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POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Proposal of a Model to Enhance Safety of Machinery during Operation and Maintenance in the Era of Digitalization and Connectivity

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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Ce mémoire intitulé :

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présenté par **shahab HAMDAVI MOHAMMAD PURE**

en vue de l’obtention du diplôme de *Maîtrise ès sciences appliquées*

a été dûment accepté par le jury d’examen constitué de :

Fabiano ARMELLINI, président

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Firdaous SEKKAY, membre

DEDICATION

To my beloved wife, Asal

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First, I would like to thank my two research directors, Mr. Christophe DANJOU, and Mr. Yuvin CHINNIAH, professors at Polytechnique Montreal. The guidance they gave me throughout this research project was a great help.

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RÉSUMÉ

Les machines sont l'un des actifs les plus critiques de l'industrie manufacturière. Malgré le fait que les concepteurs / fabricants de machines et les utilisateurs finaux déploient des efforts prudents pour rendre les machines plus sûres, il y a cependant tellement d'accidents liés aux machines qui se produisent encore pour plusieurs raisons. La revue de la littérature sur les machines a révélé que (i) le manque d'intégration de la sécurité adéquate dans la conception de la machine (ii) le manque d'évaluation systématique des risques, (iii) le manque de retour d'expérience et (iv) le manque d'expérience / de connaissances de la ou des personnes en matière de sécurité des machines, sont des causes potentielles de problèmes liés au fonctionnement et à la maintenance en toute sécurité des machines.

Ces obstacles sont principalement dus au manque de communication efficace entre les concepteurs / fabricants de machines et les utilisateurs finaux, ce qui a conduit à des évaluations incomplètes des risques des machines. En dehors de cela, les concepteurs et les fabricants de machines, en raison du manque de connaissance de la situation de travail réelle et du manque de connaissances suffisantes en matière de sécurité, ne bénéficient pas du système de retour d'expérience le plus récent qui peut aider à concevoir des machines plus sûres.

Ces derniers temps, l'amélioration des technologies à l'ère de la numérisation et de la connectivité de différentes industries telles que l'internet des objets (IoT), le système cyber-physique (CPS) et la technologie cloud, etc. ont grandement contribué à améliorer les processus, les produits, les services et les performances de manière autonome pour les activités de bout en bout ainsi que la chaîne de valeur.

Dans ce but, un travail de recherche est proposé pour un système conceptuel de gestion de la sécurité (SMS) générique basé sur les concepts des technologies clés habilitantes susmentionnées afin de surmonter le manque actuel de connexion insuffisante entre les concepteurs de machines et les utilisateurs finaux de machines. En outre, un modèle de sécurité basé sur la connaissance basée sur la hiérarchie de l'évaluation des risques introduite dans l'ISO 12100: 2010 est proposé pour capturer les données de sécurité (SRD) les plus à jour et les retours d'expérience basés sur l'utilisation réelle de la machine dans Smart Working Environnements (SWEs). Une étude de cas basée sur des scénarios a été menée sur une machine industrielle de fabrication de sacs pour

expliquer le mécanisme de fonctionnement de la solution proposée. Afin d'étudier les performances de la solution proposée, la machine sélectionnée avec différentes fonctions de fonctionnement, diverses énergies dangereuses, des capteurs / dispositifs de sécurité et un dispositif intégré pour échanger des données du niveau physique vers les niveaux supérieurs dans les SWE sont utilisés.

Les résultats de cette étude de recherche révèlent que la solution proposée peut considérablement améliorer les connaissances en matière de sécurité liées aux machines et échanger des SRD, entre les fabricants de machines et les utilisateurs finaux de machines. Le SRD transmis est tenu (i) d'effectuer une évaluation plus réaliste des risques machine en tenant compte des problèmes de conception, (ii) de tirer parti des retours d'expérience des utilisateurs finaux et d'en apprendre mutuellement davantage sur les incitations à contourner les dispositifs de protection et les dispositifs de protection par la machine opérateurs pendant le fonctionnement normal ou par le personnel de maintenance pendant les activités de maintenance. L'étude a également identifié certaines limites, qui pourraient affecter la mise en œuvre des mesures proposées. Dans les études futures, la solution proposée pourra être étendue en organisant des groupes de discussion avec des acteurs clés, y compris des utilisateurs finaux de machines, des fabricants de machines et des associations SST. Malgré certaines limites imprévues, on pense que cette étude contribue de manière significative à rendre les machines plus sûres en adaptant les opportunités qui ont été présentées par l'industrie 4.0, ses technologies habilitantes, la numérisation et la connectivité.

ABSTRACT

Machinery is one of the most critical assets of the manufacturing industry. Despite the fact that machine designers/manufacturers and end-users put careful effort in making machines safer, however, there are so many machinery-related accidents that still occur due to several reasons. The literature review about the machines have revealed that (i) lack of adequate safety integration in machine design (ii) lack of systematic risk assessment, (iii) lack of experienced feedback, and (iv) lack of individual(s) experience/knowledge in machine safety, are potential causes for problems that are linked to the safe operation and maintenance of machinery.

These obstacles are mainly due to the lack of effective communication between machine designers/manufacturers and end-users, which have resulted in incomplete risk assessments of machines. Apart from this, machine designers and manufacturers due to lack of awareness of the actual working situation and lack of sufficient safety knowledge do not benefit from the most updated experienced feedback system that can help in designing of machines safer.

In recent times, the enhancement on technologies in the era of digitalization and connectivity different industries such as the internet of things (IoT), the cyber-physical system (CPS) and cloud technology, etc. have greatly helped in improving the processes, products, services, and autonomously performances for the end-to-end activities along with the value chain.

Aiming at that, a research work is proposed for a generic conceptual safety management system (SMS) that is based on the concepts of above-mentioned key enabling technologies in order to overcome the current shortage of insufficient connection between machine designers and machine end-users. Furthermore, a knowledge-based safety model based on the hierarchy of risk assessment introduced in ISO 12100:2010 is proposed to capture the most up-to-date safety-related data (SRD) and experienced feedback based on the machine's actual use in Smart Working Environments (SWEs). A scenario-based case study was conducted on an industrial bag-making machine to explain the working mechanism of the proposed solution. In order to investigate the performance of the proposed solution, the selected machine with different operating functions, various hazardous energies, safety sensors/devices, and an embedded device to exchange data from physical level to upper levels in SWEs are used.

The results from this research study reveal that the proposed solution can significantly improve the machinery-related safety knowledge and exchange SRD, between machine manufacturers and machine end-users. The transmitted SRD is required to (i) carry out a more realistic machine risk assessment by considering design problems, (ii) get benefitted from experienced feedback from end-users, and mutually learn more about incentives to bypass the safeguards and protective devices by machine operators during the regular operation or by maintenance personnel during the maintenance activities. The study also identified certain limits, which could affect the implementation of the proposed measures. In future studies, the proposed solution can be extended by carrying out focus groups with key players, and including machine end-users, machine manufacturers, and OHS associations. Despite some unforeseen limits, it is believed that this study significantly contribute in making machines safer by adapting the opportunities that have been presented by industry 4.0, it’s enabling technologies, digitalization and connectivity.

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LIST OF SYMBOLS AND ABBREVIATIONS

BLS	Bureau of Labor Statistics
CC	Cloud Computing
CM	Cloud Manufacturing
CNC	Computer Numerical Control
CNESST	Commission des normes, de l'équité, de la santé et de la sécurité du travail
CPS	Cyber-Physical System
CPU	Central Unit Process
DDDM	Data-Driven Decision-Making
HMI	Human-Machine Interface/Interaction/Intervention
ICT	Information and Communication Technologies
(I)IoT	(Industrial) Internet of Things
IRSST	Institut de recherche Robert-Sauvé en santé et en sécurité du travail
ITB	Incentive to Bypass
I4.0	Industry 4.0
M2M	Machine-to-Machine
NIOSH	National Institute for Occupational Safety and Health
OHS	Occupational Health and Safety
OSHA	Occupational Safety and Health Administration
PLC	Programmable Logic Controller
RA	Risk assessment
RFID	Radio-frequency Identification
RRM	Risk Reduction Measures
SDM	Safety Decision-Making

SME	Small and Medium Enterprises
SMS	Safety Management System
SRD	Safety-Related Data
SRK	Safety-Related Knowledge
SWEs	Smart Working Environments
WSN	Wireless Sensor Networks

CHAPTER 1 INTRODUCTION

In the manufacturing industries, there exist different types of machinery equipment in the production lines, such as milling machines, presses, turning machines, CNC machines, robots. According to International Standard ISO 12100 (2010), a machine is defined as an assembly fitted with or intended to be fitted with a drive system that consists of linked parts or components, whereas at least one of its part or component moves and joins together for a specific application. An example of a machine is shown in Figure 1.1.

Figure 1.1 An illustration of a machine [courtesy (www.cncmasters.com)]

In workplaces, one of the critical part of accident prevention is hazardous energy control. When we look at a machine, it inherently contains mechanical, electrical, chemical, and physical hazardous energies, that pose serious safety risks to the operators and the workers in their vicinity (Bluff, 2014; 2010). In addition, the moving parts of machinery possess various sources of harm and different risks associated with them. These hazardous energies increase the risk of injuries and fatalities such as amputation, cutting, and entanglement of organs that many times lead further to cause human death.

On the other side, machinery operators and maintenance workers' intervention is inevitable during the machine's lifecycle. During the setting up of machines for production, inspections, cleaning, unjamming, repair, and troubleshooting, workers are exposed to mechanical hazards that can cause injuries or even death. Thus, it is crucial to understand the cause of accidents in order to further identify some potential solutions to reduce injuries and fatalities. An improved machine design could result in less exposure of workers to machinery-related hazards. Here, a hazard is defined as any potential source of harm (ISO, 2010).

In this regard, ISO 12100 (2010) has specified an appropriate hierarchy of risk assessment and risk reduction measures (RRMs) in order to conduct the feasible and effective control measures to eliminate or reduce the risks at minimum levels. This process primarily helps machine manufacturers to design and build safe machines. On the other hand, RRMs are used when modifications on existing machines are carried out in factories during the managing of residual risks. These principles are based on the machine manufacturers' knowledge and experience, which uses incident records and risks associated with machinery (ISO, 2010).

Meanwhile, any safety-related data (SRD) which has been described in Section 2.1.5 in details is vital for maximizing the efficiency of the risk assessment process. SRD needs to be as accurate and detailed as possible during the design phase. Besides, for a more precise safety decision-making (SDM) process, SRD can be seen as the most valuable assets for all safety practitioners (Badri, Boudreau-Trudel, & Souissi, 2018). The combination of historical and current data empowers real-time decision-making during the manufacturing process, which positively influence the performance, safety, reliability, and sustainability of industrial systems (Vogl, Weiss, & Helu, 2019).

In the machine safety, it is critical to identify all the hazards associated with machinery by collecting precise and pertinent SRD. Accurate data analysis on SRD is necessary to exploit safety knowledge for carrying out a more realistic risk assessment. However, the lack of appropriate communication between machine manufacturers and end-users further enlarges the existing problem and prevents sufficient transmission of SRD and experienced feedback from end-users (Jocelyn, Chinniah, & Ouali, 2016).

Meanwhile, in the era of connectivity and digitalization, OHS experts and safety practitioners could benefit from the gathered SRD to make more appropriate safety decisions in order to improve the safety of workplaces (Vignali et al., 2019). However, in Industry 4.0 – based risk management, there is still a tremendous challenge to correctly identify the risk factors and maintain the appropriate supervision of OHS experts, who will be less and less present on the shop floor (Badri et al., 2018). Therefore, the raised question is;

How industry 4.0 could improve and facilitate the connectivity between machine manufacturers and machine end-users to enhance machine safety?

To answer this question, chapter 2 presents the current pitfalls in the context of machine safety, particularly focuses on the process of machinery risk assessment, and explores the possibilities and opportunities of Industry 4.0 to improve the safety of workers around machinery.

Chapter 3 explains the problems, objectives, and methodology of this study.

Chapter 4 presents the proposed solution along with the development of a scenario-based case study.

Chapter 5 highlights the discussion, concluding remarks, limitations of the current study, and some recommendations for future work are presented.

CHAPTER 2 LITERATURE REVIEW

This chapter covers prior studies that have focused on the safety of machinery. Section 2.1 provides some statistics on machinery-related accidents and their causes. Then, this chapter didactically explains the process of risk assessment and risk reduction measures (RRMs) through the Sections 2.1.2 and 2.1.3. After the main concepts are covered, Section 2.1.3 presents the current problems and limitations associated with the process of risk assessment and safety integration. Next, the safety-related data (SRD) is presented in Section 2.1.5 to highlight its importance in making of safety knowledge and for making of a more reliable data-driven safety decision. After that, the main obstacles are summarized in order to investigate that how the key enabling technologies in the era of digitalization and connectivity could help us to overcome the associated problems. Section 2.2 covers the previous studies in utilizing the key enabling technologies such as CPS, IoT, and Cloud technology in the field of occupational health and safety (OHS). The previously used technologies can help us in facilitating the process of acquiring SRD and exchanging data between machine designers and machine end-users as two engaged parties in improving the safety of machinery.

2.1 Safety of machinery

As previously explained in the introduction, machine safety is one of the guidelines under Occupational Health and Safety (OHS) that desires to ensure whether a machine can perform its anticipated function within its lifecycle in a safe condition. Every year, contact with moving parts of machines is among the highest occupational risk associated with machines, which results in different consequences such as disabling injuries, amputation, or even death (Aneziris et al., 2013). In terms of machines, it generally refers to those kinds of equipment that at least have one moving parts such as presses, conveyors, band saws, or those which are used to roll, shape, or bend the workpiece, forklifts, agricultural machinery (OSHA, 2007a, 2007b). Besides, National Institute for Occupational Safety and Health (NIOSH) has reported that occupational-related accidents result in almost 18,000 amputations and 800 fatalities per year in the US (Etherton & Myers, 1990)

2.1.1 Statistic of machinery-related accident

Statistics presented in the literature show that machines are the primary source of numerous accidents and fatalities at workplaces. In connection with agricultural machinery, most accidents happened during the maintenance activities (Gerberich et al., 1998). In the UK, HSE demonstrated that among all contacts with moving parts of machinery, seventy-five percent of all accidents happened during interventions on a machine, where fifty percent of total accidents were caused by the moving parts of conveyors and printing presses (HSE, 2006).

According to the reports by occupational safety and health administration (OSHA) in 2018, control of hazardous energy – Lockout/Tagout (29 CFR 1910.147) and machinery and machine guarding – general requirements (29 CFR 1910.212) were the most cited violations (OSHA, 2018). In 2015, in Quebec, Canada, there were 2965 accidents that were linked to machinery with an 8.6 % diminution from the previous year and seven deaths were related to the machinery in production, maintenance, and repair, as reported by CNESST 2010-2014 (CNESST, 2015b). In Australia, according to Gardner et al. (1999), 28% of all compensation injuries were related to mechanical equipment. In their analysis, it was illustrated that improper work practices, incomplete implementation of safe work procedures, poor design of a machine, bad condition of a machine, and lack or insufficient guarding are the leading causes. March and Fosbroke (2015) reported that 5579 occupational machine-related fatalities happened only in the United States (US) from the years 1996 to 2010. Meanwhile, industries such as agriculture, forestry, and fishing with 2,063 (37%), construction with 1,204 (22%), and manufacturing with 776 (14%) showed a high number of fatalities that were resulted from the mobile and stationary machines (e.g., tractors, cranes). A series of reports published by the US Bureau of labor statistics (BLS) shows that contact with objects and equipment are major causes of accidents, over 717 and 722 (15%) for the years 2013 (BLS, 2014) and 2015 (BLS, 2016), respectively.

Similarly, Bulzacchelli et al. (2008) illustrated the hazards of moving parts of machinery, which resulted in injuries of over 1000 workers in 2005. According to the health and safety executive (HSE) (2006), moving parts of printing presses and conveyors caused 50% of accidents in the UK during the years 2003-2004,. In the Netherlands, annually almost 418 cases out of 1907 accidents, which is 22% of the total accidents per year, are due to contact with moving parts of machinery

(Bellamy et al., 2007). In Canada, a study taken by Gilks and Logan (2010) shows that there were relatively three occupational fatalities per day in 2008. They have indicated that considering costs such as benefit payments, compensation time-loss, health care, and vocational rehabilitation payments, and costs of occupational injuries and fatalities to the Canadian economy can be estimated at more than $19 billion annually.

