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Evaluating the application of augmented reality devices in manufacturing from a process point of view: an AHP based model

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Abstract: Augmented Reality (AR) systems in last few years show great potentialities in the manufacturing context: recent pilot projects were developed for supporting quicker product and process design, as well as control and maintenance activities. The high technological complexity together with the wide variety of AR devices require a high technological skill; on the other hand, evaluating their actual impacts on the manufacturing process is still an open question. Few recent studies have analysed this topic by using qualitative approaches based on an "ex post" analysis - – i.e. after the design and/or the adoption of the AR system - for evaluating the effectiveness of a developed AR application. The paper proposes an expert based tool for supporting production managers and researchers in effectively evaluating a preliminary ex-ante feasibility analysis for assessing quantitatively most efficient single AR devices (or combinations) to be applied in specific manufacturing processes. A multi-criteria model based on Analytic Hierarchy Process (AHP) method has been proposed to provide decision makers with quantitative knowledge for more efficiently designing AR applications in manufacturing. The model allows to integrate, in the same decision support tool, technical knowledge regarding AR devices with critical process features characterizing manufacturing processes, thus allowing to assess the contribution of the AR device in a wider prospective compared to current technological analyses. A test case study about the evaluation of AR system in on-site maintenance service is also discussed aiming to validate the model, and to outline its global applicability and potentialities. Obtained results highlighted the full efficacy of the proposed model in supporting ex-ante feasibility studies.

Key words: Augmented Reality, manufacturing process, multi-criteria, AHP.

1. INTRODUCTION

Augmented Reality (AR) tools have been applied in several industrial contexts as they could provide effective contributions in phases characterizing the product life cycle. In brief, an AR application combines the real scene viewed by the user and a virtual scene generated by the computer that augments the scene with additional information. Several pilot projects have recently outlined that AR systems are now becoming mature technologies for application in manufacturing as well as service systems (Dangelmaier et al., 2005; Chong et al., 2009; Serrano and Fischer, 2007; Ong et al., 2008; Elia and Gnoni, 2013; Novak-Marcincin et al., 2013): one focal point characterizing the information system in a manufacturing plant is to develop an effective and real-time communication between individuals and production departments (Morkos et al., 2012). AR applications are facing this issue aiming to enhance company performance in terms of shorter lead-times and process quality (Consoni et al., 2007, Lu et al., 2013). AR applications - especially ones based on mobile devices – could allow users to interact dynamically by sharing information with and from the real working environment.

Several recent pilot projects focused on demonstrating the applicability of AR systems in different manufacturing processes, such as product design, production planning and control, plant and product maintenance, etc. Even if the technological development of an AR system is based on quite common features, the evaluation of the most effective AR system for supporting a specific manufacturing process is a really complex task, as technical organizational factors have to be assessed in an integrated way. As an example, an AR system for supporting a more effective product design process could be developed based on the same technological equipment (e.g. sensors, dynamic monitor, etc.) of one designed for product maintenance, but, its overall feasibility heavily depends on process specific requirement.

The study proposes a decision support system based on a multi-criteria analysis to support production managers in evaluating most effective AR devices for a specific manufacturing process. The proposed model integrates technological with process based criteria aiming to provide an effective assessment of different factors affecting the AR application in a specific manufacturing process. The reminder of the paper is organized as follows: a brief analysis of recent pilot or full scale applications of AR technology in the manufacturing sector is proposed in section 2: AR applications have been analysed according to a process based point of view, by focusing on the specific field of application in the manufacturing sector rather than on technological issues. The proposed multi-criteria model is discussed in Section 3, and a case study for validating the approach is detailed in Section 4.

2. Applications of AR systems in manufacturing: a process-based analysis

A literature review carried out in the Science Direct database about the application of AR systems in manufacturing, show four main areas of application, such as:

- product design: it refers to the product conceptualization process and its interaction with the manufacturing one;
- process design and planning: it involves both tactical (e.g. technological design of manufacturing process) as well as the operational (e.g. machining programming) level;
- process control: it refers to both the whole shop floor or a single equipment control process;
- equipment or asset maintenance: mainly refers to industrial equipment maintenance.

In the following, each area has been analysed in detail.

In the product design, AR systems have been applied to support a faster and effective design process: using AR technologies allows to develop a semi-immersive design environment where the users (i.e. designers as well as customers) could interact in the real world while performing feature modelling on a virtual product. Based on current recent applications, AR tools for product design could be divided into two main categories (Shen et al., 2010) based on their main functionality: *visualization-based design* and *co-design* systems. The first type provides a full immersive AR-based environment allowing to visualize, inspect and modify the 3D product models collaboratively. By analysing current research projects, the first type aims to support a more participatory design process by involving designers as well as product users/customers; the latter focuses on providing a more collaborative design process especially where the design process is carried out by different and remote contributors.

