the state of the art in the evaluation of CPPSs. The organization is given by a framework of six review questions to be presented further on. The review presents different interpretations of the literature in a neutral perspective. Regarding the audience, this work is meant to be consulted by specialized scholars in the field of production/manufacturing systems. The coverage is exhaustive, as we are covering most of the literature about CPPSs evaluation.

2.2 Conceptualization of Topic

The definition of key terms is essential for conceptualization of the topic to be reviewed. In our case, 20 keywords are defined and grouped by their meaning similarity. The first group refers to the production systems themselves and the different forms that could be found in the literature: *CPPS, Cyber-physical production systems, CPS, Cyber-Physical Systems, Manufacturing Systems, Production system.* Next, 6 keywords compose the second group that refers to evaluation and some other related concepts: *Measure, Measurement, Evaluate, Evaluation, Assess, Assessment.* The third group of keywords implies the potential transformation of the production system towards a target stated that can be named in different ways: *Requirement, Request, Requisite, To-be, Target State, Required State.* Finally, the fourth group refers to the representation of the designed production system as it could be a model or a meta-model: *Model, Meta-model.*

2.3 Literature Search

Given the key terms definition and grouping, we make use of AND / OR operators to construct a query that comprises the relevant literature to our topic. For this work, we employed the Scopus database and search engine. The query assembly is shown below:

TITLE-ABS-KEY ((measure OR measurement OR evaluate OR evaluation OR assess OR assessment) AND (requirement OR request OR requisite OR {to-be} OR {required state} OR {target state}) AND (model OR {meta-model}) AND (CPPS OR "Cyber-physical production system" OR "Cyber-physical system" OR "production system" OR "manufacturing system")) AND (LIMIT-TO (SUBJAREA , "COMP")).

The operator TITLE-ABS-KEY() instructs the search engine to look for the terms in parenthesis within the title or the abstract or the keywords of each of the articles that compose the database. The operator LIMIT-TO() constrains the results to the domains of Computer Science only. As a result, 645 articles were listed and passed through a three-stage filtering process as follows: In the first filtering stage, we proceeded to assign one of the following categories to each title according to its relevance and relationship to our research subject: related (28 articles), somewhat related (49 articles) and not related (568 articles). Only the articles assigned to the first and second categories passed to the next stage. In the second filtering stage, we analyzed the abstract of each article and selected only the ones most related to the research subject which accounted for 15 articles. The last filtering stage consisted of examining their section titles, tables, and figures. We selected only 3 articles which were most related to the research subject.

Additionally, 7 works were found by means of the backward and forward search. The former consists of looking for relevant articles within the references of the articles provided by the keyword search. The latter consists of looking for which relevant articles cite the articles provided by the keyword search. Backward and forward searches do not take place in the first filtering stage since only the title is analyzed there, not the references. As a result, from the literature search, a total of 9 articles and one thesis document are passed for the analysis stage. Table 1 summarizes the results of each filtering stage with respect to the type of search performed.

Table 1: Number of works from each filtering stage.

Search Type	1st Filter	2nd Filter	3rd Filter
Keyword Search	77	15	3
Backward Search	N/A	5	3
Forward Search	N/A	10	4

2.4 Analysis and Synthesis of Literature

A framework with six review questions is proposed to review the final set of works (see Table 2).

Table 2: Framework of review questions.

No.	Review Question
1	In which stage of the CPPS lifecycle is the evaluation performed?
2	Which criteria are used to perform the evaluation?
3	Is the system performance improved through iterative evaluation?
4	What kind of notation is used to represent the production system?
5	Does the article consider the transition from legacy systems to CPPSs?
6	Does the article provide a software tool for systems evaluation?