Table 2.1 Brief overview of some accidents caused by moving parts of machinery

Country (Years)	**Sectors**	**Number or percentage of accidents**	**Caused by**	**References**
Turkey 2006 - 07	Agricultural	64.9%	Work with agricultural machines	Akdur et al. (2010)
Netherlands 2002 - 03	Manufacturing	33%	Contact with moving parts of machinery during operation	Bellamy et al. (2007)
Finland 1999–2008	Manufacturing	88%	Maintenance and repair, adjustment, installation, inspection, and transfer	Nenonen (2011)
UK 2003 – 4	Printing	50%	Moving parts of printing machines and conveyors	HSE (2006)
USA 2000–2007	Mining	41%	Struck by, entangled in, or in contact with moving machinery or equipment	Ruff et al. (2011)
USA 2018	Manufacturing	51	Contact with objects and equipment	BLS (2019)
USA 2011 – 15	Manufacturing	710+ annually	Contact with objects and equipment	BLS (2016)
USA 1992 - 2010	All industrial sectors	5579	Stationary (1297 cases) and mobile (4282 cases) machines	Marsh and Fosbroke (2015)
USA 2002 - 11	Mining industry	655+ annually	Hands being caught in tools and equipment	Pollard et al. (2014)
Canada 2010 – 14	Manufacturing	2965	Machinery in production, maintenance, and repair	CNESST (2015)
Canada 2015	Manufacturing	106	Contact with moving parts of machinery during maintenance activities	Chinniah (2015)

In another study, Chinniah (2015) analyzed 106 machinery-related accidents from Quebec's province in Canada which focused on the hazard of moving parts of machinery. According to this study, about 34.9% of accidents were related to the maintenance tasks, followed by 31.1% for handling production disturbances, 19.8% for production tasks, and 12.3% for the set-up phase. The study depicted that the higher percentage of accidents were connected with maintenance activities and were due to inevitable workers' intervention and their presence in a hazardous machinery zone. The causes of machinery-related accidents were mainly due to bypassing/defeating safeguards, easy access to moving parts of machinery, lack of appropriate supervision, the omission of lockout procedures, and unsafe working methods (Blaise & Welitz, 2010; Chinniah, 2015). Besides the statistics in Table 2.1 shows that machines are the primary source of numerous accidents and fatalities at the workplace there is still a significant number of machinery-related accidents caused by various reasons. A proper risk assessment could help in making optimal decisions about the means of risk reduction for machinery (Gauthier, Lambert, & Chinniah, 2012).

2.1.2 Risk assessment

There are several standards and guidelines for occupational risk management and the prevention of accidents that involve machinery, namely, ISO 12100 (2010), ISO 14119 (2013), ISO/TR 14121-2 (2012), ANSI B11.0 (2015), CSA Z432 (2016). There are numerous laws and regulations that have been designed on machine safety, such as Machine Directive (2006) in Europe, Occupational Health and Safety Regulations in all the provinces in Canada, OSHA regulations in the US, and national labor regulations in several other countries. For this purpose, their hierarchy of risk control is kept almost same through an early measure of elimination in the design phase or by using appropriate personal protective equipment in the workplaces (Aneziris et al., 2013). Risk assessment aims primarily to eliminate and then mitigate the level of risks associated with the machines to the acceptable/tolerable level.

International Standardization ISO 12100 (2010) defines the risk as a combination of the severity of harm and its probability. The latter is subdivided into another three essential parts: frequency and duration of exposure to a hazard, the occurrence of a hazardous event, and the possibility to avoid or limit the harm, as shown in Figure 2.1 (ISO, 2010). Consequently, we can apply these factors to machinery in order to determine various risks associated with the machine that may pose a danger to the workers who operate and maintain machinery. To achieve this aim, a hierarchy of risk management analyzes, evaluates, and controls these risks by defined controlling measures through its risk assessment process, as shown in Figure 2.2 and described as follows (ISO, 2010).

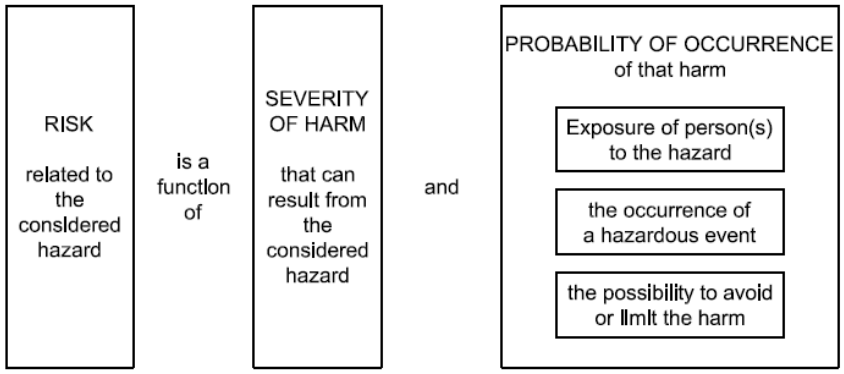

Figure 2.1 Elements of risk (ISO, 2010)

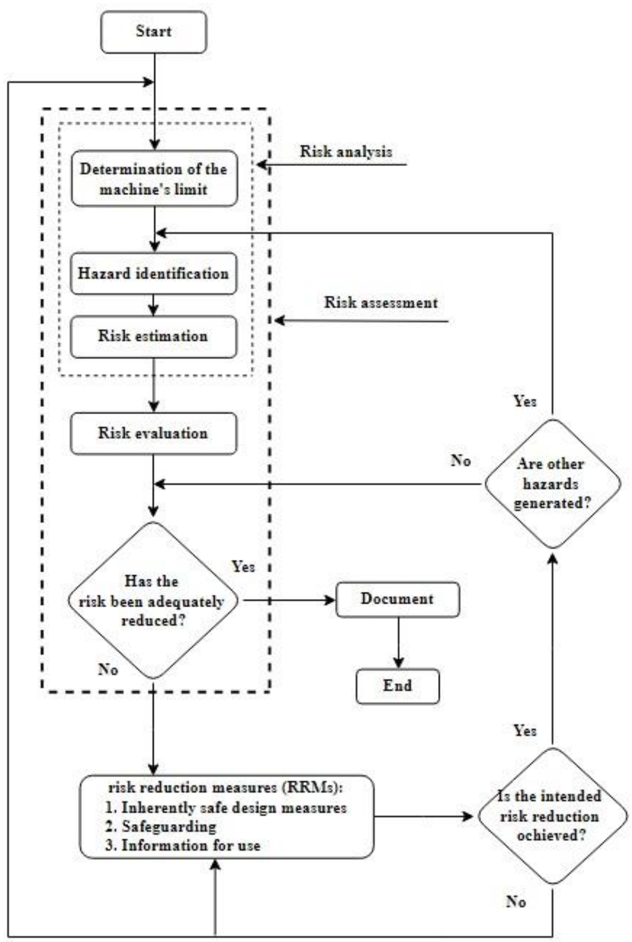

Figure 2.2 Simplified hierarchy of risk management (ISO, 2010)

- *Determination of machine's limitation,* considering the conditions that machine is intended to perform at, all machine's phases during its lifecycle, maintenance-related activities, workers exposure to hazards, human-machine interaction, properties of the material.
- *Identifying machine hazards* is one of the essential steps since all hazards are identified during this step, by taking into account the machinery's life cycle. After identification of hazard, risk estimation for each hazard is done.
- *Risk estimation*, in connection with each identified hazard, considers the following four elements; namely, the severity of harm, the probability of exposure of individual(s) to that hazard; the occurrence of a hazardous event; and the possibility to avoid that harm, as shown in Figure 2.1. An example of a risk estimation tool is presented in Figure 2.3. This risk graph was introduced in ISO/TR 14121-2 (2012), based on a decision tree, where a risk parameter is represented by each node. These parameters are the severity of harm (S1 and S2), its probability (i.e., frequency of operator(s)'s exposure to the hazard (F1 and F2), probability of occurrence of the event (O1, O2, and O3), and the possibility to avoid the harm (A1 and A2)) need to be identified. This architecture's resulting risk index leads to six risk levels or indices that range from R1 as the lowest to R6, which is the highest.
- *Risk evaluation* is the comparison of the estimated level of risk with the acceptable or tolerable risk level. It determines if any further risk reduction is required. The satisfaction level in the process of risk evaluation needs to meet the agreement of various groups such as workers with high exposure to the risk, OHS practitioners, legal requirements, machine safety standards and safety data sheets (Jocelyn et al., 2016).
- *Hazard elimination*, or risk reduction measures (RRMs), applies to various measures, which are discussed in the following section.

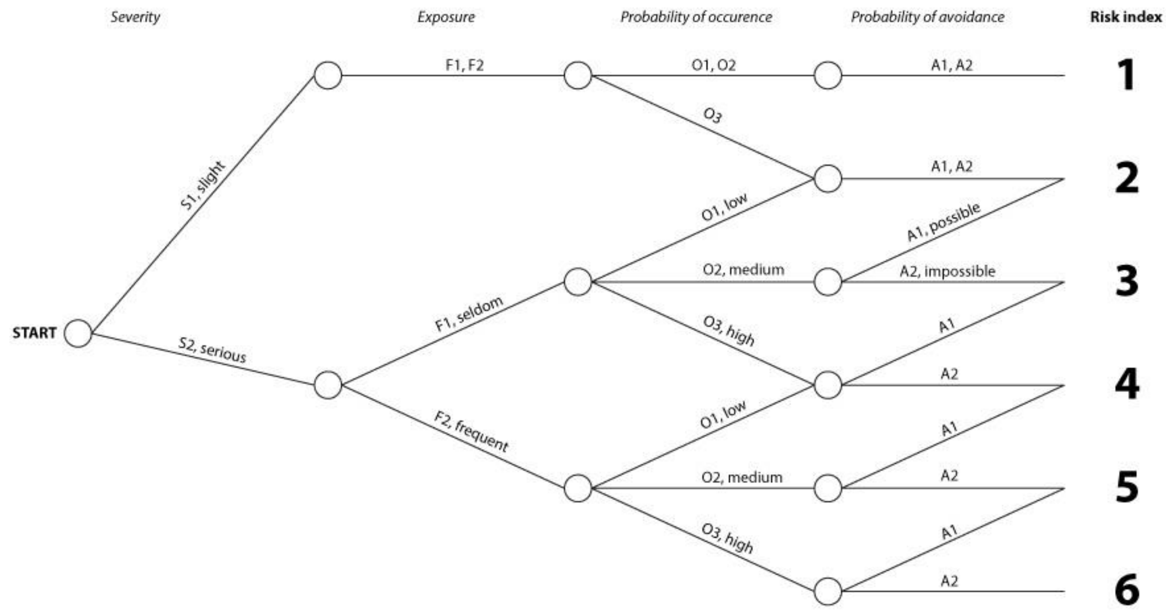

Figure 2.3 Example of a risk estimation tool (ISO, 2012)

Hence, machine safety experts must consider all the possible accesses to the moving parts of machines during the exposure of maintenance workers since their intervention is inevitable during the machine lifecycle. For machine manufacturers, an appropriate SRD is required for producing a machine safer. In the literature, many qualitative and quantitative tools have been proposed to help the safety practitioners to have a better risk estimation based on available SRD (Chinniah, Gauthier, Lambert, & Moulet, 2011; Duijm, 2015; Wang, Wu, Huang, & Kang, 2019).

SRD can be divided into two groups of “accident-related data” such as many accidents, incidents, accident reports, and “non-accident data,” which includes near-misses data, hazard data, safety-related cultures and training (Wang & Wu, 2017). Theoretically, organizations can provide a limited amount of accident-related data; however, non-accident data is generally made easily available. This shows that source of SRD is very important for the improvement of safety performance (Wang et al., 2019; Wang, Wu, Shi, & Huang, 2017b).

2.1.3 Risk reduction measures (RRMs)

As shows in Figure 2.4, the risk reduction measures are classified into two main groups: elimination and mitigation measures based on their efficient impacts. Within the design phase, machine manufacturers aim to eliminate the hazards through considering an inherently safe design.

Subsequently, with possibility of any residual risks, other measures would be applied to minimize them further in the given order. For instance, substitution by replacing the hazard; engineering controls such as guards and protective devices to protect people from the hazard; informative signs or signals; using administration controls (e.g., work method or procedures; using personal protective equipment (PPE), and lastly training and information) (CSA, 2016; ISO, 2010; Machinery Directive, 2006).

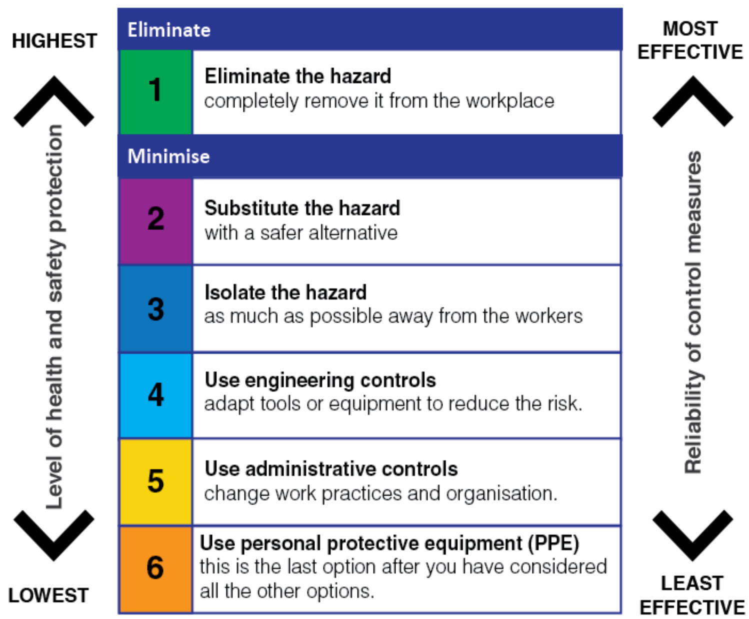

Figure 2.4 Hierarchy of risk control (Shepherd, 2018)

- *Inherently safe design*: This is a protective measure that is used for eliminating or mitigating the machines' hazards. For this purpose, the manufacturer can change the machine design or substitute some of the machine characteristics with other safer alternatives. The measures in this stage may differ from those as in guards or protective devices.
- *Guards*: Guards provide physical barriers to hazardous areas. Characteristically, guards must be secure enough to withstand workers' attempts to bypass, defeat, mute, remove, or tamper them. They also should not hinder the worker's view or prevent others from working (OSHA, 2015).
- *Interlocked moveable guards*: Interlocked moveable guards protect workers when certain hazards cannot be eliminated or mitigated by inherently safe design.

- *Protective devices*: Safeguard other than a guard that may execute one of the following tasks. Examples of protective devices are safety light-curtains, safety scanners, safety controllers, safety cameras, safety pressure mats, two-hands control enabling devices such as hold to run, and teaching pendants for robots.
- *Information for use*: consisting of communication links (e.g., text, words, maintenance or operation manuals with specific safety instructions, warning signs, signals, symbols, diagrams, siren) to convey information to the user.
- *Organizational measures*: are those measures that end-users use to manage the remaining risks associated with the machines. For instance, safe working procedures, Lockout/Tagout procedures, supervision, permit-to-work systems, provision and use of additional safeguards, personal protective equipment (PPE), safety audits, and training.

2.1.4 Risk assessment limitations

As explained previously, the iterative risk assessment process can identify risks associated with machines' hazards during their life cycle in order to eliminate them or to identify risk reduction measures to mitigate them to an acceptable level. However, in general, this approach can be complex if all the required aspects of the machine during its life cycle, such as design phase, operation, and maintenance, are unknown.

The researcher in INRS[1] have defined the concept of work situations at their workplaces (Hasan, Bernard, Ciccotelli, & Martin, 2003; R. Houssin, Bernard, Martin, Ris, & Cherrier, 2006). According to Hasan et al. (2003), the concept of work situation is defined as "*the work system [that] is composed of the means and of one or several workers (person(s) performing one or more tasks within the work system) who act together to carry out one or several tasks in a work environment under the conditions set for carrying out the work task*." Hasan et al. (2003) developed the working situation that facilitates the simultaneous consideration of multiple observation data based on the concept of risk. However, this model does not provide direct links between the design

[1] National Institute of Scientific Research (Institut national de la recherche scientifique (INRS) in French)

parameters and risk evaluation parameters, and as a result, it does not give solutions for identification of hazards (Sadeghi, Dantan, Siadat, & Marsot, 2016).

