Digital Human Models and Virtual Ergonomics to Improve Maintainability

Daniele Regazzoni and Caterina Rizzi

University of Bergamo, Italy, [daniele.regazzoni, caterina.rizzi]@unibg.it

ABSTRACT

Maintenance is one of the key drivers for future company success, due to the fact that these kinds of operations are strictly related to human labor cost, an expensive factor for western states. Furthermore, in the last decades, norms and laws on safety and ergonomics of the work place have taken importance among industrialized countries. Design for Maintenance is a design methodology that since early stages of product life cycle outlines needs and necessities of maintainers, in order to reduces time and cost; decreasing the complexity and the difficulties of these procedures and achieving a higher standard of workers' health. In order to reach this goal, Digital Human Models (DHM) have been used to simulate assembly and maintenance processes. Virtual ergonomic analysis performed with a human model allows evaluating visibility, reachability and postures, stress and fatigue. The lack of methods supporting virtual ergonomics simulation has been addressed by proposing a systematic approach based on a step-by-step procedure and proper tools. The said procedure was applied on a case study and results on the method and on its application are shown.

Keywords: design for maintenance, digital human modeling, ergonomics.

1. INTRODUCTION

Technologies for automating industrial production processes played a key role in industry in the last decades, but there are still several operations requiring manual handling due to the flexibility and the skill of human operators. Some of these handling tasks deal with heavy physical loads or uncomfortable postures, which might result in stress or overload in the muscles and joints, and further generate potential risks for musculoskeletal disorders (MSDs) [9,11]. The design of complex mechanical systems must be carried out easing the tasks of operators who assemble and maintain them. To accomplish to this goal, we need a detailed set of instructions ensuring a successful process and a safe work environment.

To provide operators with proper directions and to improve both the design of workers' task and of the product, Digital Human Modeling (DHM) techniques have been tested and validated taking human as the center of the work design system [5–8,14]. A human centric approach allows validating the workspace design, assessing the accessibility of an assembly design, reducing the production cost, and the risk of MSDs as well. Actually, Human Centered product design [2,13] is considered an effective means to fulfill the customization trend and it should be conducted through the life cycle as much as possible. In particular in the early stage of product development like Design for Manufacturing (DFM) [12,15] or Design for Assembly (DFA) [10,16] ergonomic issues must be seriously taken into account.

Nowadays, a significant set of experimental interactive human modeling and task analysis tools has been developed and some established commercial solutions have been robustly integrated into CAD tools [17,20].

By the way, even though the benefits a DHM approach to virtual ergonomics is well known and proven both in academia and in large enterprises it is still far from a wide diffusion and accomplishment. This may be due to several reasons, which may be, among some others:

- *Methodological*: lack of integrability of new tools with traditional ones along the product life cycle and in particular in the conceptual design phase.
- *Psychological*: inertia to change secure and well-known design tools and routine procedures for innovative tools and practices even if they may bring better results.
- *Organizational*: difficulties in estimating and exploiting the cost/benefit opportunity of DHM tools, in particular for SMEs.

Computer-Aided Design & Applications, 11(1), 2013, 10–19, http://dx.doi.org/10.1080/16864360.2013.834130
© 2013 CAD Solutions, LLC, http://www.cadanda.com

This study aims at addressing directly the first cause, the one related with the lack of a proper practical working method to introduce DHM into the routine design procedure of an enterprise. As a consequence the second reason, psychological reluctance to change, will be dramatically reduced by the introduction of a step-by-step method supporting designers. Analogously, also organizational issue will be indirectly faced, as a structured approach may help also in defining a clearer and defined investment scenario also for small enterprises.

The paper at first shows a brief overview of DFM and DFA concepts to identify the rational and the need for this research. Afterwards, the main approach is described together with the tools making it feasible. A preliminary case study concerning a compression unit for a commercial refrigeration plant is presented to exemplify the application of the approach. At last some conclusions will highlight results reached, drawbacks and the need for further developments.