These questions were set up by identifying the most relevant dimensions that characterize the evaluation of a CPPS. The first question refers to the stage where the evaluation occurs. This is important considering that, for example, evaluating a production system while it is being designed differs from evaluating a system after it has been implemented and it is operating. The second question examines the criteria of the evaluation, namely, what it is being measured and how. Given that an evaluation process expresses the performance of a system, the third question determines whether the results of such evaluation are feedback and used for the sake of system improvement. The fourth question looks into the notation, which refers to the way that a model formally portrays a production system. The fifth question goes beyond CPPS evaluation as it investigates which research works consider a transition from a legacy system to a CPPS. Finally, the sixth question examines which kind of software tools have been implemented in the field of CPPS evaluation. The analysis performed below is summarized in Table 3.

2.4.1 In Which Stage of the CPPS Lifecycle Is the Evaluation Performed?

A system lifecycle can be divided into three main stages according to system engineering principles (Kossiakoff et al., 2020): The first stage is the concept development which formulates and defines the system concept that best satisfies a need. The next stage is the engineering development which takes the system concept into hardware and software designs. The last stage is the post-development stage which covers the production, deployment, operation and support of the system. We analyzed the literature to assign each work within one of the stages and analyze during which stage evaluation takes place.

With respect to this lifecycle, we found one work that evaluates the system even before it has been designed by assessing potential architectures on which the CPPS can be developed (Bunte et al., 2019). Other works evaluate the production systems during their design which belongs, in turn, to the engineering development stage (B. Wu, 1992; X. Wu, 2022). Orellana & Torres, (2019), evaluate the system during its design and also during a period of 5 months of its operation. Therefore, it is classified in both engineering development and post-development stages. The work of S. Lee & Ryu, (2022), proposes to perform the evaluation over a digital twin or a simulation of the system before it is implemented. For the sake of classification, we consider this simulation as one phase of the engineering development stage in which the simulation of the system is part of its design before going into production. Most of the literature performs the assessment over production systems already implemented, namely, during their operation. For instance, Coelho et al., (2022), apply a survey of questions on three different manufacturing plants that are in operation to evaluate their maturity level. These plants render their services to different industries. On the other hand, Arjoni et al., (2018); Lins & Oliveira, (2020), evaluate the performance of assemblies of robotic arms just after implementation.

From this analysis, we classify the literature by the criterion *Evaluation in the lifecycle of the CPPS* in Table 3.

2.4.2 Which Criteria Are Used to Perform the Evaluation?

All the works reviewed make use of a certain type of criteria to evaluate their corresponding systems. We identified that those types of criteria are qualitative and/or quantitative. The latter is classified, in turn, into numeric indicators, and standardized KPIs (Key

Performance Indicators). The qualitative evaluation describes the characteristics of the system under evaluation in terms of natural language. For instance, Bunte et al., (2019), assess the systems by a survey of 13 questions, each one is related to a requirement. Some of those requirements are: does the system learn from experiences? And does it apply the action on the controller? Similarly, Arjoni et al., (2018), formulates three questions to evaluate a system: is there communication between the real machinery and the virtualized plant? Is there communication among machinery? and, how is the operation stability of the new elements added to the system? Coelho et al., (2022), propose a framework of 42 questions grouped into 15 categories.

Although they do not reveal the specific questions, some of the categories are the organization of the machines in a network, dashboard and level of autonomy. X. Wu´s qualitative approach (X. Wu, 2022) presents a framework of 20 questions categorized into three dimensions: technological, informational, and organizational. Some of the questions are: how is the connectivity of machine in the shop floor? and how is data collected?

The quantitative evaluation is based on mathematical modeling that provides data that can be expressed in numbers. The sub-category *numeric indicators* refers to indicators that are application-specific, namely, a production system to be evaluated is previously analyzed and some performance indicators are identified and measured for such specific system. However, those are not referred as KPIs since they are not directly linked to a target according to the definition of KPIs (Parmenter, 2015). One example of this approach is presented by Khan et al., (2020), who measure only one indicator that is the latency in the communication between the sensors and their supervising application when migrating an industrial SCADA system to the cloud. Likewise, Lins & Oliveira, (2020), measure two indicators: the energy consumption and response time of a manufacturing system. B. Wu, (1992), does not suggest any specific technical indicator. However, he considers the internal interest rate as a financial indicator to consider when implementing a manufacturing system. Rinker et al., (2021), only

Table 3: Literature classification after applying the framework of review questions.