For instance, if end-users alter the actual usage of whole or a part of the machine to some different conditions than the original ones, this might create new risks that were previously not identified during the design phase. Some examples of these alternations are the operating of the machine at a different frequency from its designated frequency, or operating of machines with higher power levels, operating of machines after some improper maintenance or modifications have been done, operating of machines under unanticipated environmental situations, or operating of machines by persons with low competency levels (Jones et al., 2009). In these cases, because new risk assessment is not conducted for these changes (Karimi, Burlet-Vienney, Chinniah, & Aucourt, 2019), working under these condition while takin the measures from the original risk assessment alters the purpose of the initial risk assessment (Jones et al., 2009). In addition, working of multiple users with different levels of skills and experience at the same area may also pose additional risk.

Moreover, due to lack of specialized person in “prevention” and formal resources or tools for implementing a priori risk assessment in small and medium enterprises (SMEs) increase the possibility of machinery-related accidents (De Galvez, Marsot, Martin, Siadat, & Etienne, 2017). It is mainly because mechanical and electrical engineers lack the training about machine safety in their engineering curriculum. Hence, in order to anticipate a more realistic outcome to risk assessment and traditional Safety Decision-making (SDM), both expertise and SRD are required simultaneously. The sufficient SDM is hard to achieve without having any of them (Wang et al., 2019; Wang, Wu, Shi, & Huang, 2017a; Yang, 2012).

On the other side, there are no adequate methods for SRD collection, storage, and processing due to insufficient infrastructures (Guo, Ding, Luo, & Jiang, 2016).The big amount of updated SRD and the exploited safety knowledge could significantly help in considering all required prior preventive measures in order to correctly eliminate or mitigate the risks associated with the machine hazards. Moreover, lacking in appropriate communication between machine manufacturers and machine end-users has restricted the fetching of the most recent SRD from machines during their life cycle (Jocelyn, Chinniah, & Ouali, 2016). , A practical risk assessment and risk estimation process relies on accurate and detailed SRD that makes the decision-making more effortless and more effective (Jones et al., 2009).

Table 2.2 represents the first group of problems in which machine manufacturers have insufficiently addressed safety integration into design phases of machinery. According to this table, machine end-users are unable to participate in the process of safety integration into design phase of machines where only identified problems could be assigned to this party. However, end-users with a customized machine design would be able to define functions and requirements depending on their needs and real working situations.

Table 2.2 Identified problems concerning inadequate safety integration into a machine design

Identified problems	**Engaged parties**		**Reference**
	Machine designers	**End-users**	
Design engineers are aware of the need to integrate safety into their design; however, some do not know how to make it adequately or effectively.	✓	–	Gauthier and Charron (2002)
The actual working situation is not effectively taken into account during machine design.	✓	–	Hasan et al. (2003)
Machine designers have not considered bypassing safeguards during the design phase.	✓	–	Haghighi et al. (2019)
Safety aspects are not among the crucial requirements during machine design.	✓	–	Fadier and Garza (2006)
Inconsistencies appear between productivity and safety due to the late integration in the design phase.	✓	–	Houssin and Coulibaly (2011)
The integration of safety in the design stage is complex, especially for normative or regulatory documents.	✓	–	Sangare et al. (2012)
Designers tend to use design tools and techniques that focus on the product and its utilization.	✓	–	Sadeghi et al. (2013)
Machine manufacturers do not take into account maintenance activities on machinery appropriately during the design phase.	✓	–	Jocelyn et al. (2016)
Machine designers in SMEs carry out the risk assessment once all the technical solutions have been defined.	✓	–	De Galvez et al. (2017)
The required data for implementing risk assessments in SMEs are not directly linked to the design data.	✓	–	

From this it is know that unrealistic understanding of working situations could easily escalates this type of problem, particularly for machine manufacturers and end-users in SMEs as they do not have enough experience in dealing with the integration of different machine safety aspects into the machine's design phase. Some of their examples are the ineffective coverage of routine maintenance activities, manipulation of safety devices and their incentives, human intervention, and use of insufficient safety technology solutions (Haghighi et al., 2019; Jocelyn et al., 2016). Moreover, there is a possibility that machine designers overlook safety aspects or consider it as a non-crucial requirement aspect (Fadier & De la Garza, 2006). Lack of sufficient attention to safety aspects would result in some disagreements among design phases.

On the other side in Table 2.3, the lack of systematic risk assessment tools is considered as the second identified problem. Any changes to machines' primary status due to inappropriate modifications or maintenance would revoke the acceptability of primarily implemented machinery risk assessment. Usually, the risk assessment is done based on some assumptions; and, use of the machine by end-users through a different approach, or modification in the machine would then revoke the validity of risk assessment. However, a new risk assessment would not be carried out by machine end-users due to the lack of appropriate communication and even the machine designers/manufacturers are not acknowledged about these modifications.

It is essential that the machine’s limits should be appropriately determined to cover all the possible conditions that it may encounter during its operational period (e.g., maintenance activities, human-machine interaction) in order to carry out more realistic machinery risk assessment at early stage during the design phase. For this purpose, both machine designers/manufacturers and machine end-users require more realistic assumptions about the machine’s condition in addition to using of their documented historical data. They would need to have the most updated SRD and experienced feedback, which can be accessed from end-users workplaces. Besides, SRD has to be accurate and provided with details during the design phase of the produced machines. Therefore, identification of SRD indicators is necessary which must be collected and sent to risk assessment practitioners so that the effectiveness of machinery risk assessment can be enhanced.

Table 2.3 Identified problems in connection with lack of systematic risk assessment tool

Identified problems	Engaged parties		Reference
	Machine designers	End-users	
The historical data of potential hazards associated with machine/operators are valid as long as no changes happen to the machine/operation.	✓	✓	Gadd et al. (2004)
Primary risk assessment has been altered due to inappropriate maintenance or modifications,	–	✓	Jones et al. (2009)
Over time, machines' users might have altered the safety of specific machines through some modifications.	–	✓	Chinniah (2015)
In every working environment, some machines can be found to not comply with up-to-date safety standards.	–	✓	Tremblay and Gauthier (2018)
There is a lack of appropriate risk assessment on alternative methods for controlling hazardous energy upon any modification conducted by end-users.	–	✓	Karimi et al. (2019)

2.1.5 SRD and traditional SDM approaches

The use of raw SRD is not possible before it is treated to become information and, consequently, actionable safety-related knowledge (SRK) using data analytics techniques as described by Huang et al. (2018). According to Chaffey and White (2010), Information is "*data that have been shaped into a form that is meaningful and useful to human beings*." Besides, knowledge is "*the combination of data and information, to which is added an expert opinion, skills, and experience, to result in a valuable asset, which can be used to aid decision-making*" (Laudon & Laudon, 2018).

Here, actionable SRK refers to those types of safety knowledge safety practitioners are informed to create strategies for prevention, occupational accident control, defining of safety goals, provisioning of safety training, improvements in workplace safety, safety effectiveness evaluation and re-investing in safety resources based on outcomes.

In addition, safety decisions are divided into two categories. Firstly those which need SRD to identify, inform, or clarify (e.g., risks identification and assessment or issues and demands identification), and secondly those which need SRD to take action (e.g., re-budging safety management resources, purchasing new safety facilities, implementing safety-training programs) (Wang & Wu, 2017). When the required action has been taken in place, new SRD can be collected within the anticipated time-intervals in order to evaluate the effectiveness of the implemented practices, which leads further to more organized and accurate SDM through the heading times.

Traditional SDM approaches are no longer flexible enough to comply with the organizational requirements in the era of digitalization (Badri et al., 2018). There are three types of traditional SDM approaches which include intuition-driven SDM, experience-driven SDM, and causation-driven SDM, as shown in Table 2.4 (Wang et al., 2019). According to the literature, some of their advantages and disadvantages are listed in this table (Cha & Ellingwood, 2013; Shafiee & Animah, 2017; Simanaviciene, Liaudanskiene, & Ustinovichius, 2014; Wang et al., 2017a).

Table 2.4 Pros and cons of different traditional safety decision-making approaches

Approach	**Pros and Cons**
Intuition-driven SDM	Pros: this approach works well for rapid decision-making to solve urgent and straightforward safety issues. Cons: human instincts have significantly affected it, such as safety assumptions and safety practitioners' risk perceptions. Therefore, it is subjective, random, and may not be reliable.
Experience-driven SDM	Pros: it is suitable for routine, similar, or common safety issues. Cons: safety practitioners may not have sufficient safety knowledge or reliable experiences. Besides, being subjective-based and time lag in making a decision are the other two loopholes of this approach.
Causation-driven SDM	Pros: emphasize cause-oriented safety management demands in making a targeted and effective safety decision. Cons: it is not working well if the causes are unknown and the factors, which have resulted in any specific safety problem, are unidentified.

As presented in Table 2.4, use of traditional SDM approaches in the past required considerable resources such as workforce, time, and money, and it heavily relied on the safety practitioner’s intuition and experiences. Furthermore, the lack of essential safety-related information for SDM is another universal issue for the use of traditional SDM approaches. On the other hand, SRD has become the most valued asset for safety managers in their SDM practices. For the safety management, safety practitioners prefer the use of different sources of high-quality SRD in order to manage the required practices effectively, as it is also known as Data-Driven SDM (Ouyang, Wu, & Huang, 2018; Wang et al., 2019). Hence, presently these approaches are not suitable anymore, as they could bring errors in safety decision due to the lack of reliable SRD, as concluded by Wang et al. (2019) claimed (Guo et al., 2016; Wang et al., 2017a; Yang, 2012).

A safety decision-making approach compatible with the requirement of current organizations' conditions would requires a systematic method to gather and maintain accurate safety-related information (Badri et al., 2018; Mouras & Badri, 2020; Wang et al., 2017b). As a result, it can enhance and provide support to traditional SDM approaches (Newell & Marabelli, 2015; Wang et al., 2019). Data-Driven SDM exploits more up-to-date and accurate safety-related information and consequently could exploit safety-related knowledge from SRD and apply it into the process of SDM to resolve organizational safety problems rather than traditional SDM, which purely was basing decisions on intuition and experience (Brynjolfsson & McElheran, 2016; Wang et al., 2019).

Tables 2.5 and 2.6 represent the list of the identified problems that are associated with SRD in the field of machine safety. These problems can be categorized in to two groups; namely, (i) lack of experienced feedback (Table 2.5) and (ii) lack of individual(s) machine safety experience/knowledge (Table 2.6). Both machine designers/manufacturers and end-users are adversely affected by lack of experienced feedback, where they will not be able to benefit from those feedback to carry out a realistic machinery risk assessment. By considering the actual working situation, foreseeable misuses, the likelihood of the accident, actual frequency or exposure of the machine's operator to the dangerous hazards associated with the machine. Besides, having end-users feedback, for instance, bypassing safeguards and protective devices. A good example of foreseeable misuses can help them design more user-friendly machines where the chance of bypassing decreases significantly. On the other side, end-users might have difficulties to benefit from the machine manufacturers' knowledge so that an appropriate modification on the machine can be made.

The implementation of machinery risk assessment is a subjective process, as mentioned in Table 2.6 (Caputo, Pelagagge, & Salini, 2013). Hence, the individuals knowledge about machine safety and their personal judgment could pose risk to their decision making process. They might not be able to effectively diagnose and identify all hazards associated with the machines. In addition, lack of safety-related knowledge is more highlighted in SMEs who experience the lack of safety practitioners. According to previous researches as provided in Table 2.6, it is known that both the engaged parties are required to keep their safety knowledge updated.

Table 2.5 Problems concerning lack of experienced feedback

Identified problems	**Engaged parties**		**Reference**
	Machine designers	**End-users**	
Accident analysis based on a limited sample of exposures may result in a pitfall during risk assessment to estimate an event's likelihood.	✓	✓	Gadd et al. (2004)
A risk assessment will be unrealistic if risk practitioners do not include employees who are familiar with the machine or task being assessed.	✓	✓	
A designer is not fully aware of the actual working environment.	✓	–	Fadier and Garza (2006)
There are differences between the designer's conceived working situation and the actual ones at the end-user site.	✓	–	Houssin et al. (2010)
In reality, there is no or limited communication between machine designers and end-users to benefit from accidents.	✓	✓	Jocelyn et al. (2017; 2016)
Worker’s incentives to bypass guards and protective devices are not appropriately considered during the design phase.	✓	✓	Haghighi et al. (2019)

Table 2.6 Problems concerning the lack of individual machine safety experience/knowledge

Identified problems	**Engaged parties**		**Reference**
	Machine designers	**End-users**	
Risk practitioners fail to identify all hazards associated with a particular activity.	✓	✓	Gadd et al. (2004)
The process of risk assessment is subjective and is based on the knowledge of risk practitioners, the analyst’s opinion, and personal judgment.	✓	✓	Caputo et al. (2013)
Designers of SMEs are not specialized in the prevention, and their safety knowledge is limited to the risk families closest to their field of experience.	✓	–	De Galvez et al. (2017)
Designers’ assumption during design process differs from what is really happening during the machine employment in which produces unseen sources of risks.	✓	–	Sadeghi et al. (2017)

With the recent advancements, more SRD can be captured that OHS practitioners need to exploit the information and knowledge to enhance their insights into the system that means we can expect a more effective SDM and proper machinery risk management. Traditionally, there exit several tools for accident prevention in safety-related research domains. For instance, risk analysis, safety inspection, training, and near misses; however, currently, with the emergence of new complex safety-related issues, use of traditional approaches may no longer be useful (Podgorski, Majchrzycka, Dabrowska, Gralewicz, & Okrasa, 2017). Additionally, networking and real-time communication facilitate the monitoring of any desired system where massive SRD can be collected to realize early warning signs for prevention of accidents.

From the review of literature, the main obstacles in the context of the safety of machinery have been covered. The main obstacles that have been identified from the review of literature are summarised as the followings.

(i) Inadequate machine design, which does not appropriately consider safety into early design phases of machinery;

(ii) Lack of systematic risk assessment, which does not consider new risks created during the machine operation, particularly after modifications or maintenance activities.

(iii) Lack of experienced feedback streaming back to machine manufacturers due to lack of appropriate communication between machine manufacturers and machine end-users; and,

(iv) Lack of individual(s) machine safety experience/knowledge because there are no appropriate means of SRD collection, storage, and processing due to insufficient infrastructures.

Considering these loopholes, a systematic approach is required to facilitate the acquisition of high-quality SRD so that it can be exchanged with OHS experts and safety practitioners of both machine manufacturers and machine end-users. Meanwhile, recent advances in the key enabling technologies in the era of digitalization and connectivity has made it possible to capture, store, analyze, and exchange data and information more accurately through the entire system. Aiming at that, previous studies and research works on deployment of some of the enabling technologies will be addressed in the next section to improve the safety aspects in the working environments. Review from this literature can help in using the concept of these technologies about the acquiring of SRD from machines in SWEs, exploiting of knowledge using the concept of CPS, visualizing and analysing the data on the cloud platform where it can be exchanged further with machine designers/manufacturers.

2.2 Industry 4.0

The Industry 4.0 – or Industrie 4.0 as the German version – approach that has been introduced at a fair at Hannover, Germany, in 2011 (Drath & Horch, 2014). Industry 4.0 aims to enhance the creation of industrial value through digitalization and connectivity (Ghobakhloo, 2018; Kagermann, Helbig, Hellinger, & Wahlster, 2013). Industry 4.0 is a technological transformation aimed to carry new technologies in data communication and machines' networking to make them wise (Vignali et al., 2019). Industry 4.0 uses ICT to connect humans, machines, and objects to integrate them horizontally and vertically, even from different remote places (Li et al., 2017; Veile, Kiel, Müller, & Voigt, 2019).

2.2.1 Industrial revolutions

Historically, the first industrial revolution or “mechanization” began since wood was replaced by steam and pit-coal in the 18thcentury. Mechanization slightly shifted to “mass production” in the 19th century when electricity was introduced and used into the production line to make the machinery's operation faster. In the 20th century, industries experienced the third revolution of “automation,” where information technology (IT) and electronics were used to optimize the manufacturing processes and enhance the productivity through the design of more flexible, ergonomic, and safer machinery. Currently, the fourth revolution has enriched the “digitalization” or “smart connectivity,” which is in its infancy and is triggered by the further developments in information and communication technology (ICT) (Ministry of Economy, 2016; Rojko, 2017), as shown in Figure 2.5. The third and fourth industrial revolutions focus on the use of automation and processes (Tan et al., 2010). However, the fourth industrial revolution is one step ahead and focuses on the end-to-end digitalization and integration of digital industrial ecosystems (Xu, Xu, & Li, 2018).