Some examples, recently proposed by Ng et al. (2010 and 2011), Arbeláez-Estrada (2013) Ng et al. (2010 and 2011) and Lu et al., 2013, developed an AR system to support a more effective participatory design process by directly involving customers. By combining virtual and real objects in the same environment, designers could provide customers with a tool to create, visualize and contextualize objects. Arbeláez-Estrada, J.C., Osorio-Gómez, G., (2013) described a mobile AR-based system, which allows customers to easily send effective feedback to designers; the AR system allows contextualizing in the customer environment product thus improving the overall design process efficacy. Otherwise, co-design systems focus on providing a 3D space where designers can create and modify collaboratively models in the 3D space: the focus is on supporting interactions between multiple and remote users. Multiple users (e.g. members of a multi-disciplinary team, customers, designers) in different locations can work together during the early design stage of a product to reduce the redesign iterations and cost. Ong et al (2009) and Shen et al. (2010) proposed a client/server architecture where multiple users in a distributed environment can create and modify simultaneously product features in a 3D physical space.

Another relevant field of AR technology application is the assembly process: two main phases - such as the assembly Product Design and Planning (PDP) and assembly Workplace Design and Planning (WDP) currently represent the main field of AR application. The first one mainly affects the assembly process design, e.g. in terms of activity and sequence definition; the latter mainly affects work place design and layout. Several studies focused on analysing how AR technologies could support faster product design by introducing simultaneously physical constraints due to workplace layout.

Ong, et al. (2007) proposed an AR system to support a more reliable and integrated assembly design process by manipulating virtual prototypes in a real assembly workplace. The proposed integrates the PDP process with WDP, as actual workplace constraints are outlined through AR technology. A recent update is proposed in (Ong and Wang, 2011): where the authors proposed a AR-based tool characterized by several automatic and reliable interaction features, such as an automatic on-line constraint recognition system - which allows to remove the importing process from a CAD software- and a 3D interface system providing a more realistic visual feedback during assembly.

AR technologies are also applied for optimizing a high resource effort process, such as the sequence design. Makris et al. (2013) discussed the application of AR systems aiming to support both assembly sequence and instruction generations at the final part of an assembly process. The tool has revealed effective for both production engineers and the shop-floor operators. Wang et al. (2013) proposed a two-step decision support system based on AR devices: the first one allows to evaluate assembly sequences based on manual process carried out directly by human interactions; next, precedence constraints are automatically acquired by analysing the disassembly process thus allowing to evaluate feasible assembly sequences.

Another AR application field is in providing reliable and dynamic information to field operators during the assembly process. Yuan et al. (2008) developed a virtual interaction panel based on AR devices to share assembly information to line operators during the process.

Finally, Jiang and Nee (2013) – similarly to the product design process - have developed an AR-based tool for improving the WDP process: authors applied AR technologies for assess layout criteria and constraints based on actual existing facilities aiming to evaluate new facility layout plans.

In the machine programming process, AR systems are mainly applied to verify and optimize machine tool paths: the integration of these technologies within traditional Computer Numerical Control (CNC) simulation systems is a focal research topic. The potentiality of AR application in this manufacturing field is to develop innovative tools for path verification based on AR-assisted in situ simulation systems: thus, these simulation systems have been modified from software-centric (as traditionally ones) to more effective based on machine tool-centric system (Zhang et al., 2010). Weinert et al. (2008) developed an AR system to support the machine tool operator while observing the process from his workplace for reducing collision errors in complex machine programs (such as a five-axis milling). A simulation model synchronized with the real-world machine tool movement provides expanded information to the machine tool operator, who could detect and correct real-time the machine program. A similar system is discussed by Zhang et al. (2010): authors proposed an AR tool providing operators with a simulation path directly on real machines (e.g. a three-axis CNC machine); the aim is to both simulate the process before performing machining operations and to provide real-time and more reliable knowledge for preventing path errors.

Several studies have focused on the use of AR technologies for improving Human-Robot Interaction (HRI) in robot programming and path planning. Chong et al. (2009) discussed the potentiality of AR technologies to reduce effort and time required for programming service robots: authors outlined how AR technologies could be useful for developing "programming by demonstration" approaches for industrial robot programming process. Fang et al. (2012a, b) proposed an AR-based system for simulating interactions with a virtual robot model to both improve operator safety and to decrease effort required for robot programming.

Thus, the literature review has outlined how the AR technology is currently applied to support interactive path planning and training in CNC machine and industrial robots.

By analysing the maintenance field**,** two main contributions could be outlined when applying AR systems in industrial maintenance. Traditionally, several activities are performed following pre-defined procedures provided by paper materials; AR systems aim to improve the information exchange process by training operators in more innovative ways. The first contribution is to support more effective maintenance procedures in harsh environments (e.g. in bad viewing conditions) by providing information from remote. Several papers faced this topic: Wang et al. (2008) and Ziaei, et al. (2011) discussed the contribution of AR systems in supporting maintenance operators in remote handling procedures; the purpose is to both speed up maintenance cycle time and provide safer conditions for equipment maintenance without making physical contact with the object in an indoor environment. Benbelkacem et al. (2013) proposed an AR system for supporting remote maintenance operations in training and assistance services. Thus, through an AR tool, local repairers have the capability to view tasks to be carried out directly aligned on the real working environment.

Other studies are more focused on evaluating the contribution of the AR system in training operators, before and, as well as, during maintenance intervention. Two innovative prototypes have been discussed in Garza et al. (2013) and Fiorentino et al. (2014). The one proposed by Garza et al. (2013) aims to reduce the total training time of maintenance operators by replacing paper training manuals with an interactive environment between the users and the information displayed based on AR technologies. Similarly, Fiorentino et al. (2014) proposed a laboratory study where a complex maintenance process has been carried out with interactive augmented reality instructions. Results have confirmed not only its capability to hasten execution times, but also to reduce errors (due to an incorrect item localization or tool requirement).

