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Smart operators: How Industry 4.0 is affecting the worker's performance in manufacturing contexts

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Abstract

The fourth industrial revolution is affecting the workforce at strategical, tactical, and operational levels and it is leading to the development of new careers with precise and specific skills and competence. The implementation of enabling technologies in the industrial context involves new types of interactions between operators and machines, interactions that transform the industrial workforce and have significant implications for the nature of the work. The incoming generation of Smart Operators 4.0 is characterised by intelligent and qualified operators who perform the work with the support of machines, interact with collaborative robots and advanced systems, use technologies such as wearable devices and augmented and virtual reality. The correct interaction between the workforce and the various enabling technologies of the 4.0 paradigm represents a crucial aspect of the success of the smart factory. However, this interaction is affected by the variability of human behaviour and its reliability, which can strongly influence the quality, safety, and productivity standards. For this reason, this paper aims to provide a clear and complete analysis of the different types of smart operators and the impact of 4.0 enabling technologies on the performance of operators, evaluating the stakeholders involved, the type of interaction, the changes required for operators in terms of added and removed work, and the new performance achieved by workers.

Keywords: Operator 4.0; Industry 4.0; Human performance.

1. Motivation and context

The fourth industrial revolution is a highly discussed paradigm intended to digitalize and automate modern manufacturing systems. However, in recent years, significant attention has been given to the enabling technologies neglecting the fundamental and essential role of the operator. Indeed, Industry 4.0 is also transforming the role of workers and it is involving new types of interactions between operators and machines, interactions that will transform the industrial workforce, and have significant implications for the nature of the work [1], [2]. The

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generation of Operators 4.0 is represented by qualified operators who perform the work with the support of machines; who interact with collaborative robots, advanced systems and sensors; who use augmented and virtual reality and exploit the benefits of the enabling technologies to understand production through context-sensitive information [3], [4]. The correct interaction between the workforce and the various enabling technologies of the 4.0 paradigm represents a crucial aspect of the success of the smart factory. This interaction will certainly be affected by the variability of human behaviour and its reliability, which can strongly influence safety, quality, and productivity standards. Although it is difficult to obtain valid data, the estimates agree in attributing the responsibility to errors committed by a man in 60-90% of accidents, and only for the remaining part, the causes are attributable to technical deficiencies. Romero et al. in 2016 presented a first and in-depth analysis of the new concept of 'Operator 4.0', exploring a set of key enabling technologies that can support him [4]. In particular, the researchers identified 8 typologies of operators: 1) Super-Strength Operator; 2) Augmented Operator; 3) Virtual Operator; 4) Healthy Operator; 5) Smarter Operator; 6) Collaborative Operator; 7) Social Operator; and 8) Analytical Operator.

Starting from this first classification, in the following years, the scientific literature began to face the role of the smart operator with growing interest. An important part of these studies emphasized the human centrality of the Smart Factory, enabling a paradigm shift from automated and independent human activities towards a "human cyber-physical system". This system is characterized by the cooperation of machines with humans in working systems and designed not to replace the abilities and capabilities of humans, but rather to coexist and help humans to be more efficient and effective [5]. At the same time, the study of enabling technologies to support humans and their implementation in real contexts, the analysis of the advantages brought by these technologies as well as the development of frameworks for the integration between technologies and operators have been addressed by the researchers. It is evident that in the growing and continuous attention related to 4.0 technologies the fundamental role of the operator is often overlooked, not considering that the success in the implementation of technology also depends on who will use it correctly. To the best of the authors' knowledge, a clear and systematic review of the most recent literature, published after Romero's research, is not yet present. For this reason, this paper aims to provide a clear and complete analysis of the different types of smart operators and the impact of 4.0 enabling technologies on the performance of operators, evaluating the stakeholders involved, the type of interaction, the changes required for operators and new benefits obtained by workers. The objective of this research work is therefore to understand what steps forward have been made as well as what are the gaps still present in literature.

