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# Augmented reality applications in manufacturing: a multi-criteria decision model for performance analysis

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**Abstract**: Augmented Reality (AR) applications are becoming mature technologies for the use in manufacturing systems. Their very innovative character together with the variety of devices are now forcing production managers and researchers to analyse their application from technological to organizational point of view. The aim of the paper is to propose a multi-criteria model which integrates technical and organizational metrics to provide reliable decision support system for analysing the application of AR technologies in manufacturing. The proposed model applies the AHP (Analytic Hierarchy Process) method for integrating effectively technological and organizational factors which will contribute to analyse how an AR system could be effectively applied in the manufacturing sector.

## 1. INTRODUCTION

The manufacturing context is increasingly dynamic due to the high level of integration with advanced information tools, especially with mobile devices. Part of the efficiency depends on an effective and real-time communication between individuals and production departments within a manufacturing system (Morkos et al., 2012).

AR systems are now becoming mature technologies for application in manufacturing production and service systems: the aim is to support an increase in company performance in terms of shorter lead-times and process quality.

Current AR applications allow users to interact dynamically with manufacturing by sharing information with the real working environment.

Several recent pilot projects (Novak-Marcincin et al., 2012; Ong et al., 2007; Zhang et al., 2007; Chong et al., 2009; Dangelmaier et al., 2005) focused on demonstrating the applicability of AR systems in different manufacturing fields such as design, maintenance, assembly, etc.

This study proposes a decision support system, which could assess the feasibility of applying AR devices in different manufacturing contexts. The paper is organized as follows: main AR types and their application areas are analysed in section 2; the proposed approach and the decision model developed are in sections 3 and 4 respectively; finally, a test case is proposed in section 5 to validate the model.

## 2. AUGMENTED REALITY SYSTEMS IN MANUFACTURING: A BRIEF ANALYSIS

The contribution that AR systems can provide to manufacturing systems can be classified according to several criteria, such as used hardware devices rather than software tools provided to the user or the manufacturing area where they are applied.

A recent publication (Nee et al., 2012) has proposed a classification of AR devices. A brief description is analysed 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 and provides both a display and a camera; possibly ruggedized smartphones represent perfect examples of such devices.
- *Projectors*: laser or LCD/LED projectors can be used to display visual information on real world objects without the need for workers to wear devices.
- *User tracking*: sensors and motion detection can be used to detect the user's movements, however such devices do not often encounter wide success in industrial applications because of the bulky hardware they require the user to wear. Furthermore, integration with Radio Frequency Identification (RFID) could allow to support more dynamic communication of these AR systems.
- *Haptic and force feedback*: wearable devices that provide feedback to the user without needing him to distract from the task to be performed.

By analysing literature about AR systems - which is quite recent- their main current fields of application in the manufacturing sector are briefly analysed as follows:

- Design phase: AR could be used in rapid prototyping, allowing the designer to view virtual 3D models of objects in real world environments. AR can be used as well to allow selected users to test specific features, such as colour or user interfaces, on virtual objects. Ng et al. (2010 and 2011) proposed a system for the virtual creation of 3D models and an intuitive interaction for their modification. Thus, with this AR system, designers may change virtual prototypes using gestures because it has a data gloves gesture interaction module which handles the gesture inputs and convert them into automatic operations.

- Plant layout design: AR could support a more effective simulation of virtual objects within real environments, in order to test alternative design choices.
- Assembly cycle optimization: once the work cycles to produce a specific item have been defines, putting them into practice within an assembly line in an effective way requires optimization choices. AR techniques allow the designers to test within a real environment the effects of such choices.
- Production process design: AR applications could improve CNC (Computer Numerical Control) simulation. The potentiality to combine results achieved in CNC simulation tools with the knowledge of human operators in real time through AR tools provide an effective use case of AR within this area.
- Production process control: AR techniques allow the user who's controlling the robot (e.g. through joysticks) to view additional information that can help him better accomplish his task. AR is also used while programming the robot's movements in order to preview the robot's moves according to the program that's being developed within a real environment. Weinert et al. (2008) proposed an AR tool for the NC path validation and manipulation: the tool allows to synchronize the computer simulation with the actual real process - i.e. five-axis milling- and provide operator info and data allowing him to identify critical situations and reset the estimated NC code .
- Maintenance services: AR can be effectively used to perform remote maintenance tasks. An expert employee or even an expert system can tutor a remote employee, or a customer, in performing maintenance tasks providing him with contextual step-by-step instructions directly projected onto the real scene. Porcelli et al. (2013) described a full scale application of an AR tool ( a mobile collaborative systems) for supporting technicians in service maintenance operations.