Webel et al. (2013) proposed an hybrid AR system integrating simulation and capturing techniques: the purpose is to provide a multi-level training system supporting operators with different functionality, such as distributed web-training, Immersive and Mobile training. By a different point of view, as one of the critical problems characterizing these systems is the high technical competence required (in terms of both hardware and software), Ramirez et al. (2013) have developed a prototype software program supporting the quick development of the AR process for maintenance and training.

This brief framework has outlined the complexity of AR devices together with their high potential applications in the manufacturing field; the analysis have outlined that AR devices are still applied in manufacturing as pilot projects. Consequently, few recent papers have analysed the decision problem regarding the assessment of AR devices (or applications), which has to be adopted according to specific context requirements. Arbeláez-Estrada and Osorio-Gómez (2013) proposed a qualitative multi-criteria analysis to support the design of an AR-based tool for product concept design. Seo and Lee (2013) developed a survey-based analysis to compare functionalities characterizing different AR devices by focusing on usability criteria. A similar approach is proposed in Meža et al. (2015) which have adopted a structured interview analysis to evaluate the adoption of AR systems (developed by the authors) in the civil engineering sector: the analysis aimed to compare usefulness of the designed AR application with traditional ones for building information modelling. This brief analysis outlined a lack of quantitative studies regarding the “ex ante” analysis –i.e. before the technical operative design of the AR applications in the manufacturing process – which could contribute to support researchers as well as practitioners in developing effective AR applications tailored for the specific manufacturing process in analysis.

3. THE PROPOSED APPROACH

3.1 The rationale

The aim of the paper is to develop an effective model for a preliminary evaluation of AR devices, which have to be applied in specific manufacturing processes. The preliminary feasibility assessment reveals as a complex activity when innovative technological systems have to be evaluated: the complexity arises as technological issues have to be merged in an effective way together with process-based metrics (Gnoni and Rollo, 2010; De

Souza et al., 2011; Muerza et al., 2014). The decision problem in analysis is quite complex due to at least two factors:

1) AR tools currently represent innovative systems for manufacturing; the literature review proposed in the previous section has outlined such pilot applications, as full-scale systems are not yet fully adopted. Furthermore, structured reference models for evaluating AR application global effectiveness are quite rare especially in the manufacturing sector. Few recent studies have proposed to apply qualitative approach - mostly based on survey methods – for assessing impacts of AR devices (or applications) in different industrial fields. These studies adopted survey analysis approach after the design (i.e. ex post analysis) of an AR system or the adoption of a specific AR device, thus not providing any preliminary (i.e. ex ante analysis) support to decision maker in these two complex activities;
2) by focusing on the methodological approach, technical and organizational performances have to be integrated in a common decision model as technical capability characterizing each specific AR system has to also be "measured" according to an organizational point of view. Each manufacturing process requires specific capabilities to an AR device or application that has to be assessed not only from a technical point of view, but also from a process point of view aiming to evaluate its actual effectiveness.

Thus, the proposal is based on a multi-criteria approach that allows integrating different aspects in quantitative and effective way. The model is based on a well-known AHP method introduced by Saaty several years ago. It allows assigning priorities to a set of decisional alternatives on the basis of a plurality of criteria. It breaks down a decision-making problem into several levels: the top level of the hierarchy is the main goal of the decision problem; at the bottom, possible alternatives have been introduced. The intermediate levels are the tangible and/or intangible criteria and sub-criteria that contribute to the goal. AHP models have been effectively applied to evaluate adoptions of technological systems at both strategic and tactical level in the manufacturing sector (Yusuff, et al., 2001; Farooq et al., 2012; Lee et al., 2008; Larrodé et al., 2012).

The proposed hierarchy will allow the organizational integration with technological criteria characterizing AR applications: it "translates" requirement of manufacturing processes into technological factors thus allowing to support a more effective decision making process. Thus, the proposed model will allow to integrate different types of expertise (i.e. technological experts in AR applications with manufacturing experts) in a quantitative way, which is essential when innovative IT tools have to be applied in production systems (Lee et al., 2012; Calabrese et al., 2013). Results provided by the model will support practitioners as well as industrial technicians to acquire quantitative and reliable feedbacks for supporting design and/or adoption processes of AR-based systems in manufacturing as specific features characterizing the manufacturing process in analysis will be effectively evaluated by using structured expert knowledge.

3.2 Designing the proposed AHP model

The proposed model has been developed following traditional steps characterizing a typical AHP model, such as: in *step 1*, the specific decision problem is structured; in *step 2*, pair-wise comparisons between criteria have to be carried out to obtain the judgment matrix. Local weights and subsequently, consistency of comparisons have to be evaluated in *step 3*; subsequently, based on aggregation of local weights (*step 4*), alternatives are finally ranked.

Following each step is detailed.