2. Methodology

This paper provides an overview of the scientific literature on smart operators in the industrial context. A systematic literature review on the performance of the smart operator was conducted. Systematic reviews focus on a specific topic to identify all relevant papers produced on the topic with an exhaustive and multi-source search [6], [7]. The procedure is divided into three steps: 1) Identification of keywords; 2) Research and selection of articles; 3) Analysis process. The suitable keywords for our research field were chosen to answer the research question of the paper, namely how Industry 4.0 is affecting the worker's performance in manufacturing contexts. For this reason, the keywords have been selected considering first the 4 key concepts to be analysed: operator, Industry 4.0, performance, and industrial sector. For each of these groups, the synonyms have been chosen in order to cover as many articles as possible published in the existing scientific literature. The full list of keywords is reported in Table 1. Using the chosen keywords, the articles were searched on the Scopus database and then selected through a screening process based on specific exclusion criteria. The exclusion criteria adopted were the following: 1) Articles not published in English; 2) Articles published before 2016; 3) Articles not published in journals and peer-reviewed conferences; 4) Articles that address only one of the themes chosen as main, and therefore do not address all the keywords; 5) Articles that do not have a link between the key concepts. The selected articles were then analysed and classified according to several criteria: year of publication; source; type of document; the purpose of the paper; and the innovative contribution of the paper. For the innovative contribution, we defined different categories: literature review; development of a model, method, procedure; implementation of an enabling technology; analysis of benefits and advantages of operator 4.0; development of frameworks to support the implementation of technologies. Fundamental attention was given to the enabling technology dealt with in the document and therefore the described smart operator. For all the technologies characterizing Industry 4.0, with which the operators must interact, the main characteristics, technical specifications, types of applications, advantages and disadvantages were investigated. Subsequently, the interaction with the operator was evaluated for each of the individual technologies.

Table 1. List of keywords selected for the purpose of the paper.

OPERATOR	INDUSTRY 4.0	PERFORMANCE	SECTOR
Operator; Worker; Employee; Workforce	Smart; 4.0; Super-strength; Exoskeletons; Augmented reality; Virtual reality; Healthy; Wearable; Intelligent; Collaborative; Social; Analytical	Safety; Performance; Error; Reliability; Workload; Quality; Productivity; Efficiency	Manufacturing; Industry; Factory

3. Results

The articles obtained through the Scopus search were 2050. Among these 2050 articles, only 70 papers were selected after the reading of the full text and according to the exclusion criteria previously defined. Most of the selected articles, equal to 66%, were presented at international conferences and were mainly published on Procedia CIRP (10 papers), ACM International Conference Proceedings Series (9 papers) and Procedia Manufacturing (5 papers); whereas the remaining 34% have been published in the peer-reviewed journals, mainly Computers and Industrial Engineering (4 papers); Robotics and Computer-Integrated Manufacturing (4 papers) and Computers in Industry (3 papers). The number of papers for each year shows evident growth, demonstrating the growing interest in this topic (Fig. 1). Until 2019, the prevalence of papers published as conference proceedings can be observed but since the last year, the articles published in international journals have been increasing.

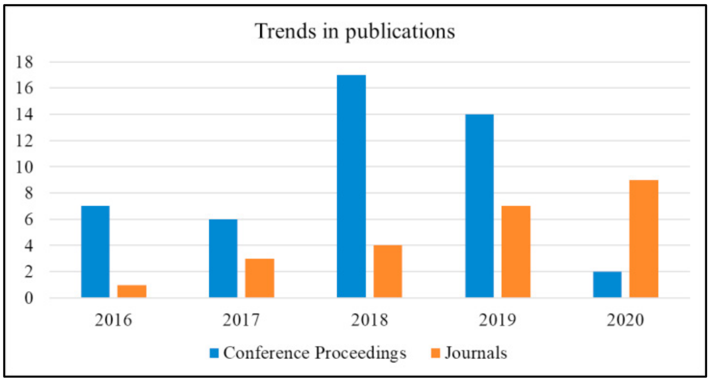

Fig. 1. Trends in publications over the years.

Fig. 2 shows the main results regarding the innovative contribution of the selected papers. The results show the clear prevalence of papers that implement one of the enabling technologies, with a particular focus on the relationship and the impact on the operator. From 2017 to 2019, the number of papers dealing with the implementation of enabling technology has increased while the number of articles dealing with the impact on the operator has increased until 2018 and then drastically reduced.

3.1. Enabling Technologies and Operators

To achieve the aim of this study, the second analysis step focused on the classification of the papers concerning the categories identified by [4]. Fig. 3 presents the main results for the individual categories considering the absolute number of studies that address the different types of operators. The prevalence of articles focused on augmented (38 papers, 54%), virtual (16 paper, 23%) and collaborative (16 papers, 23%) operators are evident, while some types of operators (as healthy, social, smarter, analytical) are present with very low percentages. In particular, 9 papers focused on the healthy operator, 7 on super-strength, 5 on smarter, 4 on social e 3 on analytical one.