This brief analysis has outlined the complexity of AR devices together with their potential applications in a manufacturing company: thus, the research problem in analysis in this paper faces with evaluating the most efficient AR devices for a specific manufacturing process. By focusing on innovative applications, the feasibility study is very complex due to several factors (Gnoni and Rollo, 2010; De Souza et al., 2011): one of the most critical issue is integrating technological with process-based metrics: the proposes study proposes a method to overcome this limit.

## 3. THE PROPOSED APPROACH

The decision problem in analysis regards assessing best AR tools applied for improving performance at a specific process in a manufacturing system. Evaluating technical performance of a complex IT tool – such as AR systems – is usually a complex task. The decision problem in analysis is quite complex due to at least two factors:

1) AR tools currently represent innovative systems applied in the manufacturing environment. Thus, few reference models are now present in the scientific literature.
2) By focusing on the methodological approach, technical and organizational performance have to be integrated in a common decision model as technical features characterizing each specific AR application have to be "measured" based also by an organizational point of view.

A multi-criteria approach could be a suitable method as it allows to integrate different aspects in a qualitative but effective way. In detail, the multi-criteria model proposed in this paper is based on a well-known method, the AHP introduced by Saaty (1980). It allows to assign priorities to a set of decisional alternatives on the basis a plurality of criteria. It breaks down a decision-making problem into several levels in such a way that they form a hierarchy with unidirectional hierarchical relationships between levels. The top level of the hierarchy is the main goal of the decision problem. The lower levels are the tangible and/or intangible criteria and sub-criteria that contribute to the goal. The bottom level is composed by alternatives to evaluate in terms of the criteria. The proposed multi criteria model integrates organizational criteria with technological ones characterizing AR applications. Organizational criteria have been derived by a well-known model, i.e. the SCOR Model: it is a reference tool applied for process performance measurement. The SCOR Model is a cross-industry diagnostic tool for evaluating performances of a supply chain according to a hierarchical index method (Irfan et al., 2008; Huang et al., 2005): it integrates all dimensions of supply chain process in a standardized way aiming to supply an effective tool to compare different contexts (Poluha, 2007). The SCOR model define a standardized method to analyse main business processes (i.e. the plan, source, make, deliver, return activities) usually characterizing a supply chain. Thus, even if the SCOR has been firstly defined for a supply chain analyses it could be also applied to evaluate complex process performance. One main feature characterizing the SCOR as it introduces quantitative metrics for each process in analysis: this is the main reason that have supported its adoption in the proposed model. Thus, in traditional SCOR model, each process which is disaggregated in different levels is associated to metrics (or attributes) outlining the ability of the supply chain to achieve the performance attributes. These attributes, defined by the SCOR Model with reference to the supply chain, in this paper are adapted to the manufacturing context remaining consistent with the rationale behind the original definitions. Therefore, benefits resulting from the introduction of an AR system can be assessed through the SCOR attributes by focusing not specifically on a supply chain but a manufacturing point of view. It is necessary, however, to identify the technological features being able to determine the achievement of these benefits. The proposed AHP model allows to "translate" "process" to "technological" aspects allowing to support a more effective decision making process.

## 4. THE MULTI-CRITERIA MODEL

**Step 1: the hierarchy development.** The first critical activity in developing AHP models is to define an effective hierarchy, i.e. to structure the decision problem into a hierarchical model. The aim of the study is to the most effective AR system for supporting performance improvement in a specific manufacturing process. Thus, HMD, handheld devices, projectors, user tracking and haptic and force feedback represent the alternatives in the proposed hierarchical decision structure, which refers to a general decision making problem. As defined previously, the proposed hierarchy has been defined by integrating process metrics derived from the SCOR Model with technological criteria which usually characterize an AR application. Thus, first level criteria have been adapted from SCOR attributes (defined in the original model for a supply chain) by focusing on manufacturing processes. Details are reported as follows:

- *reliability:* the functionality of the AR system to provide information in a consistent ad effective way (or formats);
- *responsiveness:* the feature characterizing the "speed" of the AR system to be ready for use;
- *agility:* the ability of the system to interact with modifications or changes caused by the manufacturing environment;
- *asset management:* the capability of the AR system to interact with the external environment.