Step 1. The decision problem is to outline by a multi-criteria analysis a ranking of most effective AR systems in a specific manufacturing application: this is the goal in the hierarchical model. Proposed alternatives have to be AR devices: it has to be noted that a wide variety of AR devices could be applied in the manufacturing sector. Thus, main AR categories introduced in the AHP model have been deducted from a recent classification proposed by Nee et al. (2012); the detailed description is proposed as follows:

- *Head Mounted Displays (HMD)*: a display device, worn on the head or as part of a helmet, having a small optic display in front of each eye (or only one eye).
- *Handheld devices*: an interactive device, that can be used with one hand, equipped with both a display and a camera; smartphones and tablets fall under this category.
- *Projectors*: they are usually based on laser or LCD/LED technology allowing to display visual information on real world objects without the need for workers to wear any device.
- *User tracking systems*: sensors (wireless, RFID technologies, etc.) can be used to detect the user's movements. Differently from other AR system categories they are less "comfortable" as they could require bulky hardware.
- *Haptic and force feedback systems*: they are wearable devices providing real-time feedback to the user in an automatic way without requiring an interruption in operator tasks.

All these categories, except the user tracking systems, have been introduced in the hierarchical model; the user tracking systems have been omitted as they represent a wider category of devices supporting often a mono-directional exchange of information without a real overlapping system.

Next, criteria have been evaluated. As defined previously, technological and process performance criteria have been introduced in the model. The first level of the proposed hierarchy is composed by process criteria deducted by a well-known model, the SCOR (Supply Chain Operations Reference), which is a business reference model for analysing engineering processes (Huang et al., 2005). The SCOR model has been widely applied to evaluate key performance drivers in several industries, especially in the manufacturing sector. In the following are the three criteria based on the proposed SCOR framework:

- *reliability*: it is the ability of the AR system to provide information in different ways (e.g. formats), in different contexts (e.g. bad viewing conditions) thus guaranteeing an accurate augmented process;
- *responsiveness*: it represents how fast an AR system is "ready" to provide the augmented process;
- *agility*: it is the capability of an AR system to fit variations caused by users and/or the environment.

Figure 1. The proposed hierarchy

Second and third level criteria have been evaluated based on tactical technological features characterizing a general purpose AR system; these features have been interrelated with process criteria defined at the first level in the proposed hierarchy, which is depicted in Figure 1.

In detail, the "reliability" criterion has been subdivided into three main technological criteria:

- the data format provided through the AR application (defined as *data*): one main feature of an AR device is due to its capability to transfer in an accurate way information; thus, four types of data format have been outlined, such as 2D or 3D image, but also a text or an audio file. It has to be noted that an AR device could provide a combination of these four types of data with different level of accuracy, which will be evaluated by expert judgments in the following step;
- the type of environment where the AR application have to work (defined as *places*): this criterion refers to controlled indoor contexts (e.g. within an assembly plant), outdoor contexts (e.g. in a plant area outside the factory building characterized by standard operative conditions) or extreme contexts which could be both outdoor or indoor contexts with severe operative conditions (e.g. in terms of humidity, presence of dust, etc.).;
- software typology supported by the AR device (defined as *software*). The software is the key element for the combining of real and virtual objects and supporting information registration, and real-time interaction. Four main typologies have been outlined according to Milgram et al. (1994): virtual reality, augmented reality, mixed reality and overlay based tools. The first usually provides a 3D environment where the user is completely immersed which could be extremely useful for training activities in the manufacturing process. On the other hand, augmented reality software integrates the real world with virtual objects, which coexist in the same real world: this capability will allow a more dynamic interaction with the real manufacturing process. A mixed reality tool is a type of software where real world and virtual world objects are presented together within a single device and not in a full-scale environment. It provides an overlapping of virtual with augmented reality. Finally, overlay tools usually generate 2D overlapping of information to the real world thus allowing in a more dynamic and simple way the data transmission for the manufacturing area.

Next, the "responsiveness" criterion has been subdivided into six main technological sub-criteria:

- the way of interaction with the AR device (defined as *interaction*): based on equipment typology, user interaction in AR systems could be vocal or a gesture based interaction (e.g. by touching one point of the device or by physiological feedback). These criteria outline the usability level of the specific AR device in manufacturing;
- the maximum usage time without interruption (defined as *exposition*) characterizing the device: according to most widespread AR systems currently available in the market, two main sub-criteria have been defined, low and high, i.e. respectively less or greater than 15 minutes. These criteria highlight the service level expressed in maximum usage time provided by each AR device, which could become critical especially if a rechargeable system is not quickly available;

- the degree of handiness (defined as *handle*): it refers to the required use of hands during the use phase. Four sub-criteria have been introduced: only one hand free, both hands free, only one hand free with a constraint, both hands free with a constraint. These criteria define the way of interaction between the user and the AR device also highlighting any type of burdens that the device will cause on the workers during its use phase;
- the maximum start up time (defined as *roll out*): two sub-criteria have been introduced, such as respectively less (fast) and greater (slow) than 15 minutes. This value has assumed a target level. The roll out group of criteria outline the speed of the start-up process that could be so critical in such manufacturing processes;
- the gross weight characterizing the device (defined as *weight*): based on current AR products, three sub-criteria have been introduced by evaluating two boundary values, ultra-light, light and heavy. The first one is less than 100 g, the latter is between 100 g and 500 g, the third one has been defined as greater than 500 g. These criteria highlight a sort of portability of the AR device that could become critical in highly complex process tasks e.g. when an high physical effort is yet required to the worker ;
- the allowable operating range of the device (defined as *range*): it could be limited or larger, i.e. less or greater than a threshold value, e.g. 2 meters. These features point out the level of adaptability to complex plant layout of the AR device.