Criteria	Classification		References
Evaluation in the lifecycle of the CPPS	Concept Development		(Bunte et al., 2019)
	Engineering Development		(Orellana & Torres, 2019; B. Wu, 1992; X. Wu, 2022)
	Post-development		(Arjoni et al., 2018; Coelho et al., 2022; Khan et al., 2020; S. Lee & Ryu, 2022; Lins & Oliveira, 2020; Orellana & Torres, 2019)
Type of evaluation criteria	Qualitative		(Arjoni et al., 2018; Bunte et al., 2019; Coelho et al., 2022; X. Wu, 2022)
	Quantitative	Numeric Indicators	(Khan et al., 2020; Lins & Oliveira, 2020; B. Wu, 1992)
		Standardized KPI	(S. Lee & Ryu, 2022; Orellana & Torres, 2019; Rinker et al., 2021; X. Wu, 2022)
Improvement of the system performance through iterative evaluation	Iterative improvement		(Orellana & Torres, 2019)
	Non-iterative improvement		(Arjoni et al., 2018; Bunte et al., 2019; Coelho et al., 2022; Khan et al., 2020; S. Lee & Ryu, 2022; Lins & Oliveira, 2020; Rinker et al., 2021; B. Wu, 1992; X. Wu, 2022)
Type of notation to represent the system	Ad-hoc		(Arjoni et al., 2018; Bunte et al., 2019; Khan et al., 2020; S. Lee & Ryu, 2022; Lins & Oliveira, 2020; Orellana & Torres, 2019)
	UML		(X. Wu, 2022)
	AML		(Rinker et al., 2021)
Upgrade from legacy systems proposed	Yes		(Arjoni et al., 2018; Khan et al., 2020; S. Lee & Ryu, 2022; Lins & Oliveira, 2020; Orellana & Torres, 2019; B. Wu, 1992; X. Wu, 2022)
	No		(Bunte et al., 2019; Coelho et al., 2022)
Software tool implementation	Modeling tool		(Rinker et al., 2021)
	Simulation tool		(Ferrer et al., 2018)
	Custom tool		(J. H. Lee et al., 2018)

measure the time as an indicator of performance of a graphical user interface that they develop to model production systems. Regarding the standardized KPIs, X. Wu, (2022), makes use of 26 KPI that come from the ISO22400 standard (International Organization for Standardization, 2014). The KPIs are calculated from a set of supporting data which are directly measured in the production system. Orellana & Torres, (2019), also make use of ISO22400. In the case study that they develop, they select 8 specific KPIs. S. Lee & Ryu, (2022) use another kind of KPIs that are oriented to sustainability and are stated in the Global Reporting Initiative (GRI, 2016).

From this analysis, we classify the literature by the criterion *Type of evaluation criteria* in Table 3.

2.4.3 Is the System Performance Improved Through Iterative Evaluation?

From the literature reviewed, we found three works that include iteration at least in one point of its process. We examine below if the iteration in such works is linked to their corresponding evaluation processes.

Orellana & Torres, (2019), introduce a 4-phase maturity framework for Industry 4.0: the first one refers to isolated digital applications. In the second one, the enterprise is capable of integrating and digitizing its machinery, applications and processes. In the third phase, both suppliers and partners are digitally integrated by a common and central architecture. The fourth phase refers to a factory 100% digital. They propose an 8-step iterative procedure to transit from phase 1 to phase 2. Within the reviewed articles, this is the only work that integrates the evaluation step into the iterative process which allows the manufacturing system to improve its performance continuously.