Second and third level criteria have been evaluated based on technological features characterizing an AR system; these features have been interrelated with process criteria defined at the first level. Thus, the "reliability" criterion defined for an AR application in manufacturing has been associated with two main technological criteria:

- data format provided through the AR application (defined as *data*): four types of data format have been outlined such as *2D* or *3D* image, a text file (*txt*), or an *audio* file;
- software typology supported by the AR device (defined as *software*). The software is the key element for 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); a detailed description is proposed as follows:
  - o *virtual reality* tool: it allows to provide a computer generated, interactive, usually three dimensional environment in which a person is immersed;
  - o *augmented reality* tool: it integrates the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world;
  - o *mixed reality* tool: it refers to a system where real world and virtual world objects are presented together within a single device. It provides an overlapping of virtual with augmented reality;
  - o *overlay* tool: it provides a 2D overlapping of information of the real world.

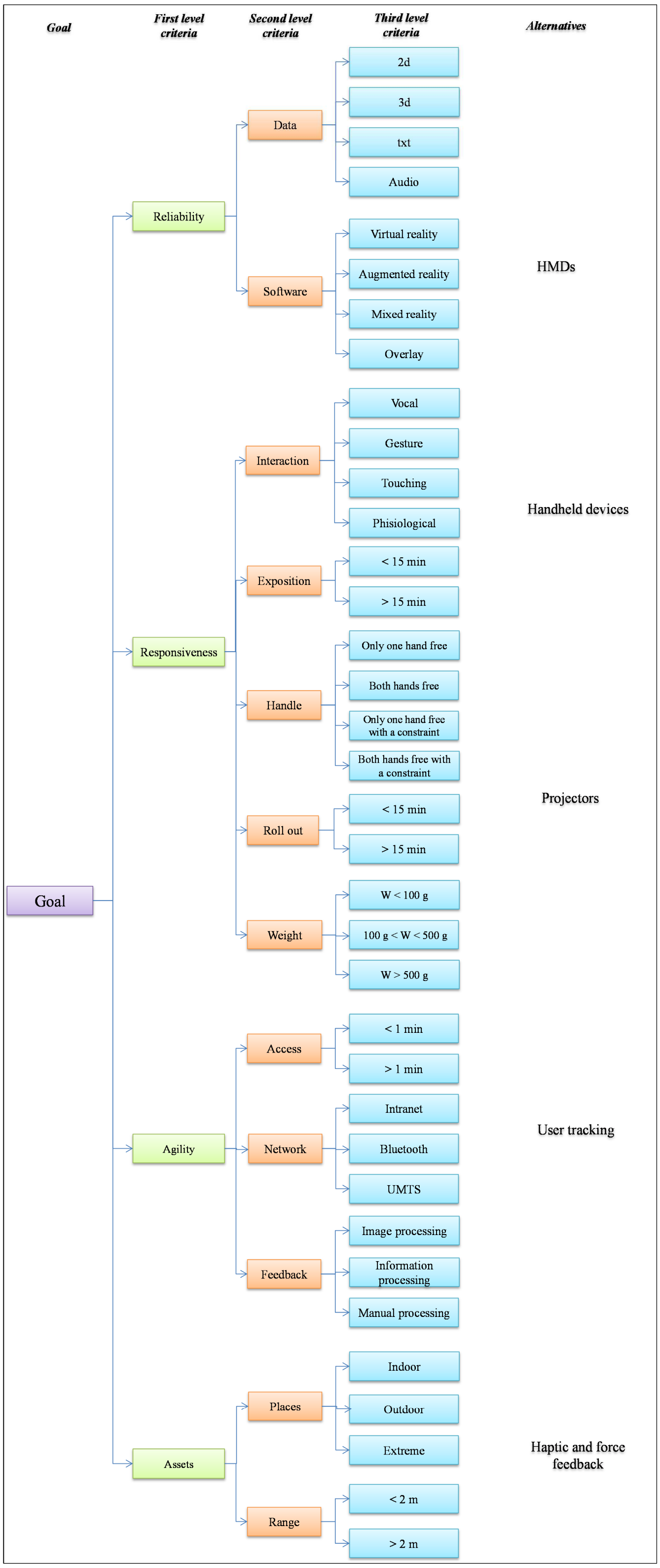


Fig. 1. The proposed hierarchy

The "responsiveness" criterion has been defined in five main technological sub-criteria:

- the way of interaction with the AR device (defined as *interaction*): which could be a *vocal* or a *gesture* based interaction, by *touching* or by *physiological* feedbacks;
- 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, i.e. less or greater than 15 minutes;
- the degree of manageability (defined as *handle*): it refers to the required use of hands during the device utilization 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*;
- the maximum allowable start up time for the AR system (defined as *roll out*): two sub-criteria have been introduced, such as less and greater than 15 minutes. This value has assumed as a target level;
- the gross weight characterizing the device (defined as *weight*): based on current market AR application features, three sub-criteria have been introduced by evaluating two boundary values, i.e. 100 g and 500 g. 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.

The "agility" criterion has been divided in three sub-criteria:

- the maximum allowable time for data recovery (defined as *access*): two sub-criteria have been defined such as less or greater than 1 minute;
- the (main) connection type required by the device (defined as *network*): three types of connections have been introduced, i.e. by internal firm network (*intranet*), by *Bluetooth* or by *UMTS* (Universal Mobile Telecommunications System);
- types of feedback process supported by the device (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 does not support any automatic feedback process (*manual processing* criterion).

The "asset" criterion has been divided in two sub-criteria:

- 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), an *outdoor* contexts (characterized by standard operative conditions) or *extreme* context which could be both outdoor or indoor context with severe operative conditions (e.g. in terms of humidity, presence of dust, etc.);
- the allowable operating range of the device (defined as *range*): it could be less or greater than a threshold value, i.e. 2 meters.

**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 validation activity has to be carried out at each level aiming to point out inconstancy of such a single judgement. Saaty (1980) proposes to estimate a defined a Consistency Ratio (CR) parameter defined as:

$$CR = CI/RI \tag{1}$$

where the Consistency Index, CI, is defined as the maximum eigenvalue characterizing the criteria matrix; the RI parameter is 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.** Finally, results analysis phase has to be carried out.

## 5. THE TEST CASE

A test case has been proposed in order to validate the previous method. The decision goal regards the evaluation of the most efficient AR systems applied to improve information sharing performance during on-site maintenance. So the goal of the decision problem is the *optimization of information sharing in complex on-site maintenance activities.* The hierarchy has been developed by software tool Expert Choice®.

The pairwise comparison phase has been developed by a quantitative judgments scale which is reported in Figure 2.

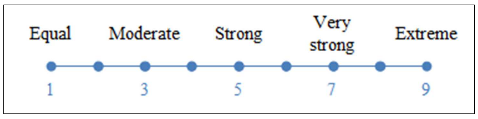
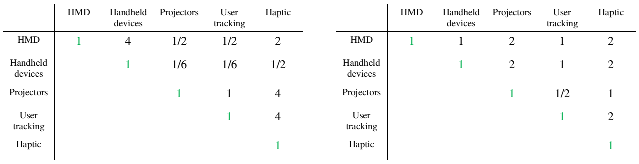


Fig. 2. The nine point scale of judgments applied in the test case

Thus, for each comparison matrix, priority vectors and CR have been estimated via Expert Choice®.

