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IFAC PapersOnLine 50-1 (2017) 12434–12439

The Role of Interoperability in The Fourth Industrial Revolution Era

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Abstract: In the manufacturing domain, interoperability represents a characteristic of a manufacturing system in which its components are capable of exchanging information with one another, using the information that has been exchanged. Even though the discussion about interoperability issues can trace back to the 1970s, system interoperability is still the "elephant in the room". Additionally, in the past few years, research topics related to the fourth industrial revolution, also known as Industry 4.0, have been gradually accepted and promoted by governments and organizations all around the world. A research question then arises: what is the role of interoperability in the fourth industrial revolution era? The aim of this paper is to provide a scientific and evidence-based answer to this question. From an academic perspective, a systematic literature review was carried out to discover the main concepts related to interoperability in an Industry 4.0 context. From an industrial perspective, a questionnaire survey was developed to guide the application of a multi-criteria decision analysis method, the Analytic Hierarchy Process, used to analyze and make explicit the relationships of the previously discovered concepts. Results of this study can be used as a basis for future interoperability research in this new industrial revolution wave.

Keywords: Interoperability, The Fourth Industrial Revolution, Industry 4.0, Systematic Literature Review, Questionnaire Survey, Analytic Hierarchy Process.

1. INTRODUCTION

In recent years, governments and organizations worldwide have noticed the trend of "The Fourth Industrial Revolution" and acted to benefit from what it could provide. More and more high-level plans and projects are continually carried out, such as, the "Industrie 4.0" in Germany (Kagermann, Wahlster and Helbig, 2013), the "La Nouvelle France Industrielle" in France (CNI, 2013), the "Future of Manufacturing" in the United Kingdom (Foresight, 2013), the "Factories of the Future (FoF)" in the European Union (EC 2016), the "Industrial Internet Consortium (IIC)" (Evans and Annunziata, 2012) and "Advanced Manufacturing Partnership (AMP)" (Rafael, Shirley and Liveris, 2014) in the United States, and the "Made in China 2025" in China (Li, 2015). Consequently, due to these driving forces, an increasing number of research centres, companies, and universities have taken part and contributed to this new challenge through either laboratory experiments (such as Smart Factory OWL), or industrial applications (such as Digital Enterprise Software Suit by Siemens).

In the realm of manufacturing, interoperability among a variety of systems, in or across industries, has been gradually accepted as one key feature along the life cycle of a product. Looking at all of the above-mentioned efforts from both the academic and the industrial areas, a research question arises: *what is the role of interoperability in the fourth industrial revolution era?* In order to provide a scientific and evident-based answer to this question, this paper firstly focuses on presenting the main findings of a systematic literature review about interoperability in an Industry 4.0 context, as a specific extension of our previous work (Liao *et al.*, 2017). Then, the relationships among interoperability and those findings are analysed and made explicit through the application of the Analytic Hierarchy Process (AHP) method. Meanwhile, to assist the criteria evolution, a questionnaire survey of industrial experts was also carried out.

In the remaining part of this paper, Section 2 presents the employed systematic literature review, questionnaire survey, and AHP method. Section 3 illustrates the collected data of interest, extracted important concepts, AHP decision hierarchy, formulated survey questions, and final data analysis based on the obtained outcomes. At the end, the conclusion and future work is given in Section 4.

2. APPLIED METHODS

As can be seen in Fig. 1, three methods were employed in this work. The systematic literature review method applies a mixed approach that combines both qualitative (Curry, Nembhard and Bradley, 2009) and quantitative research (Pickering and Byrne, 2014). Based on it, a number of important concepts were discovered and used as basis for the design of the goals, criteria and alternatives for application of the Analytic Hierarchy Process (AHP) method (Saaty, 1977). To obtain a more reliable and authentic evaluation, a questionnaire survey was created to summarize the opinions

10.1016/j.ifacol.2017.08.1248

of experts in the area. According to the survey results, a set of pairwise comparison matrices were generated. Then, priorities which represent the perception of the experts in different industrial domain were calculated. At the end, the role of interoperability in the fourth industrial revolution era could be revealed.