The proposal of X. Wu, (2022), consists of the following steps: modeling, transformation, and evaluation of the system. Although the modeling and transformation steps imply iterations, the evaluation step only happens once in the process, and it is not linked to the transformation step that takes place previously. S. Lee & Ryu, (2022), enhance an existing production system by adding reconfigurable capabilities. They propose three subprocesses that must be carried out sequentially. Evaluation takes place in the third step. Once the three subprocesses have run, the derived solution is passed through simulations. If simulation succeeds, then the new model is configured in the real facilities. Therefore, no explicit iteration is proposed.

From this analysis, we classify the literature by the criterion *Improvement of the system performance through iterative evaluation* in Table 3.

2.4.4 What Kind of Notation Is Used to Represent the Production System?

Most of the articles make use of an ad-hoc notation to represent the production systems, like it is the case of (S. Lee & Ryu, 2022). This means that no standard was followed when portraying a representation of the systems. Nevertheless, two works use standardized modeling languages. Rinker et al., (2021) make use of AutomationML (AML) as an XML-based standardized data exchange format for the storage and exchange of modeling hierarchical structures common to production systems. Likewise, the metamodel that X. Wu, (2022), proposes to instantiate is expressed in UML class diagrams. Therefore, these two aforementioned works represent the exceptions in terms of the use of a notation for systems representation. From this analysis, we classify the literature by the criterion *Type of notation to represent the system* in Table 3.

2.4.5 Does the Article Consider the Transition from Legacy Systems to CPPSs?

Upgrading legacy systems instead of investing in brand-new systems from scratch represents huge benefits for organizations (di Carlo et al., 2021). Therefore, upgrading proposals were frequently found in the literature.

One of the articles´ case study tackles the modernization of an assembly line with more than 47 years of operation (Orellana & Torres, 2019). Arjoni et al., (2018), propose some retrofit techniques at machinery level to allow old automation and mechatronic components such as robotic arms and CNC machines to be adapted to advanced manufacturing features like communication, intelligence and sensing capabilities with low implementation costs. Lins & Oliveira, (2020), propose a process for upgrading equipment based on the widely used architecture RAMI 4.0. It comprises defining the requirements, components, and technologies necessary to retrofit the industrial equipment. Khan et al., (2020), take a legacy industrial SCADA system which operate entirely local and deploy part of its information systems to the cloud by implementing secure communication links. X. Wu, (2022) exhibits a case study of implementing RFID technology to enable autonomy in a simulated assembly line. Thus, the products could communicate with workstations to decide their next operation. S. Lee & Ryu, (2022), do not explicitly propose a case study of a transformation method from a legacy system into a CPPS. Instead, they propose how to upgrade a legacy architecture of a CPPS into a self-reconfigurable one. Finally, B. Wu, (1992), proposes a methodology that helps a manufacturing system designer to decide which aspects of advanced manufacturing technology are required and how they should be integrated in a legacy system.

From this analysis, we classify the literature by the criterion *Upgrade from legacy system proposed* in Table 3.

2.4.6 Does the Article Provide a Software Tool for Systems Evaluation?

From the articles analyzed, it was very uncommon to find a software implementation, however, some related developments were found. For example, in the field of modeling tools, Rinker et al., (2021) coded a prototype that graphically models production systems whose components belong to different disciplines of science, for instance, electrical, mechanical or biological components. As a simulation tool devised to serve any type of manufacturing application, Ferrer et al., (2018) developed the FASTory Simulator platform. In the field of custom software implementations, J. H. Lee et al., (2018), showcase a CPPS dashboard that supports the prediction and operation control of a plant in the metal casting industry. Although the aforementioned tools are related to the field of manufacturing systems, they do not explicitly address the evaluation of such systems.

From this analysis, we classify the literature by the criterion *Software tool implemented* in Table 3.