As an example, pairwise comparisons matrixes regarding alternatives with respect to $3^{rd}$ level criteria are reported in Figure 3.



| | HMD | Handheld devices | Projectors | User tracking | Haptic |
|---|---|---|---|---|---|
| HMD | 1 | 4 | 1/2 | 1/2 | 2 |
| Handheld devices | | 1 | 1/6 | 1/6 | 1/2 |
| Projectors | | | 1 | 1 | 4 |
| User tracking | | | | 1 | 4 |
| Haptic | | | | | 1 |

| | HMD | Handheld devices | Projectors | User tracking | Haptic |
|---|---|---|---|---|---|
| HMD | 1 | 1 | 2 | 1 | 2 |
| Handheld devices | | 1 | 2 | 1 | 2 |
| Projectors | | | 1 | 1/2 | 1 |
| User tracking | | | | 1 | 2 |
| Haptic | | | | | 1 |

Fig. 3. Examples of pairwise comparison matrixes at last level

After compiling all the matrixes, the software calculates the overall score of each alternative with respect to each level (Figure 4) and finally to the goal (Figure 5).

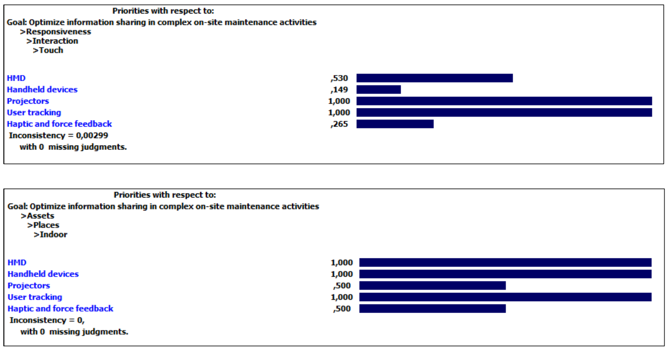


Fig. 4. Examples of priorities at last level

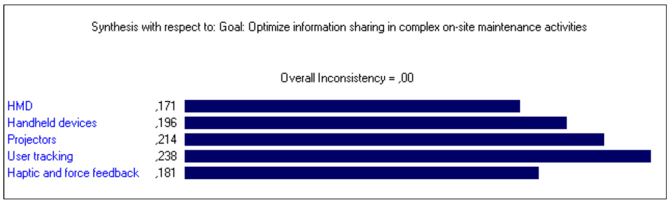


Fig. 5: Final alternative ranking

Obtained results outline as the most effective AR application for the goal in analysis is the *user tracking* which is characterized by the highest score, i.e. 23,8%, followed by *projectors* with a score of 21,4%.

Furthermore, a final consistency analysis has been carried out: the estimated CR value is less than 10%. The entered judgments are consistent.

Analysing the rankings of alternatives with respect to 1$^{st}$ level criteria (see Table 1), it could be outlined that user tracking is in first place in *reliability* and *responsiveness* rankings and in second place in *assets* together with handheld devices. The second places belong to projectors in all the rankings except in *assets*. Handheld devices and HMDs are in first place respectively in *agility* and *assets*.

There aren't large differences of score among the alternatives in the rankings. The deviations slightly larger are in *reliability*. You can notice that the rankings with respect to 1$^{st}$ level criteria reflect roughly the overall ranking.

Table 1. Ranking of alternatives with respect to each criterion of 1$^{st}$ level.

| | *Reliability* | *Respons.* | *Agility* | *Assets* |
|---|---|---|---|---|
| HMD | 7.7 % | 18.2 % | 18.5 % | 21.9 % |
| Hand. dev. | 12.7 % | 19.2 % | 21.6 % | 20.7 % |
| Projectors | 25.7 % | 22.4 % | 21.1 % | 17.0 % |
| User track. | 37.2 % | 23.2 % | 20.5 % | 20.7 % |
| Haptic | 16.7 % | 17.0 % | 18.2 % | 19.5 % |

## 6. CONCLUSIONS

AR applications currently represent innovative systems in the manufacturing sector. Due to the AR variety and their intrinsic complexity, analysing their performance on a specific task could be very difficult. This paper presents a model to assess different AR systems by selecting the most effective considering both technological features of systems and process and organizational aspects. The model proposed has been constructed by integrating two models known in literature: the AHP, a multi-criteria technique helpful to solve complex decision problems divided into different levels of evaluation, and the SCOR Model allowing to assess process performance. Assuming a goal in the field of maintenance and considering the AR alternatives, a test case has been created in order to validate the model. Future developments will be directed to analyse the sensitivity of alternatives with respect to the criteria below the goal, observing how the priorities of alternatives change when you vary the priorities of criteria.

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