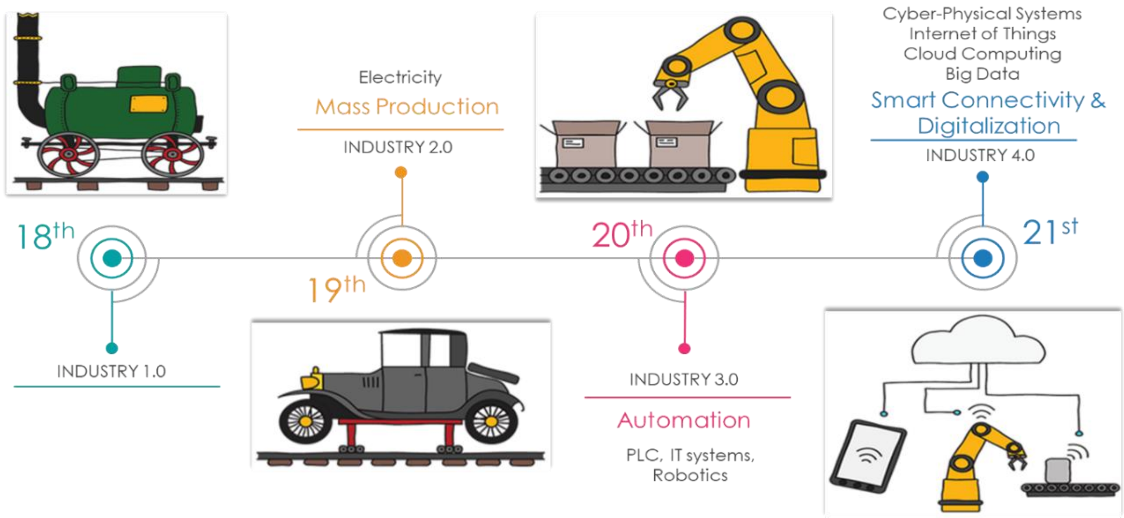

Figure 2.5 Industrial revolutions [courtesy (www.simio.com)]

2.2.2 Key enabling technologies

As illustrated in Figure 2.6, I4.0 adapts some enabling technologies such as the cyber-physical systems (CPS), Internet of Things (IoT), Cloud Computing (CC), Big Data, Simulation (Digital Twins) and Machine-to-Machine communication (M2M) (Hermann, Pentek, & Otto, 2016a; Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014; Lu, 2017; Wichmann, Eisenbart, & Gericke, 2019). The aim of using these technologies is to collect data, communicate it by creating a networked link among objects, and manage those data to reorganize and improve the production process (Schmidt et al., 2015).

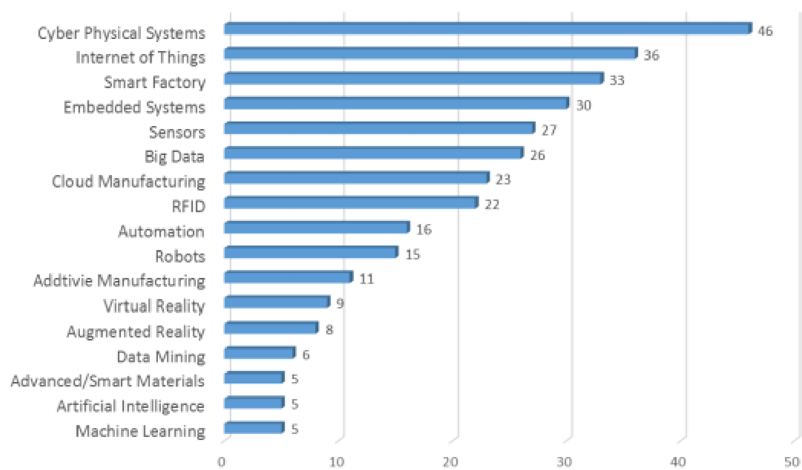

Figure 2.6 Key technologies instrumental to industry 4.0 (Wichmann et al., 2019)

Among these technologies, Cyber-Physical Systems (CPS) provide decentralized decisions by monitoring the physical processes and creating their virtual versions on a cyber-level. The Internet of Things (IoT) is used for the communication and cooperation of all entities, including humans and machines, on a real-time basis (Marcon et al., 2017). Moreover, with recent advances in sensors technologies, numerous features of any process can be acquired (Stock & Seliger, 2016). Also, unknown relationships among the captured data can easily be recognized with the help of data analysis techniques.

Nowadays, in SWEs, machines are featured with self-monitoring capabilities which make them capable of monitoring their surroundings and send information to diagnostic centers to determine if any further intervention is required (Tantik & Anderl, 2017). Although the operation of autonomous machines in SWEs are useful, however, machines always need a routine or planned maintenance such as repair or inspection.

Ultimately, it is necessary to determine that how these enabling technologies can be adapted for OHS in order to improve their management system and improve the safety of machines.

2.2.3 OHS management and Industry 4.0

Idea of safe workplaces is not new to industrial sectors. Despite the little discussion around the safety-aspects of new key technologies, the human factors and ergonomics (HF/E) in the era of I4.0, machine manufacturers and safety experts have been brought the attention to include essential element of work safety in the design phase (Stern & Becker, 2017; Veile et al., 2019). Fernandez and Perez (2015) highlighted the risks associated with OHS when conventional occupation risk analysis tools are unable to identify them. Therefore, it was proposed to implement new risk analysis models to monitor all conventional and emerging OHS risks.

On the other hand, HF/E and worker's well-being have been brought in to attention during the design of work systems of I4.0 (Kadir, Broberg, Da Conceição Carolina, & Jensen, 2019), through diagnostic tools to investigate digital environments (Richter, Heinrich, Stocker, & Schwabe, 2018), and the necessity for new prescriptive human-centered approaches for implementing CPS (Romero et al., 2016). At some places, assistance of workers by intelligent user interfaces (Gorecky, Schmitt, Loskyll, & Zühlke, 2014), the influence of CPS and HMI on the operation and design of portable applications (Wittenberg, 2016), automatic validation method for HMI displays (Lora, 2017), and design of HMI in the era of I4.0 (Ardanza, Moreno, Segura, de la Cruz, & Aguinaga, 2019) is suggested.

Enabling technologies of industry 4.0 has been successfully adapted by different industries, which has focused on worker safety. In 2013, Hu et al. (2013) proposed IoT technology (i.e., Zigbee) to alarm the operators and managers in mining industry. In the same year, Petracca et al. (2013) proposed wireless sensor networks and RFID technology to improve the safety in industrial plants'. In underground construction sites, Zhou and Ding (2017) suggested the use of IoT technology (e.g., RFID-based location and tracking technology) to monitor hazard energies to generate early warnings and alarms as dynamical safety barriers for hazard energy.

Recently, Kanan et al. (2018) presented an architectural design solution for preventing fatalities in construction sites. They proposed the use of IoT-based autonomous and real-time sensing systems to protect construction workers, prevent accidents by localizing them, and warn site laborers in danger zones. In an other project, Dhason (2018) investigated human-machine interaction in chemical plant to provide correct information to operate and maintenance more safely. In this regard, they used industrial IoT (Beacon) and Cloud technology to increase the operator's awareness about safety issues surrounded by them. However, there is still need for a holistic and practical systematic approach for machine manufacturers and safety practitioners so that the new risk associated with the new technologies and human-machine interaction can be evaluated (Fellmann, Robert, Büttner, Mucha, & Röcker, 2017; Peruzzini & Pellicciari, 2017; Stern & Becker, 2017; Zezulka, Marcon, Vesely, & Sajdl, 2016).

The previous studies on OHS have already accentuated the enabling technologies of I4.0 to leverage the OHS management system. A collection of non-negligible assets and primary key enabling technologies such as the cyber-physical systems (CPS), Internet of Things (IoT), Cloud Computing (CC), Big Data are required in the framework to address the identified concerns in the safety of machinery properly (Danjou, Pellerin, & Rivest, 2017; Hermann, Pentek, & Otto, 2016b; Lu, 2017).

2.2.4 Communication levels and data exchange

Lee et al. (2015) proposed simultaneous data acquisition from the physical world (i.e., SWEs) and informal feedback from the virtual world due to advanced connectivity in CPS. In the ICT system, CPS is defined as an infrastructure that interconnects several physical entities with the computational systems to bring self-awareness to interconnected devices and improve new system capabilities, as shown in Figure 2.7 (Podgórski, Majchrzycka, Dąbrowska, Gralewicz, & Okrasa, 2017). Intelligent data management is one of the main functions in CPS, which ensures the capability of data analytics to builds the virtual world. Besides, they have presented the sequential workflow 5C architecture to build a CPS, see Figure 2.8. This architecture has five levels, as bellow,

i. *Smart connection level*: to obtain precise, consistent, and various types of data from the entities such as machines, processes, etc. via direct measurement from sensors and controller.

ii. *Data-to-information conversion level*: this level enables self-awareness to machines by converting acquired raw data to the useful information by applying several data cleaning and data mining tools and techniques.

iii. *Cyber level*: with a massive volume of gathered information at this level, we can form the machine network that helps to exploit more information for a better understanding of the status of each machine in the physical level. Besides, this valuable information allows the comparison among the new and historical information to predict the future behavior of the machinery.

iv. *Cognition level*: in this level, the gathered information about the monitored system is converted in to the knowledge so that experts can make better decisions by observing the comparative information and status of machine, and process through appropriate infographics interfaces.

v. *Configuration level*: the decisions made in the previous level based on acquired knowledge return to the physical level in the form of corrective and preventive decisions in order to make machines self-adaptive and self-configure.

CPS makes industry 4.0 possible by providing the necessary foundation for creating industrial IoT through advanced ICT.

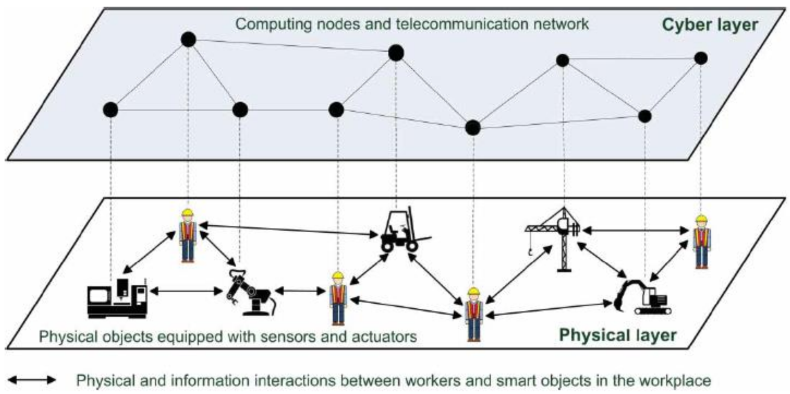

Figure 2.7 Graphical visualization of CPS infrastructure in the workplace (Podgorski et al., 2017)

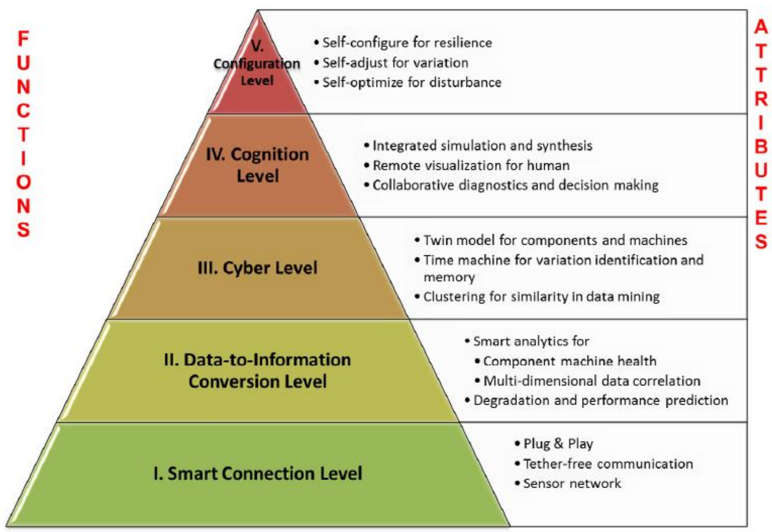

Figure 2.8 The 5C architecture for the implementation of CPS (Lee et al., 2015)

The IoT links CPS to the Cloud, the data can be stored and computation activities can be implemented (Kagermann et al., 2013). An IoT system comprises of some functional blocks to achieve its innovative desired applications. These functional blocks include: Sensing; objects in a system must be able to communicate, Identification: everything within the system should be able to identify itself, and Communication: objects need to communicate with each other (Alam, Vats, & Kashyap, 2017).

In the era of digitalization and connectivity, IoT enables various interactions between machines and humans to transfer data and provide vertical, horizontal, and end-to-end integration of exploited information and knowledge. These kinds of interconnections enable devices/objects to observe, identify and understand a situation or the surroundings without being dependent on assistance from human and to improve the effectiveness of management and the relationship among producers, end-users, and suppliers in Industry 4.0 (Tao, Cheng, Da Xu, Zhang, & Li, 2014; Thames & Schaefer, 2016).

The classification of IoT elements/components for seamless connectivity is the hardware, middleware, and user visualization. Hardware includes communication devices such as sensors, actuators and embedded devices. Middleware provides a platform and various tools for data storage, data processing, and data computation. User visualization helps end-users to monitor and control different events to facilitate different data visualization and interpretation tools accessible on various platforms driven by the collected data via hardware devices in time-based intervals (Sharma, Kumar, & Mehta, 2018). Moreover, with Cloud and Big data technologies, abilities of IoT can be expanded.

2.2.5 Data access and data treatment

In general, Cloud is a technology with a robust, ubiquitous platform over the web that provides a required computing infrastructure for different IT services and computations applications. Cloud's characteristics have significantly alleviated it from other hosting services due to certain characteristics such as (i) usage time or subscription trades on demand, (ii) flexible time and amount of service, which is under the user's control, and (iii) computer and internet access for the users (Liu & Xu, 2017). Cloud computing provides the computation capability and access to the data and IT resources (Haghighat, Zonouz, & Abdel-Mottaleb, 2015).

In the industrial sector, these capabilities are pivotal due to considerable numbers of assets, particularly in manufacturing industries with a significant stream of data from physical entities through the networked sensors. For this purpose, industrial Cloud technology offers computing resources and data integration to provide a data-mining platform. Meanwhile, due to a persistent volume of data generated by sensors and machines, Big Data is required. It is believed that there is a special interdependent connection between the Cloud technologies and Big Data techniques, in which they become useless without each other (Drath & Horch, 2014). Moreover, Cloud supplies the required storage capacity for Big Data analyses to convert the captured raw data into valuable information (Rojko, 2017).

Big data refers to a large number of data generated by interconnected physical devices. Likewise, data exchanged among integrated machines, humans, embedded systems, and processes in the physical world is known as Big Data (Lee, Lapira, Bagheri, & Kao, 2013). Data can be converted in to knowledge and intelligence. For making a more reliable decision, experts need accurate data. Therefore, it is not far from expectations that data would become the essential possession of human society (Bughin, Chui, & Manyika, 2010).

In smart factories, a significant growth in data generation and data collection has been observed which rely on Industry 4.0 enabling technologies. The reason behind this continuous generation of high volume data is the recent growth in the use of high-tech and inexpensive sensors, networked machines, data acquisition systems, and reliable communication networks (J. Shi, Wan, Yan, & Suo, 2011). Big Data has introduced several features such as data storage, data analysis, data mining (Gil & Song, 2016).

On the other side, Big Data has offered numerous capabilities for different sectors. For instance, novel models of accident causation and prediction (Al-shanini, Ahmad, & Khan, 2015), big data technology-enabled risk management and accident emergency equipment (Ouyang et al., 2018), coal mine safety (Abou El-Nasr & Shaban, 2015), traffic safety (Q. Shi & Abdel-Aty, 2015), healthcare (Batarseh & Latif, 2016), material warehouse (Huang et al., 2018), and rail industry (Walker & Strathie, 2016). Moreover, OHS can benefit from Big Data to decrease human or machine errors to avoid/reduce accidents by capturing and analyzing more SRD (Batarseh & Latif, 2016; Walker & Strathie, 2016). In general, safety science significantly needs a systematic approach for collecting and storing of high-quality SRD to make reliable safety decisions and carry out a risk assessment (Huang et al., 2018; Q. Shi & Abdel-Aty, 2015; Wang et al., 2017b).

In this chapter, safety of machinery, the machinery-related accidents, limitations and problems in connection with the process of risk assessment, and the importance of safety-related data for risk assessment practitioners was investigated. The loopholes associated with risk assessment that were identified are: y (i) Inadequate consideration of safety aspects into early design phases of machinery; (ii) Lack of a systematic risk assessment; (iii) Lack of appropriate communication between machine manufacturers and machine end-users; (iv) Lack of individual(s) machine safety experience/knowledge. At the end of Section 2.1, it is concluded that there is a need for a systematic approach to sufficiently connect machine designers/manufacturers and machine end-users to each other in order to exchange the most up-to-date SRD and SRK. This knowledge can help risk practitioners to carry out a more realistic machinery risk assessment.