The “agility” criterion has been divided in two sub-criteria:

- the maximum allowable time for data recovery (defined as *access):* two sub-criteria have been defined, short and long, such as less or greater than 1 minute. These criteria outline how the AR device will allow to update information from/to the central system thus supporting a more agile refresh process;
- types of feedback process supported (defined as *feedback*): the AR application enables to automatically acquire, process, and analyse images (image processing sub-criterion) or information (information processing) from the operational field. On the other hand, the AR application could not support any automatic feedback process (manual processing criterion). This group of criteria point out the level of automatic support provided by the AR device.

Third level criteria are the most operational ones, which are strictly related to the technological features of the specific AR devices: thus, they are also strictly dependent on the current technological innovation level. Thus, the model allows to easily update these criteria when new technological options become available.

Step 2. The criteria assessment. After the development of the hierarchical structure, the quantitative phase of the model development has been carried out. Criteria have been compared pairwise at each level with respect to the criteria in the immediate upper level. Next, a preliminary validation activity has to be carried out at each level of the AHP structure aiming to point out inconstancy of such a single judgment. Saaty (1980), proposes to estimate a Consistency Index (CI) which characterizes the comparison (Saaty, 2000) matrix developed at the previous step; it is defined by (1):

$$CI = (kmax - n)/(n - 1) \qquad (1)$$

where the k_{max} is the maximum eigenvalue characterizing the matrix and n is the matrix dimension. Analogously, the Consistency Ratio (CR) parameter could be estimated. Its calculation is in (2):

$$CR = CI/RI \qquad (2)$$

where the RI parameter is defined by Saaty (1977) as the Random Index: it represents the average CI value estimated for 500 randomly filled matrices. Thus, if the estimated CR value is less than 10%, the current matrix could be characterized by an acceptable level of consistency (Saaty, 2000); otherwise, the decision makers should review and revise the pairwise comparisons. Once all pairwise comparisons are proved to be consistent by the CR analysis, the overall actual ranking is available.

Step 3. Results analysis. After evaluating the judgment consistency analysis, several quantitative results are available for the decision makers. Firstly, a quantitative ranking of AR devices assessed based on the estimated goal is provided. Together with the "best" AR devices, additional information could also be provided to the decision maker aiming to assess more "knowledge" about the problem in analysis. One capability is to provide quantitative estimation about impacts of each AR device towards each technological and process criteria and viceversa. Although technological performance could be more easily evaluated, as they are strictly dependent onto the specific AR device equipment, the model also provide rankings based on process based criteria (e.g. the best AR device according to responsiveness criterion) which are usually more intangible to estimate. This information will support a more detailed feasibility analysis aiming to evaluate which AR device (or the optimal combination of AR devices) has to be designed to the specific manufacturing process in analysis.

Step 4. Sensitivity analysis. Finally, a sensitivity analysis could be carried out aiming to point out how different impacts (i.e. weights) estimated for technological as well as process criterion could affect the final solution and related data. Sensitivity analysis will also contribute to outline to decision makers how most important features characterizing the manufacturing process could contribute quantitatively to the AR device assessment process.

Step 2, 3 and 4 are quantitatively discussed in a test case described in the following section.

4. THE TEST CASE

A test case has been developed to verify the feasibility and the potentialities of the proposed AHP model. The test case regards a manufacturing firm producing high technological equipment for railway infrastructures. The company provides innovative on-board controlling and measurement equipment for railways and trains (e.g. brake systems, wheel surface etc.). On-site maintenance activities developed by the firm mainly regard controlling measurement equipment installed on board. These maintenance activities are usually very complex due to several factors: trains during maintenance activities are not fully disassembled to reduce unavailability periods and maintenance costs. Thus, on-site inspections and maintenance processes are carried out in limited spaces and visibility as well as harsh environments: as an example, inspection and maintenance tasks are usually carried out in special depots where several tasks are carried out into a basement below the depot floor train cars. Furthermore, typical tasks (e.g. inspects the undercarriage of train's rail cars) are usually characterized by a high complexity level. Thus, data acquisition is a very hard process due to outlined operational conditions. The firm management is evaluating the possibility to apply AR technologies for improving the overall information management: main purpose is to outline AR devices for supporting a more effective information visualization process from and to the work field by adopting an augmented window on the real operative world.

The four AR device categories have been selected as a potential tool to be applied by the firm for developing their own AR-based solution: haptic and force feedback devices could be used to support operators about how to perform a specific task in restricted spaces, HMD and projectors could provide flexible system for providing operations sequences of maintenance tasks as well as data about equipment. The aim of the analysis is to evaluate how different technological features characterizing each AR device could be "measured" in terms of process based requirements. Thus, the proposed model has been tested in order to support firm managers in evaluating a preliminary feasibility study about applying a specific AR device (or a combination) for supporting on-site maintenance activities supplied by the firm to its customer location.