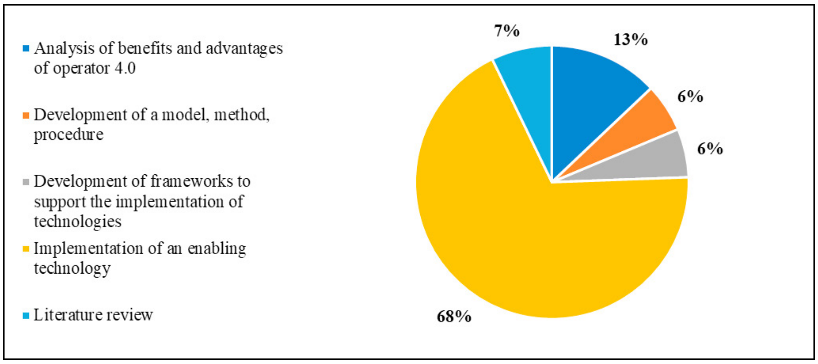

Fig. 2. Results on innovative contribution of the paper

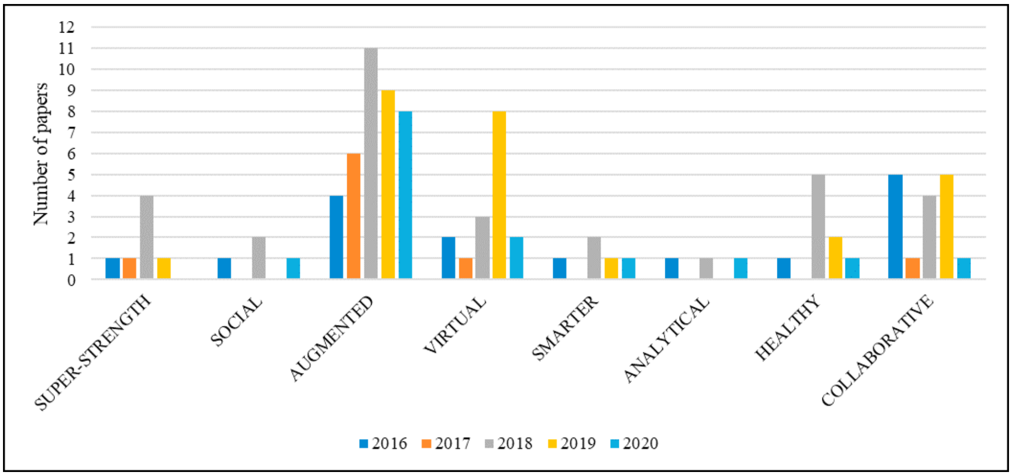

Fig. 3. Presence of different operator's typologies in the selected papers over the years.

However, individual papers also deal with more than one technology and so more kinds of operators, as reported in Table 2. The cross-analysis has allowed us to divide the studies focused on single technologies from those that instead consider the impacts of combined technologies. For example, it can be observed that 66% of the articles (25 papers) relating to the augmented operator consider only this category while 15% of the selected papers also consider the virtual operator.

Table 2. Classification of papers according to the taxonomy of Romero et al. 2016.

	SUPER-STRENGTH	SOCIAL	AUGMENTED	VIRTUAL	SMARTER	ANALYTICAL	HEALTHY	COLLABORATIVE
SUPER-STRENGTH	**4**	2	1	1	2	2	2	2
SOCIAL		**1**	1	1	3	2	1	1
AUGMENTED			**25**	6	2	2	4	5
VIRTUAL				**9**	1	1	1	3
SMARTER					**1**	3	1	1
ANALYTICAL						**0**	1	1
HEALTHY							**4**	2
COLLABORATIVE								**9**

Other technologies, on the other hand, see for example smarter or social operator, are mostly present in combination with other technologies, just as the analytical operator is never individually at the centre of a paper. In the following paragraphs, the selected papers have been analysed in greater detail, both concerning the considered typologies of operators 4.0 and their impact on human performance.