Accomplishing the first part of this study, the key enabling technologies introduced in the era of digitalization and connectivity were investigated which could help in fulfilling the current research gaps. Therefore, literatures on research about OHS was included and reviewed that have benefited capabilities of these technologies such as use of CPS, IoT, etc. to improve the safety aspects. It was known that how these technologies were utilised to capture data from shop floor on smart connection level, analyzed it to exploit actionable knowledge and valuable patterns by experts' judgment, and then exchanged it by using the cloud technology.

However, despite all enabling technologies and their capabilities, there is little evidence about the existence of data model, technical solutions, structure compensating and appropriate communication between machine manufacturers and machine end-users. Besides, there is little evidence on methods to acquire the required SRD for risk practitioners in order to have a more realistic risk assessment to improve safety of machinery and consequently to improve the safety of workers operating and maintaining machines.

Aiming at this, the use of CPS, IoT, and Cloud technology is proposed to pave the way connecting machine designers and machine end-users in order to identify the sort of SRD and way it could be gathered and exchanged between these two engaged parties.

CHAPTER 3 OBJECTIVES AND METHODOLOGY

3.1 Research gap

According to loopholes as highlighted in the chapter 2, it is very well known that the main important problem is the lack of appropriate communication between machine designers/manufacturers and machine end-users. As a result, machine designers and end-users are restricted to properly exchange SRD and experienced feedback to exploit SRK. This also results into two additional problems of lack of systematic risk assessment, and lack of individual(s) machine safety experience/knowledge. Aiming at that, to overcome the problems and fulfil the research gaps, the main purpose of this study is to answer questions on two important issues on "data exchange" and "safety knowledge" as below

1. How to provide the required safety knowledge for the process of machinery risk assessment?
2. How to exchange data between machine builders and machine end-users to enhance connectivity and to keep the risk assessment process up-to-date and practical?

The study will focus on each identified problems however, due to some certain technical constraints the lack of inadequate consideration of safety aspects into design phase shall be excluded. Moreover, it will be illustrated as a mandatory part of the whole process of machine design. This is mainly due to the fact that each machine manufacturer adopts to its design and manufacturing process with different design methods and approaches. However, for more information, there is a comprehensive study available in the area of integrating safety aspects into the design phase of the manufacturing system conducted by Sadeghi et al. (2016).

3.2 Research Objectives

In order to answer the raised research questions, the objectives of this study are

1. To propose a safety model encompassing the SRD to exploit safety knowledge;
2. To propose a safety management system to exchange SRD and SRK;

3.3 Methodology

Inspiring from the community of practice, the following methodology has been accomplished to address the objectives of this research study, as described below and presented in Figure 3.1.

1. Literature review,

    i. Safety of machinery: first, we investigated the possible reasons that cause significant number of machinery-related accidents. Among different contributing factors, insufficient machinery risk assessment was highlighted. To have a more detailed investigation, International Standard of ISO 12100, technical documents and articles have been carefully reviewed. Based on the review of theses documents, it was known that two groups of machine *designer/manufacturer* and machine *end-user* have a direct contribution on carrying out the machinery risk assessment for having a safer machine. However, inappropriate communication between machine designers and machine end-users, results in ineffective machinery risk assessment where the risk practitioners have no/limited access to the most up-to-date SRD.

    ii. Digitalization and connectivity (i.e., Industry 4.0): to overcome the above-mentioned problem and to propose a generic solution, the concepts and the capabilities of key enabling technologies of Industry 4.0 was studied. In the meantime, the ways of utilizing these technologies as a tool was investigated to overcome the problems in the field of OHS in general and safety of machinery in details.

2. Safety Management System (SMS)

    i. Objective 1: for this objective, we needed to answer a couple of questions such as what type of SRD can be used to collect data from machines and their operators? How do they are correlated to each other? How to integrate them into the process of machinery risk assessment? And so on. To answer these questions, we first needed to define different tasks for accomplishment of a working procedure. Hence, two tasks of *Technical* tasks and *Socio-technical* tasks were defined which required *Object* (Machine) and *Subject* (Worker). Then, according to the requirement of

ISO12100:2010, we have proposed a knowledge-based Safety Model to demonstrate what are the required SRD and how to correlate them for carrying out a more efficient machinery risk assessment.

ii. Objective 2: To achieve this goal, we needed to find an answer to some critical questions on; how can we collect SRD from machine and worker at shop floor? How to transmit these data through different layers of CPS in smart factories in order to manage them (i.e., storage and analysis)? How to take actions during the unsafe events and send feedback to safety experts? How to visualize safety knowledge and share them with machine designers/manufacturers? How to receive recommendations and feedback from machine builders? Etc.

For this part, we have presented an approach that demonstrate how raw SRD from the physical level can be gathered (i.e., shop floor) of machine end-users where it can be further transmitted to the machine designers/manufacturers through a cloud-based platform (i.e., PaaS). This model facilitates an appropriate real-time communication between machine builders and machine end-users.

3. Implementation process,

Before the proposed solution can be provided, there is a need to change approach from an industrial case study to a scenario-based case study. This was mainly due to restrictions imposed for COVID-19 pandemic. For this purpose, an industrial machine has to be acquired in which it should (i) have different functions to facilitate representation of different regular tasks on it (e.g., productions task, service/maintenance task, etc.), (ii) have different sources of hazardous energies (e.g., mechanical, electrical, etc.), (iii) be equipped with a PLC for the purpose of data exchange, and (iv) have different safety devices. The machine is assumed to have all three specifications to fulfill the requirement of this scenario-based case study. On the other side, machine operators need to be equipped with safety devices to enable their safety practitioners to locate and to identify them for further actions such as sending location-based information or alerts.

4. Explanation process:

A developed scenario-based case study has been presented to explain the functionality of the proposed safety model so that any probable pitfalls in the model can be highlighted and corrected. Through this process, all the required SRD from both machine and operator have been presented. Moreover, different elements and phenomena such as dangerous zone, dangerous situation, and dangerous event beside other elements have been demonstrated. Finally, the process of intelligent risk assessment has been represented.

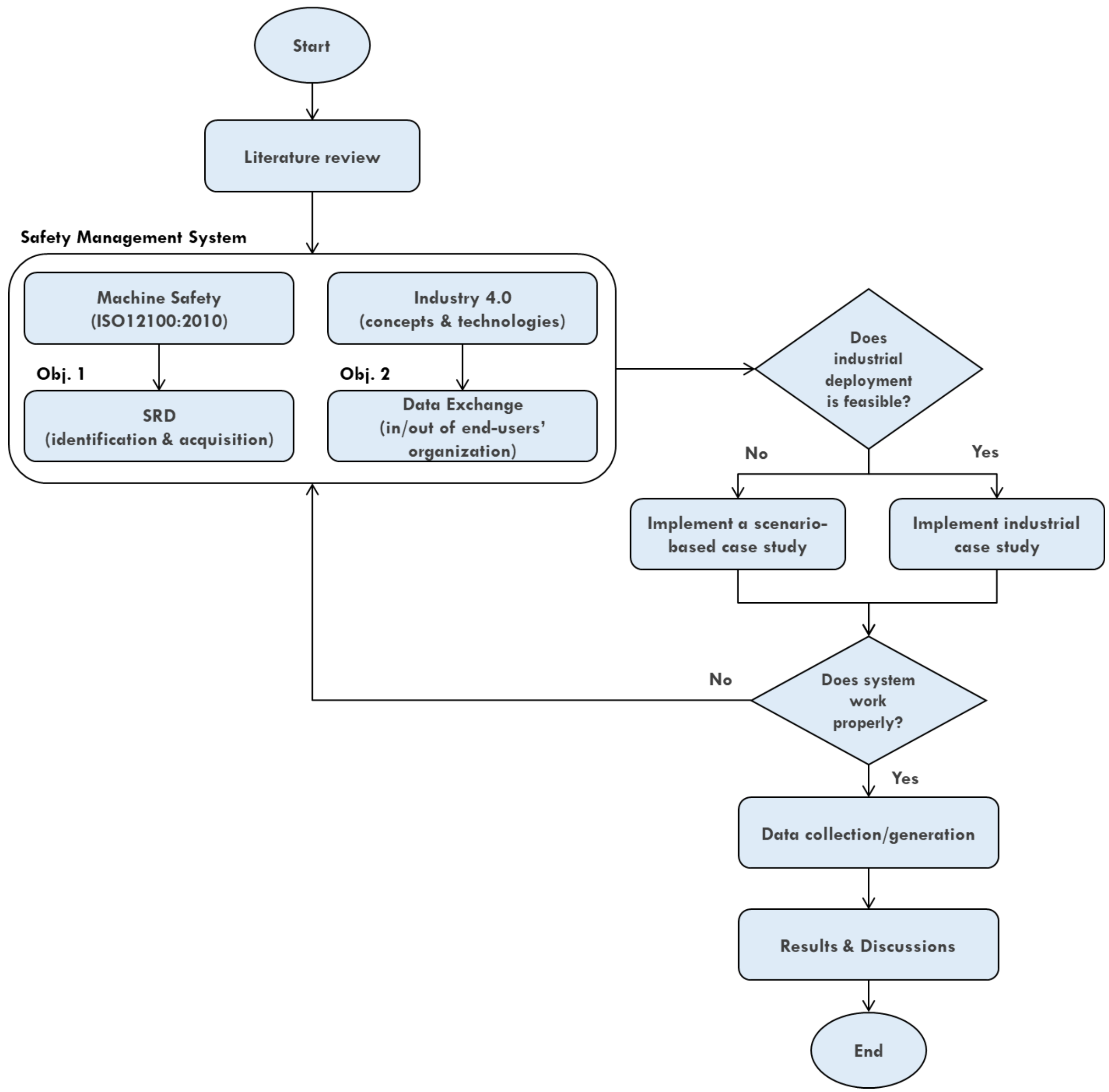

Figure 3.1 The methodology of the study

CHAPTER 4 PROPOSED APPROACH

The review and analysis of the literature has resulted in the identification of problems in the field of safety of machinery. As discussed in Section 3.1, to propose a solution for two important identified issues on "data exchange" and "safety knowledge", first in section 4.1, we will propose a Safety Model to identify the sorts of SRD required to acquire from end-users side and how they are correlated to each other to be used for implementing an intelligent risk assessment. Then, a Safety Management System (SMS) approach is proposed to conceptually illustrate how raw SRD becomes SRK and how it will be transmitted from end-users side to the machine designers/manufacturers and vice-versa. It will be explained in section 4.2. Finally, a scenario-based case study is developed to demonstrate how the proposed solution can function.

Our proposed solution is developed based on adapting of the following four characteristics delivered in the research work of De Galvez et al. (2017).

- Generic: It should be applicable for various types of risk and so that it can be used in different design approaches;
- Inductive: It should consider real working situation that machine operates in order to determine active and latent hazards;
- Dynamic and traceable:, In order to allow a dynamic interaction between machine designers and end-users in real-time as well as to observe and analyze the evolution of safety raw data to the safety knowledge during machine lifetime; and
- Integrated and/or compatible with current design tools and methods to ensure interoperability.

4.1 Safety model and its elements

Before a safety knowledge is made, a knowledge-based safety model is designed with its generic classes that represent the sorts of SRD required and how they can be correlated in order to enable safety practitioners to carry out a more realistic risk assessment. The hierarchy of risk assessment introduced in ISO12100 (ISO, 2010) is considered as a foundation for identifying the relevant SRD in the proposed safety model. Likewise, some other resources such as occupation safety regulations, reports, peer-reviewed academic papers, and best practices were also reviewed and investigated. From these the working situation model (MORA) presented by Hasan et al. (2003), Technical tasks and Socio-Technical tasks denoted by Houssin et al. (2010), RAMIRES model, and MAPE-K loop proposed by Teimourikia and Fugini (2017) were considered. In the safety model, it is required to define the concepts related to Working Procedure (tasks), Object (machines), Subject (workers), and intelligent risk assessment, as presented in the following sub-sections.

4.1.1 The concept of "Working procedure"

The working procedure consists of different tasks to fulfill. The "Task" concept comprises of Socio-technical tasks and Technical tasks (Houssin et al., 2010). The "*Technical tasks*" are automated ones that fulfill at least one system – i.e., machine (object) – functions to be accomplished. Therefore, it is needed to know at least two characteristics of a machine's name and its functions allocated to the technical tasks, as shown in Figure 4.1.

On the other side, the concept of "*Socio-technical tasks*" refers to non-automated tasks that necessitate Subject's (worker) intervention to execute them. In order to perform these tasks in an intervention mode presence of workers is compulsory. The intervention mode refers to as regular operation, maintenance mode, repairing mode, setting-up mode, unjamming mode, manual mode, inspection, and troubleshooting mode,. The operators' trade and their position can characterize the socio-technical tasks and perceive whether a qualified worker is in a safe zone of a machine during the intervention period.

Some of these tasks would engender multiple dangerous phenomena, which might cause risks to the machine and its operator during their interventions and would trigger automatically. Hence, in this study, the types of tasks from the risk practitioner's perspective, which affect machine operators' safety or are necessary to be recognized once the machinery risk assessment is carrying out are considered. Some details on attributes considered for Object (machine) and Subject (worker) will be presented as follows.

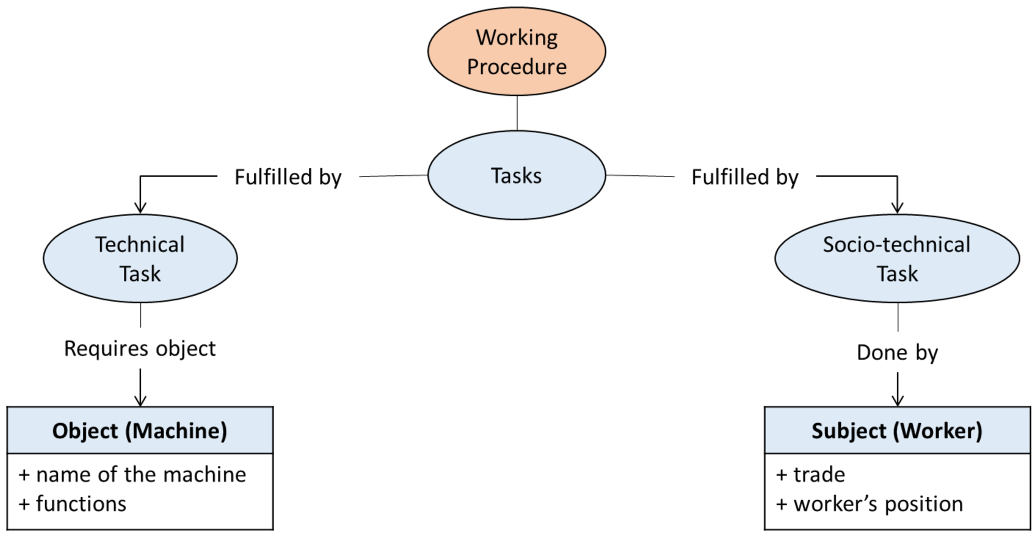

Figure 4.1 Technical and Socio-technical tasks

4.1.2 The concept of "Object – Machine" and "Subject – Worker"

Human intervention with "*Object – Machine*" in the working environment is inevitable. Workers have interventions with a machine to conduct primarily socio-technical tasks and conduct regular or emergency maintenance activities. Another important concept in our knowledge-based safety model is "*Subject - Worker*," which addresses machine operators or workers in the SWE, as depicted in Figure 4.2.

Machines have some limits that could affect their regular operation due to their failure, defects, poor design, and inadequate maintenance presented in the "*Machine Limits*" class. Therefore, three sets of data properties are required for the class of machine limits that include, data on user's intervention needed by machine's malfunctions, the anticipated level of user's qualification (e.g., operators, trainee, maintenance personnel, or technicians) to accomplish this intervention (ISO, 2010), and the user's misuses (i.e., use of a machine in a way not intended by the designer).

Another attribute is the "*Dangerous Zone*" of the machine, which defines any zone inside or around a machine when a worker is exposed to as a risk of injury or health damage. Machines might contain various dangerous zones in which two properties of their name and their origin need to be seen appropriately.