2. HUMAN FACTORS AND DESIGN FOR ASSEMBLY AND MAINTENANCE

Design for assembly (DFA) should be considered at all phases of the design process, and in the early phases it can prevent most of cost of a late design review. As the designers conceptualize alternative solutions, they should give serious consideration to the ease of assembly of the product or subassembly [3,16]. According to common understanding, any DFA tool should provide quick results and be easy to use and it should ensure consistency and completeness in its evaluation of product assemblability. It should also eliminate subjective judgment from design assessment, enable easy comparison of alternative designs, ensure that solutions are evaluated properly, identify assembly problem areas, and suggest alternative approaches for simplifying the product structure thereby reducing manufacturing and assembly costs. By applying a DFA tool, communication between manufacturing and design engineering is improved, and ideas, reasoning, and decisions made during the design process become well documented for future reference. The design should be studied and improved at the conceptual stage when it can be simply and inexpensively changed. The DFA method accomplishes these objectives by:

- *Providing a tool for the designer, or the design team which assures that considerations of product complexity and assembly take place at the earliest design stage.*
- *Guiding the designer, or the design team to simplify the product so that savings in both assembly costs and piece parts can be realized.*
- *Gathering information normally possessed by the experienced design engineer and arranging it conveniently for use by less-experienced designers.*
- *Establishing a database that consists of assembly times and cost factors for various design situations and production conditions.*

Besides these fundamental but generic concepts, designers need specific tools able to measure and report quantitative results about manual operations of a heterogeneous group of workers accomplishing assembly tasks. Actually, on one hand empirical guidelines such as reduce part count or make symmetrical components are self-explicative and don't need any ad-hoc tool to be actuated, while on the other hand, since manual operation are performed by a set of people whose size is not controllable, we need a way to design a product that meet the requirements of the largest group of potential workers. Reachability and visibility of the product are common examples of standard requirements to be accomplished, but due to the complexity of human body, designers cannot forecast non workers' single performances neither trends without proper simulation tools.

The same kind of problem arises while taking into account the design of maintenance aspects. Maintainability can be defined as the ease with which an item to be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skills using prescribed procedures and resources at each prescribed level of maintenance and repair [19]. It's a function of equipment design and maintenance task design. According to Tsai et al. [18] five are the issues to consider in maintainability analysis: disassembly sequence, selection of tools, time required for disassembly and human factors such as accessibility and visibility. In literature several product configuration and assembly criteria have been considered in determining maintainability index [1].

By the way, most of the R&D efforts are focused around the product, bill of material, detailed procedures, assembly and disassembly sequences. This is a correct and well-established approach for several applications. It works well typically for small, simple and/or light products and components onto which the human contribution can be forecasted and designed easily. However, there are several other applications in which the human factor is determinant and must be accurately taken into account because what is a good design for a part of the working population may be bad for another part we cannot neglect. The tools used for human factors in design for assembly and design for manufacturing are basically the same since, at high level, both methods share the same goal in terms or ergonomics. By the way, when going into details the operations prescribed in DFA may differ a lot from those for DFM. Maintenance activities, actually, are not always repeatable and vary depending on (i) the location which may be in-house

© 2013 CAD Solutions, LLC, http://www.cadanda.com

or to the customer, (ii) the kind of operation which may be planned or accidental and (iii) the cause of the failure which may be known or to be determined. For instance, a maintenance operation to fix an unexpected failure on a plant due to unknown reasons will be done following planned procedures in which human factors consist in the mere capability to perform the required actions, no matter what the effort is. On the contrary, assembly tasks are always performed in a controllable environment where product and tools are in proper positions and operations are known and optimized to shorten cycle times.

The approach we are trying to move on is much more human-oriented because there is a significant margin of improvement towards design that, besides its main performance, fit with human necessities along its lifecycle. Next paragraph shows the architecture of the proposed approach together with all the tools required to make it viable.

3. PROPOSED APPROACH

It is plain and clear how design stage in the lifecycle process must take into account of a number of requirements and indications to produce an outcome respecting high quality, low cost, but also being easy to be manufactured, (dis)assembled, maintained, discarded, just to cite some. There are several indications, sometimes too many, designers are asked to fulfill and, occasionally, the empiric rules coming from different Design For X (DFX) methods give opposite directions or suggest different technical solutions. One of the reasons for this to happen is because DFX rules are sometimes very generic and in order to cover all possible conditions they miss the chance, for each specific case, to give the best indication, and provide the right tool.

The approach proposed in this paper addresses the lack of method to manage human factors to give the designer a better chance to succeed in DFA or DFM. It is based on a deep knowledge of the product and on its related processes. In particular, we will focus on what concerns ergonomics for human-operated tasks. Figure 1 depicts the flow of activities that can be used anytime a manual operation must be analyzed and improved, if already existing, or designed, if brand new. No matter what the task the worker is asked to perform is (e.g. assembly, maintenance, and disassembly) for the procedure is not limited to one method or another.