The specific goal evaluated for the test case is the AHP model has been synthetized in *optimization of data exchange in complex on-site maintenance activities.*

A commercial software tool, Expert Choice ®, has developed the hierarchy described in the previous section. For each comparison matrix, priority vectors and CR parameters have been estimated (see **Step 2**). The pairwise comparison process has been developed by using a quantitative judgments scale starting from 1 (not relevant) to 9 (high relevant). Judgments have been provided by an interdisciplinary team of 12 experts by applying a group decision-making technique for judgments aggregation: the team is composed by university researchers experts in both maintenance and AR technology, and firm managers involved directly in the maintenance service. The assessment process has been developed, at first, by a detailed interview analysis aiming to share basic knowhow about AR technologies (with firm managers) and criticalities characterizing the firm maintenance processes (with university researchers). This preliminary sharing process carried out before interviews has allowed considering the same "weight" for judgments expressed by each expert, even if they have different expertise. Thus, according to Saaty and Peniwati (2008), if the members of a group are all experts with the same level of experience, the geometric mean function could be used to obtain an overall final outcome. By assuming the same weight (i.e. importance) to each expert, the geometric mean has been used to develop the judgment process in the proposed test case. Thus, the final ranking, derived by applying group decision making to each pairwise comparison, was obtained; results are in Figure 2. A final consistency analysis was carried out highlighting a global CR value less than 10%; thus, the judgments are consistent and a final ranking solution could be analysed.

Figure 2. The estimated final ranking of alternatives

Next, **Step 3** has been carried out. Results show a slight preference among alternatives: the most effective AR category for the analysed goal is the *handheld devices* (with 26.4 score); second alternatives are *projectors* (25.6% score); third and fourth alternatives are respectively *haptic and force feedbacks* and *HMDs* with a similar score of about 24%.

As defined in the previous section, another capability supported by the proposed model is to quantify the "performance" of each AR device in terms of process metrics. Data about relative rankings obtained by evaluating separately each first level criteria (i.e. reliability, responsiveness and agility) are depicted in Figure 3.

Figure 3. Rankings of alternatives with respect to each first level criterion

Results highlight that *handheld devices* are the most reliable system in the analysed test case; on the other hand, *HMDs* and *projectors* are the most responsive and agile AR systems respectively. This information is very useful for supporting an effective feasibility study about AR technologies in manufacturing applications as the model points out their potential impacts estimated on a process based point of view. These relative analyses are very critical for supporting the decision making process as they outline actual relationship between process and technological performance of AR systems. This analysis has provided an important knowledge as performance of innovative ICT tools (as AR devices) have been measured in terms of impacts from a manufacturing process point of view.

Furthermore, the proposed model has provided another interesting analysis about what are the most critical features contributing to the final solution: the relationship between higher and lower level criteria could be outlined by analysing each estimated local score at each level; local weights represent coefficients measuring the importance of each single element towards the previous one in the hierarchy. Local weights estimated in the test case for first, second, and third level criteria are in Table 1.

Table 1. Estimated local weights of 1st, 2nd and 3rd level criteria in the proposed test case

Starting from the first level, local score estimated for each first level criterion has been analysed to assess each single contribution to the final ranking solution. By analysing first two rows in Table 2, local weights analysis points out that reliability and, subsequently, agility are the most relevant process based metrics affecting the final ranking in the analysed test case; thus, less importance has been assigned by expert judgments for the responsiveness criterion in this test case. Therefore, reliability and agility represent the two most important features requested to an AR device which have to support the information exchange process during the maintenance activity analysed in the test case. By analysing local weights estimated for second level and third criteria respectively, the data format provided through the AR device has been estimated as the most important (i.e. with a score of 45.2%) feature contributing to reliability criterion. The possibility of providing data in 3d format has been also estimated as the most important technical feature, since it is characterized by the highest local score at the third level, i.e. 45.7%. For the responsiveness criterion, the most important feature is its handiness as the criterion "handle" has the highest score (i.e. 24.6%) between all second level criteria under the responsiveness criterion. Furthermore, the most important feature which contribute to the handiness of the AR device has been estimated by the "both hands free" criterion which has the highest score among third level criteria under the "handle" criterion. For the agility criterion, the most important feature is the type of feedback process (i.e. the estimated score is 66.7%) supported by the AR device which has to be provided by using image processing, characterized by the highest local score, i.e. 53.3%.

Finally, the overall contribution of the multi-criteria model is also outlined by overlapping results obtained for the final ranking and local weights, an interesting result could be outlined: the absolute ranking outlines projectors as the best AR alternative, and reliability and agility as the two most important process based evaluation criteria. However, results in Figure 3 show that the most "reliable" AR systems are *handheld devices* (26.3%) followed by *haptic and force feedbacks* (25.9%) and *projectors* (24.0%) respectively; the most "agile" are *projectors* (27.6%) followed by *handheld devices* (27.2%). This is not a contradictory result as the final ranking is estimated based on both the scores obtained by judging each alternative respect to each first level criterion and local weights characterizing these criteria, which depend on judgments made on following the levels of criteria.

As final scores are quite similar, a sensitivity analysis (**Step 4**) has been carried out aiming to evaluate impacts due to variations in local weight estimations on the previous final ranking. As an example, by assuming a ± 10% variations for weights assigned to first level criteria (i.e. reliability, responsiveness and agility), modified final rankings (expressed in percentage) are reported in Table 2.

Table 2. The sensitivity analysis of the estimated final ranking

Estimated data for the current test case outline a general tendency of confirming previous final ranking. It has to be noted that sensitivity analysis could be carried out between all levels of the hierarchy, thus providing decision makers with knowledge about how "stable" and consistent is the obtained ranking.