3.1.1. Augmented and virtual operators

Augmented and virtual operators are the most analysed in literature and the most associated with each other, given the similar characteristics of the two technologies. As evident from Figure 3, the interest of researchers in these types of technologies and their interaction with operators is growing over the years.

Augmented Reality (AR) is a technology that enriches the real factory environment of operator 4.0 with information and digital data superimposed in real-time in its field of sight (e.g. headphones, smartphones, tablets, or AR space projectors). This technology, as evident from the results obtained, is the one most investigated to date and on which researchers have focused in recent years (38 of the selected papers) [1], [3], [4], [8], [9]–[14], [15]–[24], [25]–[34], [35]–[42]. Virtual reality (VR) is, instead, a computer-simulated multimedia reality that can digitally replicate a design environment and allow the intelligent operator to interact with any presence inside (e.g. a product, a machine tool, a robot, a line production, a factory), with reduced risk, real-time feedback, and cost minimization. Among the selected papers, 16 of them focused on this kind of operator [4], [17], [26], [27], [32], [42]–[47], [48]–[52] and the results of our analysis underlined that virtual reality has many strengths that support its use mainly as a training tool [44], [45], [48], [49], [52].

3.1.2. Collaborative operator

The collaborative operator, as defined in the literature, cooperates with the robots to achieve full integration and sharing of tasks increasing the operator productivity and satisfaction. The operator indeed no longer carries out "boring" and repetitive tasks or lift heavy loads. On the contrary, the collaborative worker performs tasks that require intellectual effort, as only humans can do. This type of operator is one of the most investigated in the selected papers and 16 papers, that show a uniform distribution over the years, deal with this type individually or integrated with other technologies [4], [9], [23], [27], [37], [51], [53]–[57], [58]–[62].

3.1.3. Healthy and super-strength operators

The categories of healthy and super-strength operators, on the other hand, are still not very present in the literature and with a greater focus since 2018. According to the selected literature, the operator becomes "healthy" when he/she uses wearable devices that are used to monitor his/her state of health in real-time, like physical activity, heart rate, breathing, or stress. The operator, with the aid of these technologies can exploit the analysis of her/his data to program work shifts, for example, to modulate the physical activity, or to manage the times of her/his duties. He can set alarms for himself, which tell him when his body is too stressed, and continuing the task would surely produce errors. He can also decide to increase his workload when the data shows that he is strong (both mental and physical) to perform tasks that require more time and/or more effort. The 9 papers addressing this kind of operator have underlined that several applications have been developed and proposed in literature but without a strong focus [4], [18], [24], [28], [57], [63]–[66], indeed only 4 papers are specifically on "healthy operators" [63]–[66].

On the other hand, industrial exoskeletons represent a biomechanical system powered by engines that support workers in carrying out several tasks to allow increased resistance and strength of a human operator for those activities that require great physical effort. The powered exoskeletons ensure that man and technology cooperate, in this way man's work is simplified and his physical stress is reduced and the whole system becomes more efficient and productive. The results of the analysis of the literature highlight only seven papers [4], [57], [67]–[71] that have addressed the problem of interaction between exoskeletons and operators and only four evaluate and analyse the exclusive use of exoskeletons without considering further enabling technologies [67], [69]–[71].

3.1.4. Other operators

The smarter, social, and analytical operators were found to be the least investigated categories in the literature. The smarter operator uses an intelligent personal assistant (IPA), equipped with artificial intelligence (AI), which helps the operator to interface with machines, computers, and every part of the production system that, in an Industry

4.0, is connected and integrated with all the others. Few papers investigated this kind of operator [3], [4], [68], [72], [73]. The interaction between man and assistant is cognitive and not physical since the operator does not wear any device and does not use exoskeletons, or smartwatches, or viewers. In the selected documents, the use of voice assistants is almost implied, because these have been a reality for some time, so they are already used abundantly. IPA systems allow the users to improve the productivity, efficiency, and quality of performed operations, especially in cases of highly customized and complex tasks, providing related information to the history and current state of the device/system. The social operator, instead, uses social networks that allow him to always be in contact, even if at a distance, with his company and his industrial plant. For example, if faults arise, with a simple click he can be in contact with his company and actively intervene to solve the fault. Only one paper [74] considered exclusively the social aspect, whereas the remaining three [4], [68], [72] addressed this aspect treat in combination with other technologies, as reported in Table 2. Finally, the "analytical operator" uses Big Data Analytics to predict failures, to determine when to carry out preventive maintenance and much more. Thanks to the availability of data in real-time, he can prevent failures, quickly identify errors and increase the efficiency of his company. This kind of operator is addressed in few papers [3], [4], [68] and never alone.