The algorithm begins whenever the analysis of a human performance is required in the design process and the first step consists in acquiring all the information on the existing process or, for a new design, of any data already produced by the design team. This normally includes the access to enterprises databases holding product information, e.g., CAD parts, assembly procedures and process models. CAD models are available in most of the cases and they are fundamental to visually evaluate product architecture, modularity and the way it is assembled. Also assembly and maintenance procedures are normally codified but their detail or completeness may vary a lot depending on the industrial sectors and on the single enterprise's practices. Process models can be used to describe product development, manufacturing or any other product related process. According to authors' experience the best way to perform the modeling of a product development process consist in using a functional language and in particular tools of the IDEF family [4]. This step may be time consuming but it must be accomplished only once for the entire process in which several manual tasks may have to be analyzed. Moreover, whenever a process model is available, either it is modeled with IDEF, ARIS or other available techniques, the effort to understand the process and the time required dramatically decrease. Generally, not all the tasks composing a manual activity need a deep analysis and only a sub-set is selected for investigation. Of course, in case of need any task to be performed can be analyzed. After the selection of tasks to be analyzed, we must consider whether we can find all the required information inside enterprise documents and, eventually, in non-formalized knowledge. In case all the data about a specific enterprise practice are available we can extract information about postures, movements, loads to be carried and detailed task to fulfill. On the contrary, if such information is available but not exhaustive or complete, we must find a way to determine which are all the conditions related to ergonomics in a certain task. At this point, in most of the cases we can directly capture the movements of real people in charge of the specific task and we can do it either in our laboratory or in the real working environment. Actually, we developed a Motion Capture (Mocap) method based on cameras or depth sensors for the acquisition of the movements of the human body. On the contrary, in the case we cannot access to enterprise practices, or there are no formalized practices at all, before doing the Mocap we will have to examine the work environment to understand which are the working conditions, the product and the tools to be analyzed. After the activities described so far have been performed and one of the branches of the algorithm of Figure 1 has been chosen, the last two steps are the same for each branch. At first we must run a simulation using Digital Human Models (DHM) on the basis of the data coming from the Mocap (left and central branches) or coming from detailed enterprise information (right branch). The last step consists in analyzing the simulation data and, finally, providing the design team with guidelines and quantitative results to let them perform a better design.

The first part of the algorithm, from "start" to "task and posture analysis" or to "enterprises practices exhaustive?" is aimed at collecting information and, even if it can be time and resources consuming, it does require knowledge management tools that are normally handled by the technicians in their everyday