2.5 Gap Analysis

Once the framework of review questions has been answered in its entirety, it is time to recall the research question posed: “How do existing methods evaluate a CPPS along its lifecycle, especially during its design?”. Thanks to the characterization of the subject performed with the framework, we are able to identify how well this problem is addressed by existing propositions from different perspectives as follows:

The literature showed that the evaluation of CPPSs can be performed at any given stage of their lifecycle. However, most of the works focus on the operation stage (post-development) underestimating the design stage (engineering development). It is furthermore necessary to address the focus on the analysis and design stages since the tuning and changes over the system are less expensive at those points.

Most of the reviewed works opted for a quantitative evaluation. This reveals the advantage that quantitative evaluations have over qualitative ones in terms of accuracy and objectivity. However, among the quantitative approaches that relied on KPIs, very few works were found to set target values for them. Therefore, it is convenient to set target values for each KPI considered.

The fact that only one work utilizes the evaluation results to iteratively improve the production system, reveals an important gap in the review. Iteration-based evaluation would bring the benefits of feedback since the early stages of the system lifecycle. It is essential for future developments on this subject to encourage the system improvement by iterating on the evaluation results.

We can affirm to the best of our knowledge that, as of today, no software tool has been implemented to aid the model-based evaluation of CPPSs. The development of a software tool would be particularly useful for the researchers working on the CPPS evaluation subject.

Given that the comprehensive analysis and synthesis on evaluation of CPPSs have been performed, we see the need to organize all the concepts reviewed so far in a formal manner. Consequently, in the following section we introduce a conceptual model for the evaluation of CPPSs as a preliminary approach to develop a solution that bridges the gaps previously identified in the literature review.

3 A CONCEPTUAL MODEL FOR EVALUATION OF CPPS

3.1 Model Description

Figure 2 shows a meta-model that is composed by object classes that represent the concepts and relationships that must be considered for further developments on this subject. The description of the meta-model is as follows:

A *Production_system* is identified by its name. It is represented in a *Model* by instantiating a *Meta-model*. In order to represent the *Model*, a *Notation* must be adopted. The *Notation* could be AD-HOC for each specific system or it could be STANDARDIZED. As we are considering the transformation of production systems, two child classes can be inherited from the class *Model*: *Legacy_System_Model* and *CPPS_Model*. The latter refers to the upgraded system after a transformation sequence has been applied.

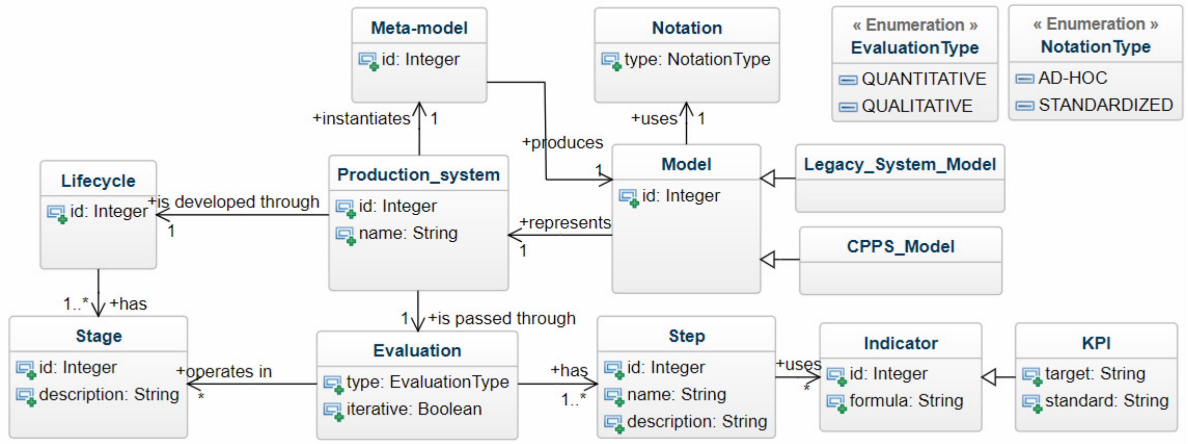

Figure 2: Meta-model for the evaluation of CPPSs.