Data provided by the model application has supported the firm technicians in the technical feasibility study developed to design a prototype proprietary AR application, which will be adopted for the firm on site maintenance processes.

Finally, even if quantitative results are strictly dependent on this test case so they are not characterized by a general validity, the test case development has shown the efficacy of the proposed multi-criteria model in assessing AR devices in the manufacturing sector: the main innovative feature is that it provides an integrated analysis based on technological as well as process based parameters.

5. CONCLUSIONS

The application of AR devices in the manufacturing field could now represent a disruptive innovation for improving performance in production systems despite their capabilities are not yet fully explored as few pilot applications and laboratory tests are still applied. Reference models for evaluating its global effectiveness from a process-based point of view are quite rare. Evaluating the most effective AR device for the specific manufacturing problem is a very complex task due to a high technological and process based skill required. On the other hand, investments in these technological systems also require an assessment of positive (or negative) impacts on the manufacturing process where an AR device (or application) will be adopted. Few recent studies have faced with this research problem; most of them have adopted qualitative analysis (often survey method) to evaluate "ex post" – i.e. after the design of the adoption of the AR system - critical features (e.g. the usability) of the AR device applied in such manufacturing process. On the other hand, aiming to assess efficiently the adoption of these new technologies in manufacturing processes, a preliminary feasibility study is essential as they could represent a disruptive technology (Lee et al., 2010; Seo and Lee, 2013).

This paper proposes a multi-criteria model to support quantitatively production managers and researchers in evaluating performance of different AR devices based on both technological - i.e. characterizing each AR systems- and organizational performance – required by the specific manufacturing process. The focus of the study is to develop an expert based tool to support, in a more efficient way, the design of AR applications in specific manufacturing issues. The multi-criteria model has been developed by the well-known AHP approach; the hierarchy of criteria is based on both process indicators (i.e. agility, responsiveness and reliability) required to a manufacturing process and technological criteria, characterizing the application of AR systems in the manufacturing area. The AHP model has allowed to integrate effectively different expert knowledge thus providing reliable output data for supporting the adoption of AR technologies in manufacturing.

The model will provide production managers as well as researchers with a structured tool for evaluating AR devices by a more comprehensive point of view as it allows to overcome limits of current studies, focused mostly on technological issues. Thus, the most important feature of the proposed model is that it allows to "translate" typical process based criteria (i.e. reliability, responsiveness and agility) in technical criteria characterizing AR devices technologies thus integrating effectively different types of expertise as required when a complex IT tool has to be adopted in production process (Lee et al., 2012). As an example, reliability has been "translated" in technological criteria trough data format, software typology provided by the AR device and the type of environment where the AR device has to work.

A test case is proposed to validate the model: it regards a complex maintenance task carried out in harsh workplace; the goal is to evaluate the most effective AR device for supporting effective information management process during complex on-site maintenance services regarding high technological equipment installed on board the trains. The test case has also provided overall potentialities of the proposed model in supporting a more structured and effective decision making process. Result discussion has outlined how the proposed AHP method could be applied to support an effective feasibility study about the application of AR technologies in such manufacturing problems. Results provided by the model application has supported the firm in designing an AR application tailored efficiently for their specific process requirements.

The model has outlined its fully capability in providing reliable and quantitative knowledge, which could be used both for designing AR applications and for evaluating the most suitable AR device based on organizational requirement of a manufacturing process. This will allow production managers to assess quantitatively how different process requirements could influence the performance of an AR device and viceversa. One main limit of the proposed model is to not integrate the economic dimension of the problem that could also influence the decision making process: economic issues will be also added to the model aiming to integrate the cost dimension in technological and process ones.

Further developments will be oriented to apply the proposed AHP model in different manufacturing processes, i.e. a feasibility study about applying AR tools for supporting a more efficient man-machine interface, for increasing knowledge sharing about actual state of production lines.

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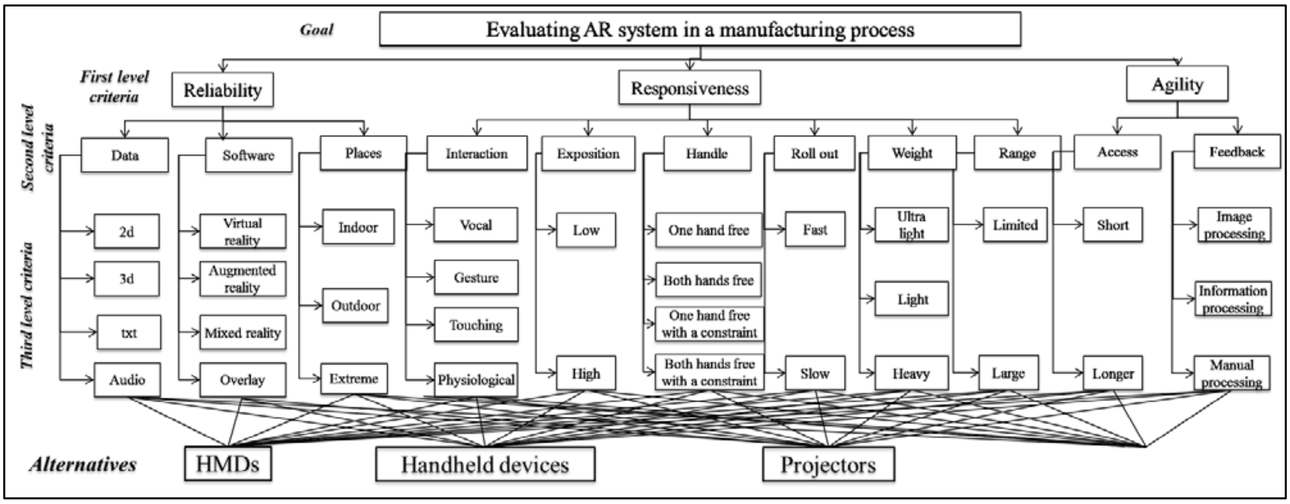