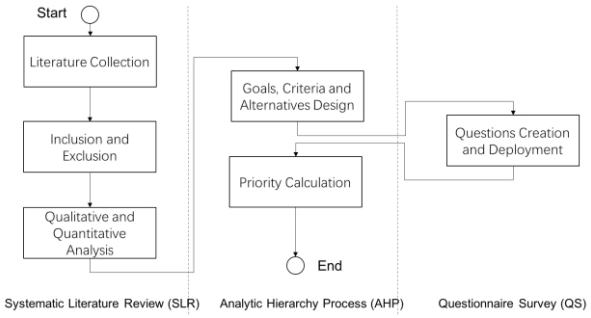

Fig. 1. The Three Applied Methods: SLR, AHP and QS

2.1 Literature Collection

To collect a comprehensive set of references from the published literature, the first search string was constructed by combining the operator "or" between "Industrie 4.0" and "Industry 4.0". The largest abstract and citation database *Scopus* together with *Science Direct* were used during the systematic search. All collected references should satisfy the following four conditions: (1) they were published online before November of 2016; (2) they contain at least one of the two search terms in their titles, abstracts, or keywords; (3) they were published in journals, conference proceedings or book series; and (4) they were written in the English language.

2.2 Inclusion and Exclusion

To ensure that all collected references could be more objectively assessed, as seen in Table 1, seven main inclusion and exclusion criteria were applied. After removing duplicates, the following three processes were performed.

Firstly, references were screened to remove those that did not explicitly relate to interoperability. It is based on the *NER* principle in Table 1, for which the term "interoperability" does not appear in any fields of a literature (e.g. title, abstract, keywords, main body text, and references).

Secondly, all the references that passed the first screening process were briefly reviewed by reading the paragraphs where "interoperability" appeared. Besides those without full-text (*WF* in Table 1), this eligibility checking process aims to exclude those references that (1) are not academic (*NA* in Table 1), (2) are not in the Industry 4.0 context (*NR* in Table 1), and (3) are not focused on interoperability issues (*LR-1*, *LR-2*, and *LR-3* in Table 1).

In the end, all eligible references were studied in detail, and then organized into corresponding inclusion categories (*PR*, *CR-1*, and *CR-2* in Table 1).

Table 1. Inclusion and Exclusion Principles

I/E	Principles	Principle Explanations
Exclusion	Not-Explicitly Related (***NER***)	It doesn't contain the term "interoperability"
	Without Full-text (***WF***)	It is without full text to be assessed.
	Non-Academic (***NA***)	It is a non-academic reference, e.g. conference reviews.
	Not-Related (***NR***)	It is not within the Industry 4.0 context.
	Loosely Related (***LR***)	To deal with interoperability issues is not its main focus. **LR-1**: "Interoperability" only appears in its future work/trend. **LR-2**: "Interoperability" only appears in the description of someone else's works. **LR-3**: "Interoperability" only appears in its reference list.
Inclusion	Partially Related (***PR***)	"Interoperability" appears as one of the research objects.
	Closely Related (***CR***)	Its main research effort is explicitly and specifically dedicated to Interoperability within the Industry 4.0 context. **CR-1**: It gives solutions for some specific interoperability issues. **CR-2**: It reviews or analyses existing interoperability solutions

2.3 Qualitative and Quantitative Analysis

During this step both qualitative and quantitative methods were applied. To be specific, before any statistical and graphical descriptions about the collected data (quantitative analysis), several data pre-processing techniques (qualitative analysis) were applied.

In psychology research, as it is highlighted by Bullinaria and Levy (2007), statistics of word co-occurrence in the same sentences express relationships that can be used as a basis for semantic representations. Therefore, the data of interest were those *sentences* that contained "interoperability" in the title, abstract, and main body text of each included reference. They were collected as the inputs for the qualitative and quantitative analysis.

Firstly, a qualitative data analysis tool, named ATLAS.ti, was employed to extract word frequencies from those collected sentences. To export and highlight only nouns and adjectives, some specific words, for example, definite and indefinite articles (e.g. the), pronouns (e.g. it), and prepositions (e.g. from), were removed from the frequency list.

Secondly, an automatic sentence coding was carried out according to the top 15 words in the frequency list. For each code, their top two co-occurrence words were also identified to assist the summarization of meaningful noun phrases.

In the end, a list of important concepts concerning interoperability were generated based on both (1) the