© 2013 CAD Solutions, LLC, http://www.cadanda.com

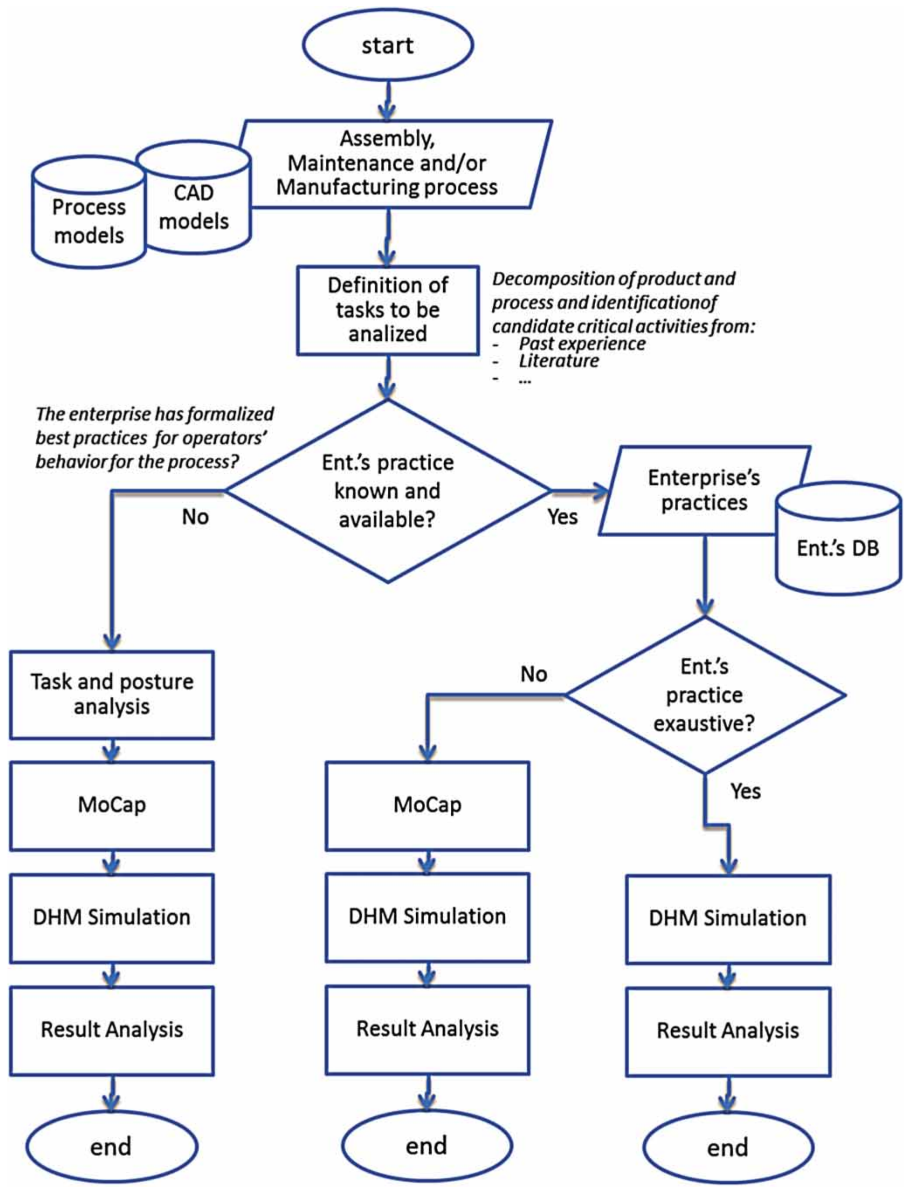

Fig. 1: Algorithm showing the activity flow for human-related tasks analysis.

activities. The second part, instead, is dedicated to a detailed study of some specific tasks using Mocap techniques connected to DHM tools, which are much less diffused in design departments because of a lack of structured approach. Figure 2 shows the flow of activities for the human centered operations (second part of Figure 1) and in particular Motion Capture and simulation with Digital Humans are exposed. According to the general algorithm, we are able to virtually test a manual task once we have got a clear definition of the working conditions, the tools available and the environment in which the human performs. This information can be derived from two sources: the description of the task already available in the enterprise in some documents (e.g., quality book, assembly procedures) or, in case this is not available, we can generate the required information by means of a preliminary rough analysis of the scene. In the rare case in which the procedures are so exhaustive to provide all data for a simulation with virtual humans, or in case of a completely new product or machine implying a new working condition, we can skip to DHM simulation activity. Otherwise, we have to perform a motion capture session either setting up a scene in the lab, building a physical model of the products and tools, or, better, moving Mocap instruments to the real working environment (e.g., the shop floor) to capture workers in their normal environment.

The portability of the instruments for Mocap is possible thanks to a working method and tools based