3.2. Impact of technologies on the performance of operators 4.0

3.2.1. Augmented and virtual operators

AR and VR involve various company stakeholders, as Managers, Employees, Maintenance Operator, Production Operators, and Logistics Operators, through a purely cognitive type of interaction. The main difference in the use of these technologies lies in the fields of application. The augmented operator is, in fact, an operator who uses this technology as a support to his daily work activities, while virtual reality is used as a perfect simulation environment for training sessions.

The analysis of the selected papers underlined that AR technology can offer significant benefits: faster cycle times and reduction of completion times [20], [35], [40]; improvement of reliability and reduction of error rates [17], [20], [35], [40]; shorter learning curve [19], [24], [29], [35]; increase of perceived efficiency in performing the task [10], [33]; improvement of health and safety [17], [29], [35]; increase of employee engagement, motivation, flexibility and employability of operators [17], [24], [33]–[35]. These benefits depend on the improvement of cognitive capabilities led to the AR, as the enhancement of problem-solving and decision-making [35]; the improvement of memory and understanding and reduce cognitive load [35]; the reduction of the mental workload associated with a task because only the task-relevant information is displayed [20]; the reduction of the cognitive distance because the information space and the physical space coincide [20]. However, operators who use this technology must have skills relating to the use of the new digital interfaces and the ways of iterating with holograms; ability to read, interpret the data that is provided in real-time, quickly make the right decision and solve complex problems because the right information is available. In addition to the necessary skills, the analysis of the papers highlighted that for AR, trust in technology and the level of acceptance by operators are essential elements for implementation in the workplace. The participants of the study presented in [10] have reported that the AR prototypes were easy to understand and easy to use, although they were completely new to the technology, demonstrating that good user acceptance is fundamental. On the contrary, several aspects of AR were found to be negative. For example, the HoloLens was found heavy to wear for a long time, with a field of view too small, and hindering the operator's movement [12]. Other negative feedbacks and doubts about ergonomics and comfort arose in [31], [33], as difficulty in wearing the AR glasses if the user wears prescription glasses, but also some foreseen implementation difficulties and risks connected to the adoption of new technologies in the field of health and safety, in this case, several users experience headaches and visual disorientation.

In its use for training, virtual reality, instead, has proven to be a safe environment, accessible with limited or no physical prototypes, simple to modify for variants of models, or new versions of equipment and can be used with limited supervision. Virtual reality has also been shown to result in higher levels of engagement in learning compared to traditional teaching methods [44], [45], [48], [49] and the costs of mistakes in virtual reality are low compared to the potential costs in the real environment. The main benefits identified in the selected literature are: the reduction of training time and focusing the operator in the virtual application; the development of the reflexes of operators by acquiring new abilities combining sensory acuity (verbal, visual, physical); the simulation of different scenarios without implying risks that may endanger the user in any way; the assessment of the operator's performance easily and exposing the required information according to its performance; the increase of skill development, the improvement of safety, the reduction of downtime, and environmental protection, higher productivity, lesser number of accidents, and lesser damage to the environment.

3.2.2. Collaborative operator

In the selected papers, there was a broad consensus on the benefits that the introduction of a collaborative robot will bring to productivity, quality of production, competitiveness, and working conditions of the workers [56], [62]. The advantages of operator and cobot are combined: cobots are precise, robust, repetitive and subject to few errors, men are capable, intelligent, able to decide and quickly change even production plans previously chosen, because they are mentally flexible, allowing, for example, a significant reduction of the cycle time, as reported in [23]. Through interviews with workers, also [57] analysed the advantages and disadvantages found by two groups of workers and non-workers. Workers reported that work is done faster increasing the productivity with a robot that performs part of the task and this leaves workers more time to better execute their part of the work. However, the interviews reported that the use of cobot can produce the fear of job loss and the workers do not want to delegate their technical gestures to a robot. On the other hand, how trust develops between workers and robotic systems is a crucial Human Factor issue that needs to be thoroughly understood yet is reported in [53].