In this zone, a different "*Hazard*" is associated with the machines that might engender an injury or damage to the user's health once a worker is in the machine's dangerous zone during his/her intervention. The hazard represents any incident that is capable of causing an injury or damage to the users' health during their work in the working situation. Here, hazard has three attributes: the name of the phenomena (e.g., moving parts of machinery, hazardous shapes, potential energy, live machine components), type of energy (e.g., mechanical, electrical, chemical), and the number of affected workers to that hazard are considered. Having more knowledge about these attributes could help the safety practitioners make optimal decisions to apply the best corrective measures.

Moreover, the so-called "*Dangerous Situation*" is when a worker gets close to a hazard or a dangerous phenomenon in which it might engender a "*Dangerous event*." A dangerous event can cause harm to workers during their intervention. Dangerous event contains different properties to make this event clearer such as the event's name, frequency of occurrence, the associated dangerous situation, and its probable damage to the worker. Figure 4.2 illustrates all the classes mentioned above in their properties in the knowledge-based safety model.

The class of "*Mode of intervention*" must be considered depending on the tasks that the machine's operator needs to accomplish. This class deals with four properties that need to be classified and documented regularly. It consists of the name of the mode, frequency of required intervention, duration of this intervention, and possible incentives to bypass or manipulate safeguards and protection devices during this mode of intervention. They might make mistakes, misuse machine, ignore or forget to apply safety procedures.

Another important concept is "*Users qualifications*." The required properties associated with this concept are training and experience about safety aspects and intended socio-technical tasks. However, other properties such as their organizational roles, safety PPE that are currently being used could be added to present properties (Teimourikia & Fugini, 2017).

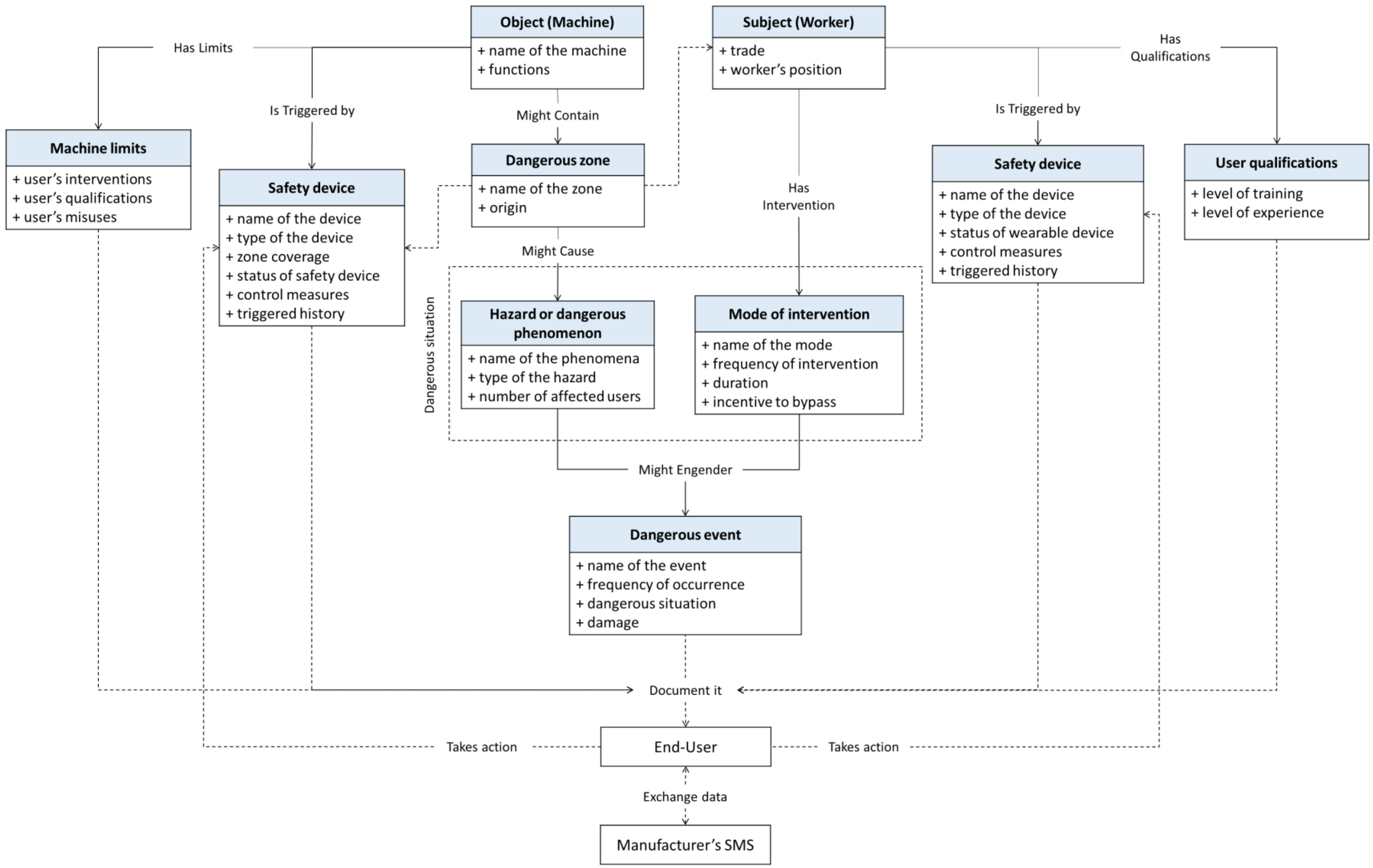

Figure 4.2 The concept of “Object” and “Subject” in the safety model

This safety model targets those machines and their operators in the SWE that are equipped with safety sensors and actuators with wearable safety devices, respectively. This knowledge-based safety model will facilitate SRD acquisition, monitor the working environment, and execute appropriate emergency actions. For instance, stopping of the machine or reducing the operational speed, alarming of the operator, or sending of the appropriate safety precautions once the operator/worker is in a machine's danger zone.

Hence, the class of "*Safety Device*" is necessary to be considered for both machine and operator. For machines, this class consists of the name, type, status, and zone coverage of the safety devices. The Embedded safety device class covers the history of triggered events and the control measures for the safety devices installed on a machine. For the machine's operator, these devices help in keeping them safe and far from hazards associated with the machine through generating the warnings.

Finally, end-users document the SRD in order to use them for further actions and to send them to the Manufacturer's SMS. Safety practitioners can utilize this SRD to have better monitoring capabilities in their existing working situation. More importantly, analyzing of these data will help them in making better data-driven safety decisions and carry out a realistic risk assessment based on the actual working situations that machines and their operators encounter in the SWEs.

4.1.3 The concept of "Intelligent risk assessment"

The concept of "*Intelligent risk assessment*" has the potential to improve the safety of machinery. In this section, both machine designers/manufacturers and machine end-users can independently use the risk assessment tool according to the hierarchy of machinery risk management introduced by ISO 12100 (2010),. They can use the available SRD to exploit SRK or utilize the knowledge shared by other party. As presented in Figure 4.3, the first step in performing this concept in the hierarchy of risk management is the determining of the machine's limits to find the hazards and the associated risks with them during the machine's operation.

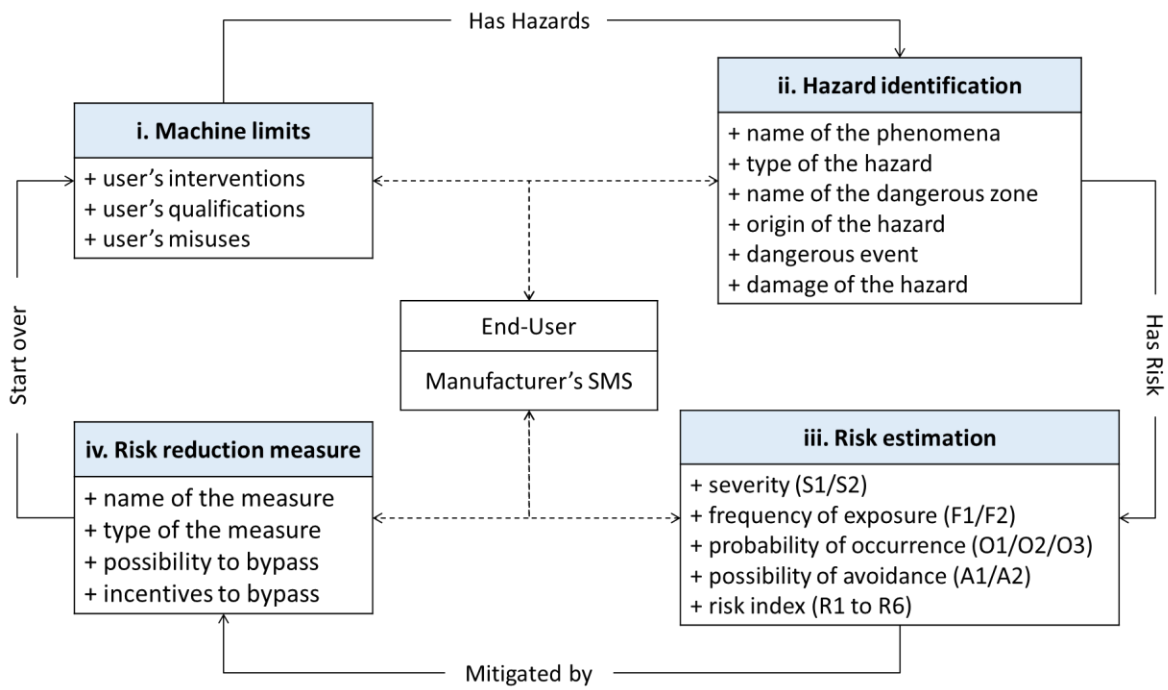

Figure 4.3 The concept of "Intelligent risk assessment"

Firstly, the "*Machine limits*" has to cover the whole lifecycle of the machine to discover when human interacts (e.g., operation, maintenance activities, interventions) during different statuses of the machine (e.g., regular operation, malfunctions due to failure, design errors) and their unintended behavior or reasonably misuses of the machine. The range of coverage must include employees, machine operators, and other workers where there is a chance they use the machine. Therefore, three properties of the user's intervention, user's qualification, and reasonably foreseeable misuses need to be considered.

Meanwhile, the most up-to-date SRD and experienced feedback of the machine operators will help safety practitioners to understand how operators interact with the machines. Besides, it helps to understand whether machine operators have experienced any sort of limits. These limits are concerning; (i) the usage of the machine; (ii) the allocated physical space for a routine operation, maintenance, and range of movement of movable parts of machinery; and (iii) the expected lifetime of the machine to see whether the maintenance intervals and cleaning tasks have been appropriately considered.

Therefore, if certain safety aspects are appropriately taken into account at the early stage of the machines' design phase, the machine can be designed safer. Likewise, it can help the end user's safety practitioners to provide a safer working environment for workers.

The next important step in the iterative process of intelligent risk assessment is "*Hazard identification*." Ideally, once the machine limits were recognized, all the hazards associated with them can be identified. However, lack of safety knowledge about machinery and human interactions might place some pitfalls in this process. It becomes incomplete when safety practitioners cannot see the risk and cannot eliminate or reduce it to an acceptable level. Therefore, all the hazards, dangerous phenomena, dangerous situations, and dangerous events must be described and seen within the hazard identification process. Some properties in this concept are the phenomena's name, its type, its origin, its relation to any specific dangerous zone, its dangerous event, and finally, the damage of that in case of happening. Then, safety practitioners can use their own or the shared safety knowledge to better estimate the risk elements under the concept of "*Risk estimation*" associated with the identified hazard.

The following important concept is the estimation of "*Risk estimation*," which has four parameters as defined in ISO 12100 (2010) and are associated with the hazards or dangerous phenomenon, as showed in Figure 2.1. We also use the risk graph introduced in ISO/TR 14121-2 (2012) in this study, as illustrated in Figure 2.3. The known risks need to be mitigated or eliminated by applying the best available "Risk reduction measure." As mentioned in Section 2.1.3, these measures start with inherently safe design (e.g., process modifications, selection of alternative shapes and materials) during the early stages of the machine design process with the highest impact on the risk's magnitude to measure with the lowest impact (e.g., training, information for use, PPE). In this concept, there are some properties, namely, the name and type of the controlling measure, the possibility of bypassing the applied control measure, and incentives to bypass. The last two properties help to keep the selected control measure as practical as possible.

Meanwhile, the Manufacturer's SMS contains all necessary statistics about all the above mentioned properties that have gathered from different SWEs. Besides, it also helps the safety practitioners on the end-user's side to get benefitted from all updated SRD to make better safety decisions based on their acceptable safety level.

4.2 Safety Management System (SMS)

The proposed SMS approach through research study provides a systematic loop to engage machine designers/manufacturers and machines' end-users in SWEs. As illustrated in Figure 4.4, there are four segments that include Machine end-users, Machine designers/manufacturers, cloud-based platform (i.e., manufacturer's SMS), and the intelligent risk assessment.

Machine end-users capture raw SRD on a real-time basis from their physical level (i.e., shop floor) and transmit it to safety practitioners on the cognition level through the gateway level. The stored SRD/SRK and experienced feedback that is streaming from various machine end-users with different types of equipment and safety cultures on manufacturer's SMS will allow machine designers to have a more realistic perspective of different situations that their products encounter.

Machine builders can also analyze all the shared data to increase their safety knowledge and to integrate more adequately safety aspects into the design phase of machinery. Likewise, machine builders are also able to share their own exploited knowledge and their RRMs with machine users.

Between two main actors, an "Intelligent Risk Assessment" can be used independently by each party using captured and exchanged SRD/SRK and experienced feedback. Consequently, the intelligent risk assessment will be more realistic by taking into account the latest and most up-to-date SRD to select a more appropriate and tailored RRMs, instantaneously.

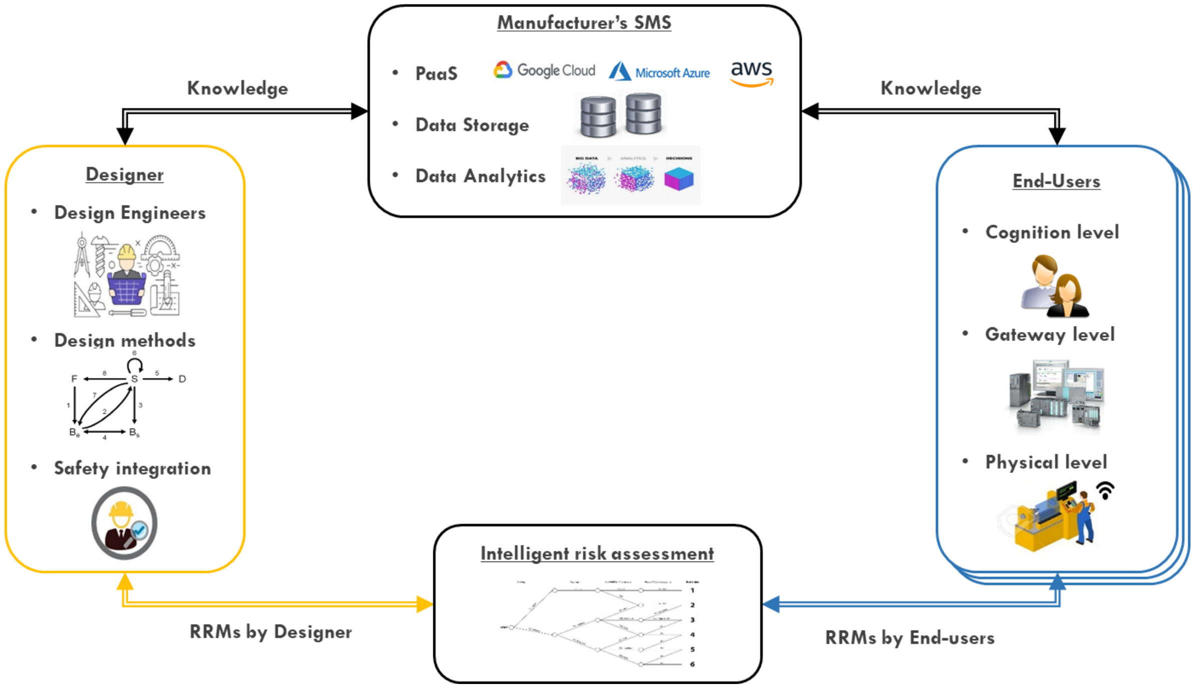

Figure 4.4 The architecture of the proposed systematic safety management system (SMS)

Considering the earlier descriptions given to the intelligent risk assessment in the Section 4.1, the other segments are defined in this section in more details, which require more clarifications, particularly the segment that is allocated to machine end-users.

4.2.1 Machine End-Users:

As shown in Figure 4.5, the end-user segment has three main levels of physical (smart connection) level, gateway (data-to-information) level, and cognition (information-to-knowledge) level, inspired from the 5C pyramid model proposed by Lee et al. (2015). The participation percentage of human intervention and computer programmability in making instant safety decision varies at each level. Where human intervention has its lowest percentage at the physical level and the highest one at the cognition level.