© 2013 CAD Solutions, LLC, http://www.cadanda.com

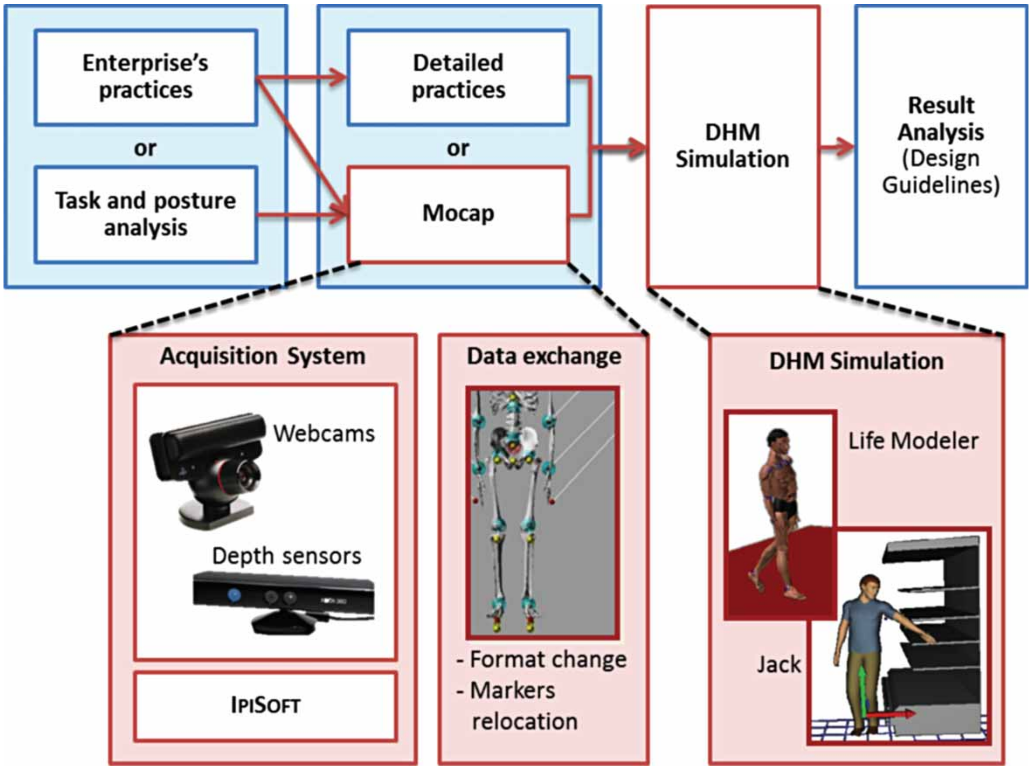

Fig. 2: Role of Mocap and DHM simulation.

on low cost hardware resources coming from the entertainment domain. After the acquisition of people movements a data exchange activity is required to pass the data to the DHM tools so that ergonomic outcomes can be gathered.

We considered two Mocap systems, both optical and marker-less: the former based on Sony Eye webcams and the latter on Microsoft Kinect sensor. Both solutions are not expensive and can be easily moved and used also outside the lab in potentially any work environment we want to acquire. Both solutions foresee the adoption of iPisoft Software, a non-real time marker-less system developed to work with Sony Eyes Webcams or Microsoft Kinect. The acquisition system based on webcams is composed by six Sony Eye webcams with a resolution of 640×480 pixels at 60 Hz mounted on photographic tripods, a portable workstation and iPiSoft software solutions. The system acquires synchronized video sequences obtained with the cameras, automatically recognizes the different body segments and, for each time step, calculates joints position and orientation. We decided to use 6 cams to be sure not to lose the tracking when some body segments are hidden by any device. The second Mocap solution is composed by two Microsoft Kinect sensors with a resolution of 640×480 pixels at 30 fps, mounted on photographic tripod, a portable workstation Dell XPS and iPiSoft software solutions. As in the previous case iPisoft manages the recording of images and depth videos coming from Kinect and performs environment calibration and video analysis.

To reproduce the humans' movement we need to pass the data acquired from the Mocap system to the simulation environment (e.g., LifeMOD or Jack). The data format of the Mocap system is not compatible with those of the DHM tools; therefore, we developed an ad-hoc algorithm in Matlab, which translates the information relative to the joint hierarchy and to the motion contained in the BVH file to the format used by the DHM tools.

In LifeMOD the creation of a model starts with the generation of a basic set of connected human segments (e.g., bones and skeleton) based on the dimension contained in an anthropometric database, then the joints, the muscles and the tendons are created and contact force with objects are defined. Each simulation starts with the virtual human in a specific initial position and each model can be active or passive. Passive models react to forces coming from the environment around them, for instance gravity and contact with the ground. Active models produce reactions in the environment due to their movements. To obtain accurate simulations with the muscles and the articulations it's necessary to execute a first inverse dynamic simulation to drive the body with motion agents describing the movements to execute. Once that the movements are stored a direct dynamic

© 2013 CAD Solutions, LLC, http://www.cadanda.com

simulation is run to calculate the forces created by the muscles and the stresses the body is subjected to. LifeMOD needs as input the Motion Capture data in SLF format; this file format can be used also to provide model anthropometric characteristics, initial position and markers positions. The outcome provided by the system consists of forces and momenta acting on each joint in each time step of the analysis.

Jack simulation and analysis tool is preferred when we can skip Mocap phase and define the task directly in the virtual environment.

4. APPLICATION TO THE CASE STUDY

The case study refers to the field of commercial refrigeration industry, in which typical products are plants made of a compressor unit e.g., placed on the roof of a supermarket, connected to and serving a number of refrigerated display units containing fresh food for the sale. The case is particularly meaningful because there are several issues concerning ergonomics both for the display units (e.g., reachability of goods for customers, workers in charge of filling out the shelves, and maintenance workers) and for the compressor units which must guarantee a continuous functioning for several years in row despite some well know issues related to maintenance. In the followings, we are describing the application of the presented method and tools to a specific maintenance task performed on the compressor unit.

The case study has been performed with the active collaboration of a company designing and manufacturing the product object of this study.