3.2.3. Healthy and super-strength operators

Despite the few articles in the literature on healthy and super-strength operators, the selected articles provided us with several ideas to evaluate their impacts on worker performance. The selected papers have perceived that many devices are currently used to monitor the health status of workers to increase safety and to improve human performance in the workplace. In particular, the results collected in [57] on the use of wearable sensors noted that operators find significant advantages in learning the ergonomic way to perform a movement in order to reduce MSDs risks, as well as in the online self-assessment and self-correction of movements. Furthermore, the use of wearable sensors allows to provide information to improve workstations design. However, wearing and using wearable sensors was considered uncomfortable by many of the interviewees and performing activities in an ergonomic way resulted in a significant lengthening of the time spent completing the activity.

The analysis of the selected papers underlined that industrial exoskeletons: offer protection; support and strength to operators by improving the ergonomics of manual operations; increase the endurance time and the level of precision in the task execution; help to reduce injuries and accidents due to heavy work; increase productivity and quality of work; help keep older operators longer by compensating for their strength losses due to aging. However, the results presented in [57] showed that there is a lot of fear on the part of people about this technology. Industrial workers are aware that an exoskeleton can help the operator carry out heavy work, and that humans continue to have full control of movements and decisions, however, they believe that wearing an exoskeleton for many hours could be uncomfortable and cause others types of damage because in any case there is an additional weight to bear.

4. Discussions and challenges

Review results show an increasing interest in smart operators, although not for all types and the attention of researchers mainly focused on the implementation of new technologies (48 papers) and not on the analysis of the impacts on operators with only 9 papers and the development of a framework with only 4 papers. One of the first things that emerge from the review is that the technologies under investigation are not new and already exist in an industrial context but the challenge that most of the researchers aim to overcome is to interconnect these technologies to enhance the role of the operator. The operator 4.0 must benefit from technologies that do not hinder him but enhance him and make him carry out each action with confidence without mental or physical stress or insecurities. Furthermore, the review highlighted how the current scientific literature has concentrated on some technologies, leaving out others, both due to the minor diffusion of the technologies themselves and to the technological development still in progress. While for the most investigated technologies, such as AR, VR, and cobot, it was possible to conduct a more complete analysis, for the other types of operators, especially smarter, social and analytical, little useful information has been identified. What is clear is that the researchers' goal is to develop increasingly advanced technologies capable of supporting operators, increasing their physical, mental, and perceptive performance without inducing further stress or problems. However, in all the papers analysed the main focus has never been on the study of the performance of the operators but rather on the implementation of the technology itself. What is evident is that the role of the 4.0 operator is still placed in the background compared to the technology that characterizes it and this represents an important research gap on which we must focus in the future. The development of technologies must be associated with a careful and accurate assessment of the impact on the performance of the operator and consequently on the system, taking into account the great uncertainty and variability of human behaviour. It should also be emphasized that despite the numerous benefits that technologies can bring to the development of operator 4.0, there are several questions still to be addressed to overcome the disadvantages, including several ethical and social issues. The trust and acceptance of technologies by the operators represents one of the crucial challenges to be overcome. Over the years, automation and digitalisation have been associated with the reduction of jobs and this often leads operators to react with distrust of new technologies. Furthermore, the use of some devices, for example, exoskeletons or wearable devices to support and assist the operators in the execution of a task can be perceived as discriminatory or penalizing by some operators, for example, the elderly ones. Future research should also focus on these aspects and investigate the effectiveness of using technologies to support different classes of operators, depending on age, educational and cultural level, job duties and so on. The articles analysed also highlighted that for the correct implementation of the technologies, additional skills and abilities are often required compared to those of current operators. The analysis of the skills gap is necessary and fundamental for a successful "birth" of the 4.0 operator.

The review presents several aspects to be improved in the future to investigate the field of interest in greater depth. In particular, to obtain a more precise picture, the individual types of the operator should be analysed to obtain detailed and specific frameworks. Furthermore, for the less investigated and even more labile types of operators in the definition, the number of keywords and fields of application should be expanded to obtain more relevant results.

5. Conclusions

The main objective of the present research work is to investigate the recent scientific literature and represents only a first step towards framing the new role of the smart operator. The 70 selected papers highlighted the growing interest in this topic. The main results showed that new technologies have an impact and involve numerous corporate stakeholders, both at a strategic, managerial, and operational level bringing numerous advantages and benefits while still presenting some limits and challenges to overcome.

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