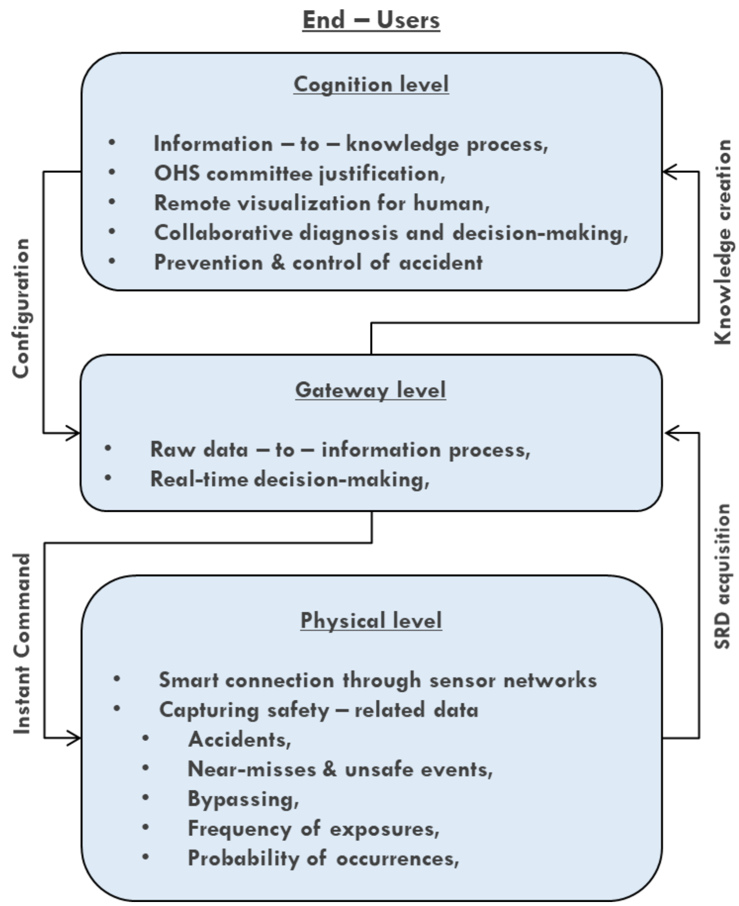

Figure 4.5: Data exchange process within the end-users side

- Physical level:

This level mostly represents the operative part of this approach. In this level, the working situation is under observation to capture any SRD on some critical systems, here, machineries. Here, SRD includes but is not limited to unsafe events, accidents, frequency of exposure, human intervention. To do so, in smart factories, the machines are equipped with smart safety sensors to capture an unsafe event, do the programmed reaction while sending the feedback to the upper level for further consideration on that specific event, and receive commands through Programmable Logic Controller (PLC).

Besides, the location and identification of operators are recognizable for the system in order to have relevant data of any unsafe human intervention or presence in the dangerous zone using various technologies such as RFID tags and readers, wearable devices, etc. In this level, human involvement is low, while, a computer programmed embedded sensors and actuators have higher capabilities on sensing and implementing orders coming back from gateway level to control unsafe events and activities, respectively. Through the wireless sensor networks (WSNs), SRD are acquired from the physical level and transmitted to the gateway level on a time-based interval.

- Gateway level:

The capability of controlling system with a decentralized decision-making on a real-time basis, primary data analytics process and physical level monitoring are important characteristics at this level. In case of occurrence of any unsafe condition, the appropriate command will be instantly sent to the actuators to stop machine's operation or to alarm the operators about the available. With the help of IoT and data transition infrastructures, the aggregated raw data will be processed to make "information". The process of data analytics at this level are implementing for classification, sorting, acquiring, conducting calculations, and finally a selection of valuable information (Curtis, Cobham, & Cobham, 2008).

Human and computer systems have almost the same level of involvement in the cognitive process to perform this transformation. According to Laudon and Laudon (2018) "Information is data that have been shaped into a form that is meaningful and useful to human beings."

- Cognition level:

In this level, OHS experts are able to visualize the safety-related information streaming from the physical level as well as the safety-related knowledge shared by other parties on the network level. Hence, safety practitioners can have better analysis on aggregated data to make "safety knowledge." They can benefit from this knowledge to make a more realistic safety decision in order to prevent or control the unwanted accident on the physical level within the best response time.

To obtain safety knowledge at this level, human involvement is highly necessary compared to computer programmability. Based on Chaffey and Wood (2005) knowledge is "the combination of data and information, to which is added an expert opinion, skills, and experience, to result in a valuable asset, which can be used to aid decision making." The created knowledge results in corrective and preventive measures in order to make machines self-adaptive and self-configure.

For instance, some measurements such as redefining the existing safety thresholds, (re)training, modification on working manuals, and so on.

Figure 4.6 illustrates how IoT can help us to capture SRD from the physical level and send it to the upper levels for more data analysis. At each level, gathered data become more valuable compared to the previous level in terms of its importance in the process of making critical safety decisions. At the physical level, either safety sensors or RFID antennas will gather all desired SRD from machines and the operators, respectively. Then, they will be transferred to the Central Unit Process (CPU) through each machine's PLC or RFID readers, respectively. Local operator can visualize the raw data through a Human-Machin Interface (HMI) and send the related information to the cognition level for deeper analysis by OHS committee. Finally, end-users can share their safety knowledge and experienced feedback with machine designers or get advice from them in order to make a collaborative safety decision making through SMS platform, as it was shown in Figure 4.4.

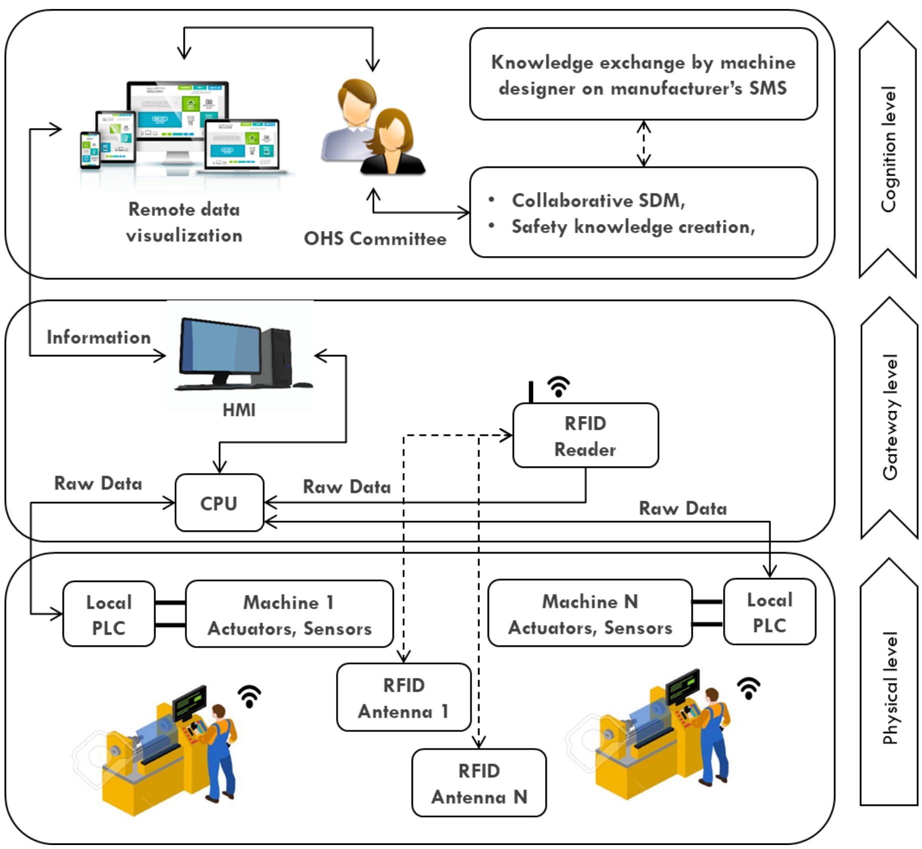

Figure 4.6: From SRD to SRK – End-users side

4.2.2 Machine designers:

On the left side of the proposed SMS, machine designers can benefit from the SRD, the experience feedback, better insight about the actual working situations, and safety knowledge shared by all of their customers to produce safer and more user-friendly machines. Notably, this helps them conduct a more realistic and efficient risk assessment for feature products during the early stage of the machinery design process or any probable corrective measures on the current ones by considering different usage contexts and future user activities. Moreover, machine designers can also share the experience and safety knowledge they have created with their customers based on all feedback to improve the safety of machines and, consequently, safety of machine operators while operating and maintaining those machines.

4.2.3 Manufacturer's SMS

We have explained how machine designers and machine end-users could create SRK and share it with each other. Both parties can connect to the manufacturer's SMS, which is a Platform as a service (PaaS) that can be private for the use of engaged parties. All customers that have bought any machinery from the machine designer/manufacturer can have an access to manufacturer's SMS. This service would encourage the machine end-users for a better cooperation and contribution on providing a safer intervention during machine's normal operation and conducting any service/maintenance activities. Another characteristic of this platform is the capability of data storage in which all data streaming to this online platform would be stored for visualization or further analysis. Data analysis capability is the next module that is necessary to be available on this platform for any data mining purposes such as classification, prediction, prevention, etc.

4.3 Results and Discussion

4.3.1 Selection and development of a scenario

Due to the restrictions imposed by COVID-19 and Pandemic conditions, the following of the industrial deployment of our proposed approach was not possible. Alternatively, the study based on a scenario-based case study with the conditions described in the Section 3.3. (3) was adapted and carried out.

A scenario-based case study on a plastic bag-making machine, as shown in Figure 4.7, as an "object" is developed. This machine has different functions including feeding, cutting, and sorting. Among the possible functions, two socio-technical tasks were selected to cover one normal production task and one regular maintenance activity. It was assumed that (i) the safety considerations were not taken into account during the designing and manufacturing (i.e., poor design and inappropriate conduction of machinery risk assessment), (ii) a worker is newly hired (i.e., lack of experience and sufficient training), and (iii) the equipment is installed between two areas in which a joint circulation is necessary.

Figure 4.7 A plastic bag-making machine

4.3.1.1 A production task

To feed a machine with a plastic roll, a worker needs to intervene with capability to conduct a socio-technical task eight times per shift repeated for two shifts (i.e., 16 times per working day). For each intervention, the worker is required to spend around 20 minutes to fulfill the task. Hence, as presented in Figure 4.8, the worker enters a machine's danger zone to feed it with the plastic roll. The zone between rollers has a danger that can be originated from the convergence of rollers and cause the mechanical hazard, also called in-running nips.

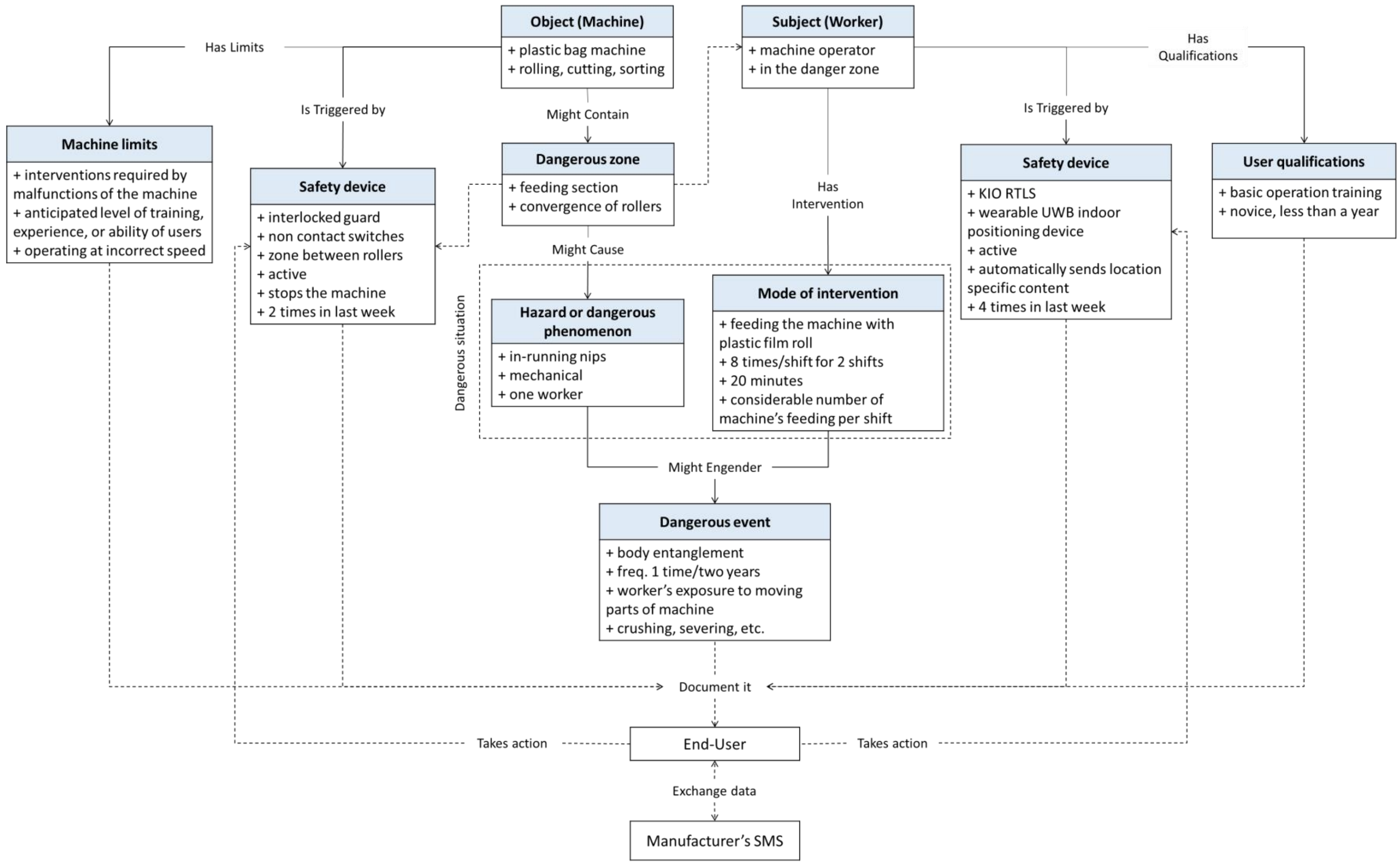

Figure 4.8 The concept of safety model for Production Task

The worker's presence in this zone can engender a dangerous event of body entanglement that could cause a severing or crushing. When the worker is in a machine's danger zone, safety devices could trigger that event and send their information to the upper level through PLC. Then, a programmed action will take place that can trigger to alarm the worker, send location-specific contents, or can stop the machine if required. This SRD includes machine limits documented by the end-user for the organization's safety practitioners' for further actions. Later, the end-user could send these data to the manufacturer's SMS.

On the other side, Figure 4.9 depicts that the intelligent risk assessment starts with recalling the identified machine limits. Meanwhile, machine manufacturers, for instance, realize that a worker with the safety-required qualifications less than what it was expected operates the machine at an incorrect speed or in a different way other than the manufacturer's specifications. To implement an RRM, machine manufacturers might consider in-running nips as a highly probable hazard associated with this machine limit. Installation of a fixed nip guard and safety light curtain – taking into account the incentives to bypass – could be among all-possible risk reduction measures. Other control measures such as automatic feeding or lifting tables to reduce the ergonomic-related risks could be considered. Likewise, employers can provide more specific safety training to the worker or improve their safety audit program. This process will continue to reach the acceptable level of risk for more machine limits or different hazards associated with the machine.