The first activity is the less organized because the study of the product and of the related documentation strongly depends on each specific case. Nevertheless, the company provided us with complete information about the product and its functioning, all the requirements to be taken into account for a good design, manufacturing and assembly workflow and maintenance activities. After the analysis of the documentation and a visit to the shop floor where compressor units are assembled, we had also the precious chance to ask directly to expert personnel about critical manual activities in production and maintenance. 3D CAD models were available and we were able to recognize the different modules composing the entire machine (Figure 3).

The compressor unit comprehends a modular steel frame provided with anti-vibration devices, two to six piston compressors of different sizes connected with the line to and from the display units with a complex system of copper pipes including filters, valves, instruments to monitor the functioning and some other auxiliary devices. The power connections are managed by junction boxes and a modular electric control unit, which may be located inside the frame or on its top. All the possible configuration of compressor units have a “closed” or “open” version depending

Fig. 3: 3D CAD model of a complete compressor unit having three compressors and open configuration.

on the fact that they can be exposed to natural environment when installed outdoor, and, thus, they need to be protected from them by closing panels, or they can be mounted indoor in an open configuration.

After the study of all data available for the product and its process we passed to the definition of the tasks requiring an analysis. The decision was taken on the basis of several inputs coming from the design department, the manufacturing experts, workers and a team in charge of maintenance operations. A ranked list of tasks was defined and in the followings we will consider the activity of substitution of a filter for the refrigerant fluid. Even if this is not a frequent condition, it is extremely crucial because it implies the cut and the welding of copper pipes which may be very difficult to access and operated as shown in Figure 4.

Fig. 4: Copper pipes to be cut and welded for filter substitution.

Once defined the task we need to know how it is accomplished. The company’s documentation was very detailed from the product point of view and

© 2013 CAD Solutions, LLC, http://www.cadanda.com

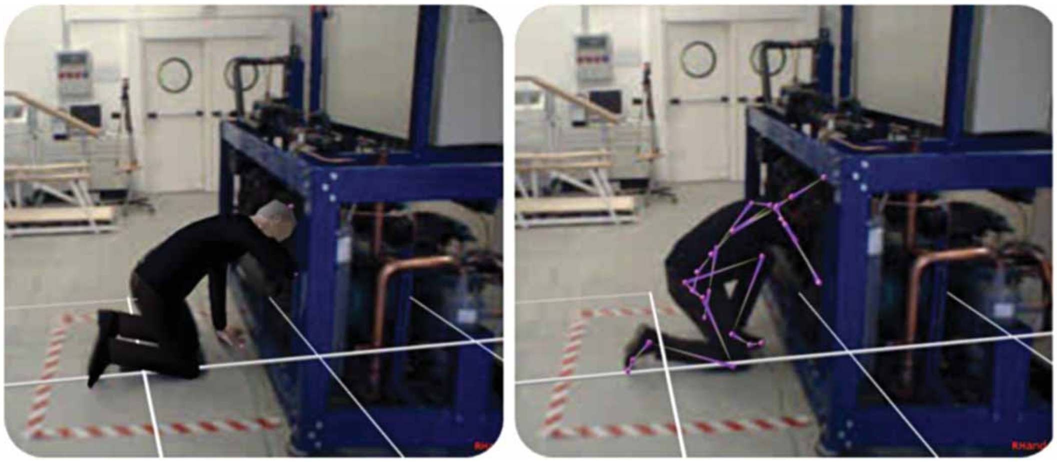

Fig. 5: Frames of Mocap process with worker in two different postures.

precise instructions and drawing were available to understand what should and what should not be done to change the filter. By the way, the focus was on the components and on the tools to perform each step in the operation and the human factor was not opportunely taken into consideration. A lot of safety prescriptions were given in a suitable way but information on how to reach the components or where to stay to have the best view or posture was missing. According to authors' experience, this is a recurrent situation even in leading companies and, thus a Mocap activity is frequently needed. So, according to the algorithm of Figure 1 we followed the central branch, having plenty of data about the company's practices for the maintenance activity but missing some crucial information on human behavior in performing the task, required for directly skipping to the DHM simulation.

So a scene was prepared in the V&K lab and an expert worker was asked to perform some specific operations in order to track his movements and gather the information required for the following step. Figure 5 shows two screen shots with the worker in two different postures taken from of the tracking sequence obtained by using the webcams as acquisition means. In Figure 5 the image on the left shows the iPisoft avatar overlapped to the silhouette of the real worker, while the image on the right shows the skeleton obtained calculating the position of the key joints.