Likewise, the *Production_system* is developed through an associated *Lifecycle* which, in turn, is composed of one or more stages represented by the class *Stage*. The *Production_system* is also able to be evaluated. Such *Evaluation* is represented by a class that has two attributes. The first one defines the type of evaluation which is represented by the literals QUANTITATIVE and QUALITATIVE from the enumeration *EvaluationType*. The second attribute determines whether the evaluation is iterative or not by means of a boolean value. *Evaluation* is associated with the class *Stage* because, it may be applied to every stage of the production system lifecycle.

The evaluation procedure can be broken down in several steps by means of the class *Step*. One step may use indicators to measure the performance of a production system. The class *Indicator* contains the attribute formula, which is the mathematical representation of the indicator. One kind of indicator is the *Key Performance Indicator (KPI)* which differs to a regular indicator in the fact that it is linked to a target value and may belong to an industry standard. Therefore, the class *KPI* extends the class *Indicator* and adds the attributes target and standard.

3.2 Discussion

The value of the conceptual model introduced above lies in how it can be used to address the review questions in a way that no other proposition did. We discuss below the case for each one of the review questions. Regarding the first question, in which stage of the CPPS lifecycle is the evaluation performed? The conceptual model associates the evaluation of the system with any of its lifecycle stages, which means that a system could be evaluated even before it is designed (Bunte et al., 2019) and/or during its operation (Khan et al., 2020). On the contrary, the reviewed works focus on one specific stage. With regard to the second question, which criteria are used to perform the evaluation? The conceptual model considers not only a qualitative approach but also a quantitative one with the possibility of using basic numeric indicators or standardized KPIs. This represents a step forward in comparison to existing works in terms of exploiting the use of KPIs. Standardized KPIs, may be used to compare the performance of two or more production systems in the same industry. With respect to the third question, is the system performance improved through iterative evaluation? The model includes a boolean attribute called *iterative* in the class *Evaluation* that determines if the performance of the system improves by iterating on the evaluation. A *true* value would mean that the evaluation results are feedback for system improvement, like the work of Orellana & Torres, (2019). Concerning the fourth question, what kind of notation is used to represent the production system? The conceptual model includes the class *Notation* which is linked to the class *Model*, meaning that every single model should have a notation defined as proposed by Rinker et al., (2021). Respecting the fifth question, does the article consider the transition from legacy systems to CPPSs? The conceptual model suggests two classes called *Legacy_System_Model* and the *CPPS_Model* which extend the class *Model* and enable any system to be upgraded unlike some works reviewed (Bunte et al., 2019; Coelho et al., 2022). Regarding the sixth question, does the article provide a software tool for systems evaluation? The conceptual model, in its entirety, sets the foundation for the construction of a software tool that allows to evaluate a CPPS in an intuitive manner.

4 CONCLUSIONS AND FUTURE WORK

This paper presents a literature review that identifies and analyzes research works in the domain of CPPSs evaluation by employing a framework of six review questions. A conceptual model was proposed to fill the gaps identified by the analysis of the literature. A comprehensive discussion was given to show how the conceptual model differs from existing propositions and sets out a path towards an enhanced evaluation method for CPPSs.

Concerning the research method, the review scope defined in the first section allowed us to have the review clearly characterized from the beginning. This is typically a challenging task since literature reviews can serve a wide range of very different purposes. Although the number of articles found by the search query was initially high, the final number of articles reviewed was low. This means that the filtering strategy helped to identify the relevant works hidden within a large set of results. Likewise, the backward and forward search helped to expand the final set of articles. However, it is a matter for further developments to formulate an enhanced query that leads to a larger quantity of results.

As future work, the conceptual model can be used as a base to propose a complete approach of CPPSs evaluation that considers, for instance, the improvement of the system by means of an iterative evaluation method and the use of a custom set of standardized KPIs. It could also be linked with existing metamodel proposals like X. Wu, (2022). In addition, the approach may propose a different evaluation procedure for each stage of the lifecycle.

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