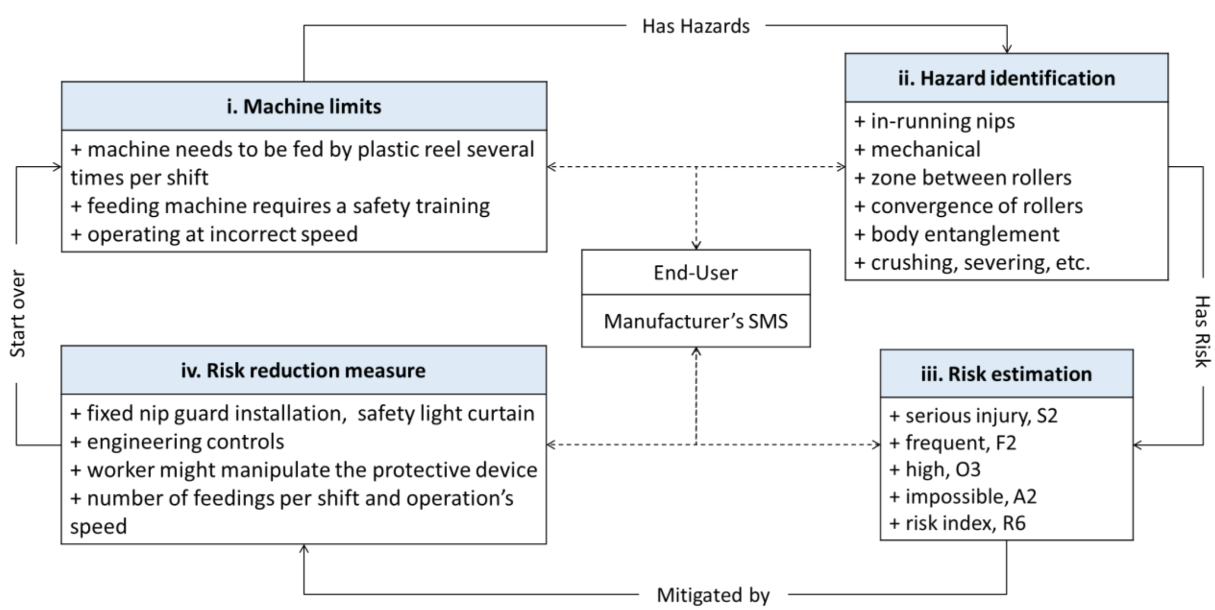

Figure 4.9 Intelligent risk assessment for Production Task

4.3.1.2 A service/maintenance task

In order to service and maintain the machine, a worker is required to inspect, adjust, or replace the cutting beam regularly. To replace the cutting blade, a worker is required to do a socio-technical task on a frequency of three times per week for almost 30 minutes each, as presented in Figure 4.10. However, maintenance activities are not adequately seen during the design phase, and disturb the worker's intervention into the cutting section area to replace the cutting blade easily.

The worker must follow a Lockout/Tagout procedure to prevent the unexpected release from machine's hazardous energies'. This procedure is described in Quebec's occupational health and safety regulation and the CSA Z460 standard about hazardous energies control. However, the worker did not isolate machine power during his intervention. Instead, safety devices have triggered two unsafe events in one week that resulted in stopping of machine. Likewise, the worker gets an alarm due to his presence in the machine's danger zone via his safety device. The SRD shows that the machine movable guard's interlock has been bypassed to facilitate the cutting section's access. Unsafe practices can engender a dangerous event that could result in severing, cutting, or amputating the worker due to moving of hazardous shape machinery. These data will be gathered by end-user and later sent to the machine builder through the manufacturer's SMS.

With the new data on machine limits, machine designers/manufacturers and machine end-users can capture a more realistic view of the working situation and human-machine intervention. On the one hand, the employer will have a better monitoring system and more accurate SRD during the conduction of machinery risk assessment, as presented in Figure 4.11. For instance, they can easily see the Lockout/Tagout procedure has not been followed correctly, which needs to be revised. Moreover, they can provide specific training to the worker, conduct better safety audits, and identify new incentives to bypass and inform the worker of the danger of such practice.

On the other side, machine manufacturers revise the machine design during the implementation of risk assessment where they see if lockout program is not done. Hence, they reconsider the risk associated with this hazard based on new statistics during their risk estimation process. Considering new data on incentives to bypass the movable guard with interlock, they might offer a more reliable interlock, place a local disconnect switch that is more easily accessible, or offer a better solution for maintenance activities.

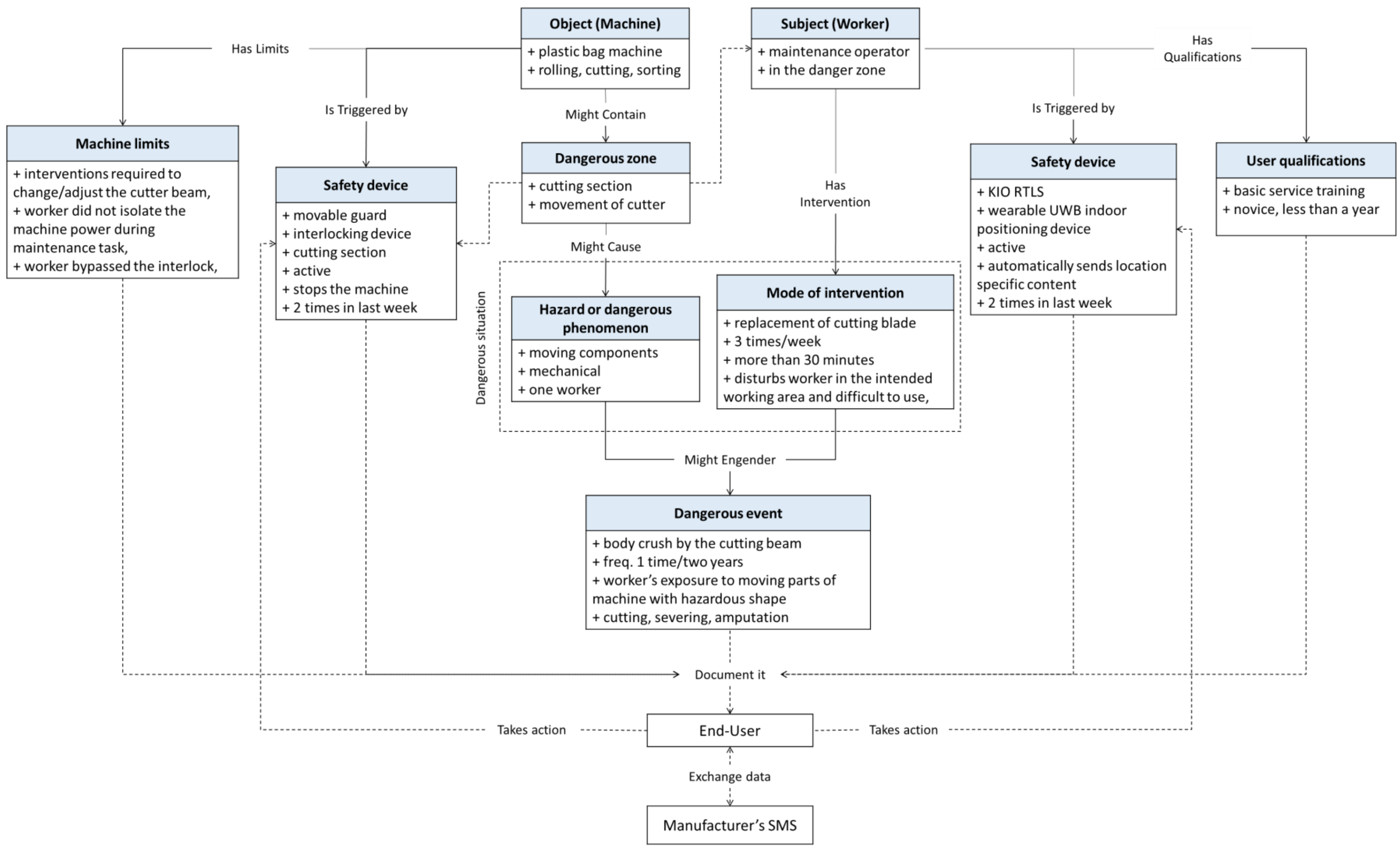

Figure 4.10 The concept of safety model for Maintenance Task

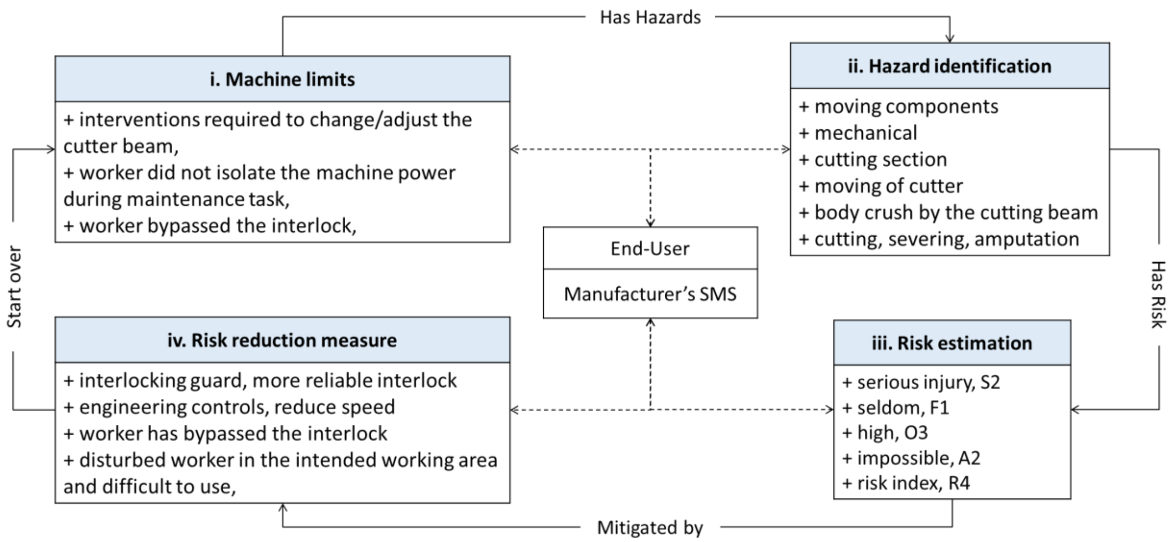

Figure 4.11 Intelligent risk assessment for Maintenance Task

4.3.2 Discussion on the scenario study

In this chapter, a scenario-based case study on a plastic making machine with different operational functions was presented. To illustrate the feasibility of the proposed safety model, two regular socio-technical tasks were selected, which include (i) production task, and (ii) service/maintenance task to explain how the proposed solution can be helpful for machine designers or machine end-users. Likewise, for the SMS approach, the conceptual process of data exchange was presented. In this model, it is shown that how a SRD in a 5C architecture in SWEs can be triggered and sent to the upper levels for knowledge exploitation by OHS justification. Besides, it was demonstrated that how an instant action can takes place. Moreover, configuration level was enabling the safety practitioners to use the exploited knowledge in order to have a more realistic machinery risk assessment for an effective RRM. The proposed safety model identified the sort of SRD required from both machine as an object and worker as a subject if different technical and socio-technical tasks are required to accomplish a working procedure. By adapting this knowledge-based model, machine end-user would be able monitor all the activities around the danger zone of the machine in order to keep the human and machine interaction as safe as possible. Besides, they could find out the latent hazards, incidents, and unsafe events by the help of the correlated concepts as demonstrated in the safety model. By the use safety model, the risk assessment will be more effective and the RRMs will be based on the more realistic interpretation of actual working situation.

CHAPTER 5 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion

Considering the two parties of machine designers/manufacturers and machine end-users in the presented SMS approach, OHS and risk practitioners would significantly benefit from the most updated SRD. The type of SRD and their interaction were well defined in the proposed Safety Model. Machine end-users could capture and analyze the valuable SRD, such as identification of operators and their frequency, duration of exposure to machines' hazardous energies, safeguards status, and possibility of bypassing it to improve the safety of their employees and safety decision-making process. The real-time connection between the main actors on this proposed SMS approach can significantly enhance machine safety. Then, the gathered SRD can be adapted by machine designers so that they can also use and the exploit SRK more effectively to integrate the safety in the early stages of the machine designing processes. They can exploit the actionable SRK independently and share it with each other.

Mainly, machine designers/manufacturers have the biggest contribution on the safety of machinery in which they can design an inherently machine safer by profiting from using end-users' most updated experience feedback. High-quality SRD can be shared on a cloud-based platform – i.e., Manufacturers SMS – to produce machines safer through conducting a sufficient prior machinery risk assessment during the design phase. Likewise, they can return the outcomes of their new risk assessments to end-users in the form of technical solutions, after-sales services while considering their safety cultures, maintainability and reliability of the machines, and other essential factors based on the real need of their customers.

The early safety integration into design phase of machinery or during its operation in the end-users workplaces would greatly improve the safety of workers during their intervention for operating and maintaining the machine. These sorts of interventions are required to fulfil the defined socio-technical tasks. Implementation of this safety model can help to reveal the unsafe work practices at the early stages before any machinery-related accidents take place. The ability to monitor safety aspects in smart workplaces empowers the OHS practitioners so that they can have an efficient control on machines and risks associated with them or manage human-machine interaction more appropriately during the operation and maintenance.

5.2 Concluding remarks

This research work has focused on the available standards, laws, regulations, and peer-reviewed scientific articles in the context of machine safety. A detailed literature review on the contributing factors which cause significant number of machinery-related accidents was carried out. From the literature, it was identified that lack of appropriate communication between machine designers and machine end-users result in insufficient machinery risk assessment. Furthermore, this research work has helped in achieving two objectives to answer the two research questions on “Safety knowledge” and “Data exchange”

Firstly, for the first objective on providing the safety knowledge, we have proposed a Safety Model which helps to define the sort of SRD required and how they are correlated to each other based on the hierarchy of machinery risk management as introduced in ISO 12100 (2010). Then, two important elements of Object (machine) and Subject (worker) were identified that are necessary at workplaces to carry out the working procedure and its allocated technical and socio-technical tasks on the machine end-users’ side.

On the other side, to cover the second objective, we have used the concept of adapting some of the key enabling technologies such as CPS, IoT, and Cloud Technology that have been introduced in the era of digitalization and connectivity. As a result, we were able to propose a safety management system (SMS) approach to define how the safety knowledge can be exploited from acquired SRD on the physical level and how it can be transmitted between machine designers and machine end-users.

For both parties, the experienced feedback and updated SRD can also be used to perform a continuous, systematic comparison of different risk control/reduction options so that the optimal selection among all available RRMs can be made while considering the machine limits, reasonably unforeseeable misuses, hazards and incentives to bypass. Besides, end-users can systematically implement risk assessment once the machine's state has changed due to any modifications on a machine status that might create new risks to machine operators during their inevitable intervention and when the primary risk assessment is no longer acceptable.

In contrast to the existing risk assessment tools, the contribution of the proposed approach to the safety of machinery and its importance is the availability of up-to-date and high-quality SRD from the customers, specific type of machine and also from too many customers with a different variety of machines. Availability of these data could bring valuable safety knowledge for two main actors of machine designers/manufacturers and machine end-users so that more realistic risk analysis and risk assessment can be performed. This feature allows different machines with a wider range of limits and incentives to bypass to get recognized and taken into account when carrying out the machinery risk assessment by relying on this knowledge-based safety model.

The previous researches for this particular problem did not considered these aspects in a dynamic and end-to-end format. As a result, this research study has assisted us to build a more generic model. More specifically, the proposed solution from this research study can help machine builders to consider more appropriate risk reduction measures based on a real working situation that machine encounter, particularly for machine safety. Besides, end-users also can get benefits from the exploited knowledge by machine builders so that more accurate safety decision can be made, preventive/corrective measures can be taken an, new organizational policies can be developed.

5.3 Limitations

Although this systematic safety model proposes different capabilities, however, it comes upon some limitations so that it can be adapted. Some of these restrictions are as follows:

- It is only applicable for smart factories where there are enough resources for implementing this system available;
- Machine operators would require to disable tracking sensors that restrict receiving the alarm or location-based information if their entrance and presence is in the danger zone of the machine;
- There is some possibility that some end-users do not to take advantage of this system specifically those who are disconnected from machine manufacturers and those who have some intellectual property matters.;

- The financial aspect might be seen as a restriction for the deployment of this system for machine manufacturers or machine users;
- Adaption of this feature would require an innovative approach as manufacturers and end-users familiar with the ISO 12100 approach based on qualitative risk assessment and risk reduction based on the hierarchy of control may be less willing to adopt new practices.
- The compatibility of old machinery and new machinery will be a challenge since end-users, especially SMEs, have machines that vary in technology.
- Privacy concerns may arise since workers may feel that they are being monitored continuously.

5.4 Future research directions

This research work can be extended further whereby it

- Implements the solution by involving all parties, i.e., manufacturer, end-user, and OHS specialist. The solution needs to be implemented and tested,
- Defines a data analytics model in the systematic safety management system for the creation of safety knowledge,
- Provides an authentication process on the SMS approach to secure the connection between manufacturers and end-users,
- Design and develop a software-based model with an effective user interface to deploy on an actual case study,
- Propose a more mature safety model by considering more engaged concepts such as environmental aspects with a variety of properties and attributes, and
- Expand the proposed SMS by incorporating additional stakeholders such as safety device providers and standard organizations.

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