Afterwards, data were appropriately elaborated with the exchange module and passed to the digital human simulation environment. We used both Jack and LifeMOD to simulate the task and to measure the virtual human performance according to standard ergonomics analysis.

The digital human models, together with the virtual prototype of the compressor unit, gave us the chance to recreate a scene with the exact working conditions or the real case. We used DHM tools in order to:

- Re-create the exact postures and movement of a real operator: this allows acquiring the precise working method of the expert that we could not obtain in any other way (e.g., with interviews or reading maintenance reports). The analysis was used to highlight known problems about posture or comfort in general, but also issues never taken into consideration formally can be defined. In the specific case study, the pipe is on the bottom of the compressor unit and the operator was on his knees to reach operative zone.
- Define a set of standard operations in order to create predictive simulation for new scenarios. Actually, we were able not only to consider the same operation on the same product performed by virtual humans of different sizes (e.g., 5 and 50 percentile for women and 50 and 95 percentile for men), but also to quantitatively assess the impact of any change in the original design. For the case study we simply decide to cut and weld the pipe in different positions and we were able to get an optimum solution given all the other parameters. We did not proceed to analyze different architectures of the compressor units since a design review was started during the work on the basis of the preliminary results but it was not deployed in time.
- Extrapolate indications and formulate them into guidelines for any technician involved in the design process. Analyzing the result of a number of simulations allowed providing the designers with indications having a general value for a product and task to be performed. For example, in the company's maintenance team tall men were preferred to perform repairing activities,

© 2013 CAD Solutions, LLC, http://www.cadanda.com

while simulations results showed that average men and women had better reachability performances.

4.1. RESULTS ANALYSIS AND DISCUSSION

We can distinguish two levels of results for this work: the level of the methodology and the level of the case study. For what concerns the method we can observe that the formalization into a precise algorithm met the need of the enterprise for standardized procedures at any level: in the product development department as well as for the manufacturing and assembly process and for teams in charge of maintenance of plants. The implementation of the first part of the algorithm strictly depends on the way information is codified in the enterprise body of knowledge, and it encourage, if needed, the process of formalization of explicit and tacit knowledge. A complete formalization and proper tools for knowledge management, actually, dramatically contribute in reducing time required to accomplish the whole procedure, making it much more efficient and convenient for a larger number of situations. The high level of formalization and the good amount of information on the product the company provided us were a good starting point for a successful implementation of the case study. The main drawback of the presented method at this level of discussion consists in the cost for the acquisition of the software and hardware solutions for the Mocap activity and for the DHM tool, besides the training of the designers. By the way the hardware used for the present work, being derived from videogames technology, is low cost and easy to use; more than one CAD vendor in their simulation suite proposes DHM and, thus, also this cost may not be challenging for the enterprise. Anyway, the benefits in term of "right design at the first time" can pay back even major investments in enterprises in which the human factors play a key role.

For what concerns the results of the application of the procedure to the case study we decided to perform analysis both with LifeMOD and with Jack. The first was used to evaluate the stress and fatigue of the worker performing the operation, while the second has been preferred for its flexibility of use when predictive simulations were to be performed. Anyway, we could use only one of the two tools reaching the same results with approximately the same effort. The Mocap activity was used for postures assumed by the real worker in front of the compressor unit but could not be used to track movements of arm and hand inside the machine because they were hidden by machine components. By the way in this phase we were much more interested by the posture of the entire body and the exact position of the hand does not impact significantly on the determination of ergonomic parameters, such as, for instance, the OWAS class. Since the position of the filter and of the pipe is near the ground the operator cannot help assuming a position that, if kept for long time, could provoke musculoskeletal diseases. We decide to test the positions of Figure 6, i.e. kneel on one (a) or two (b) knees, squat (c) and crawl (d) positions.

This simple operation was the starting point for evaluating the presence of human working on the compressor unit and, actually, this preliminary analysis highlighted how the indication on the indoor installation of the machine can impact on maintainability. Actually, the filter is positioned on the back of the compressor unit and the minimum distance from the wall to the backside prescribed in the installation manual is of 1 meter: this prevents the operator from working in the craw position.