Figure 1. The proposed hierarchy

Figure 2. The estimated final ranking of alternatives

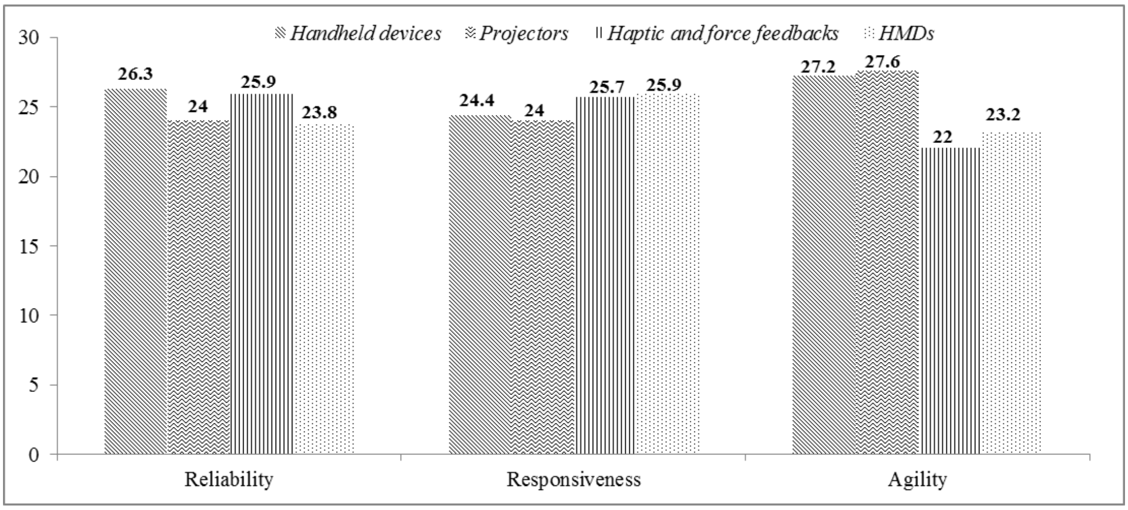

Figure 3. Rankings of alternatives with respect to each first level criterion

1st level criteria	Local weights [%]	**2nd level criteria**	Local weights [%]	**3rd level criteria**	Local weights [%]
Reliability	**43.0**	*Data*	**45.2**	*2d*	21.9
				3d	**45.7**
				Txt	16.6
				Audio	15.8
		Software	32.7	*Virtual reality*	30.7
				Augmented reality	26.8
				Mixed reality	24.5
				Overlay	18.0
		Places	22.1	*Indoor*	15.9
				Outdoor	38.2
				Extreme	45.9
Responsiveness	16.0	*Interaction*	14.2	*Vocal*	17.5
				Gesture	27.4
				Touching	10.8
				Physiological	44.3
		Exposition	11.1	*Low*	33.3
				High	66.7
		Handle	**24.6**	*Only one hand free*	17.3
				Both hands free	**44.2**
				Only one hand free with a constraint	10.3
				Both hands free with a constraint	28.2
		Roll out	15.7	*Fast*	66.7
				Slow	33.3
		Weight	23.2	*Ultra light*	53.3
				Light	29.9
				Heavy	16.8
		Range	11.2	*Limited*	50.0
				Large	50.0
Agility	41.0	*Access*	33.3	*Short*	55.0
				Longer	45.0
		Feedback	**66.7**	*Image processing*	**53.3**
				Information processing	29.9
				Manual processing	16.8

Table 1. Estimated local weights of 1st, 2nd and 3rd level criteria in the proposed test case

1st level criterion	**Rankings obtained with variation of the criterion weight of**					
	+10%			**-10%**		
	Ranking	***Alternative***	***Score [%]***	***Ranking***	***Alternative***	***Score [%]***
Reliability	1	handheld	26.4	1	handheld	26.4
	2	projectors	25.4	2	projectors	25.7
	3	haptic	24.3	3	haptic	24.0
	4	HMDs	23.9	4	HMDs	23.9
Responsiveness	1	handheld	26.3	1	handheld	26.4
	2	projectors	25.5	2	projectors	25.6
	3	haptic	24.2	3	haptic	24.1
	4	HMDs	24.0	4	HMDs	23.9
Agility	1	handheld	26.4	1	handheld	26.3
	2	projectors	25.7	2	projectors	25.4
	3	haptic	24.0	3	haptic	24.3
	4	HMDs	23.9	4	HMDs	24.0

Table 2. The sensitivity analysis of the estimated final ranking