Further analysis took into account reachability and visibility of the Operative Zone (OZ) and a sensitivity analysis was performed not only by changing the size of the human models, but also its position respect to the machine. To this aim, the first step consist in setting a target function in terms, respectively, of reachability of the OZ, visibility of the OZ, posture quality (e.g. OWAS CLASS) that influences the ease of keeping the position for the required time, and, eventually, the time consumed to clear the task. Then, a number of posture of the human model were easily determined by varying, one at a time, three variables: distance of the trunk from the machine frame (from contact position to 30 cm back, step 1 cm), head sagittal rotation ($\pm 5^\circ$, step 1°) and head front rotation ($\pm 5^\circ$, step 1°) (Figure 7). Visibility and reachability data, and a score for each posture were then easily gathered. This simple analysis showed some critical operations in

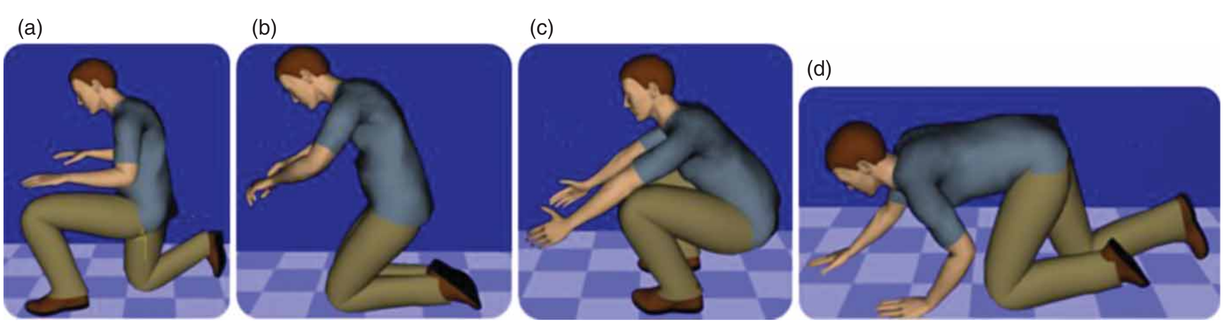

Fig. 6: Starting postures considered.

© 2013 CAD Solutions, LLC, http://www.cadanda.com

which reachability was not guaranteed for all workers and visibility was not possible. For instance, in the case of welding the back portion of the pipe, no matter how the human is tall or positioned the visibility requirement will not be satisfied.

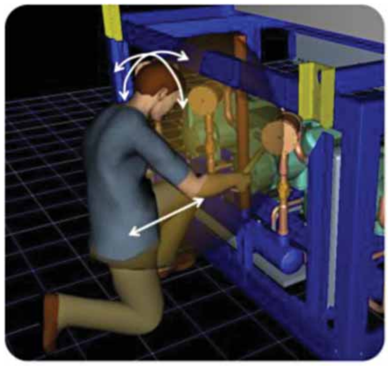

Fig. 7: Digital human in the working posture and degrees of freedom for the determination of optimal condition for reachability and visibility.

The results, post processed and presented to the design team, in many cases were not trivial and opened a discussion toward new design solutions that could have been tested and compared easily. Thus, designers were in the condition of self-test their own technical solutions to take into account human factor from the very first step of design process.

5. CONCLUSIONS

Industrial automatization has still left a significant space for manual activities for manufacturing, assembly and maintenance of machines and devices. In order to perform a successful design of the man-machine interaction existing simulation tools required a step-by-step method organizing the activities and easing the integration with the number of tools used to support product lifecycle. The proposed algorithm, hardware and software solutions meet this need and successfully enable to bring a systematic and pragmatic approach to human factors design. The application to the case study highlighted many benefits and also some drawback (e.g., for the Mocap solution in narrow spaces) but the overall valuation of the company considered this approach highly innovative. The design of workers' operation was introduced in the product development process and several alternative product solutions were generated considering new inputs and constraints. Introducing a human-centered in sectors where traditionally ergonomics was not highly taken into consideration may bring results that easily pay back the investment in terms of software licenses, hardware and technicians' education.

ACKNOWLEDGEMENTS

The authors would like to thank Giorgio De Ponti for his precious collaboration for the case study, Michele Bombardieri and Marco Magri for their contribution to the lab activities.

REFERENCES

[1] Abdullah A.B.; et al.: Utilization of design for assembly guideline to enhance product maintainability, Journal of Applied Sciences, 7 (21), 2007, 3234–3241.

[2] Baek, S.Y.; Lee, K.: Parametric Human Body Shape Modeling Framework for Human-Centered Product Design, Computer Aided Design, 44(1), 2012, 56–67.

[3] Balanchard, B.S.; et al.: Maintainability, John Wiley and Sons, 1995, New York.

[4] Bertoni, M.; et al.: PLM paradigm: How to lead BPR within the Product Development field, Computers in Industry, 60(7), 2009, 476–484.

[5] Chaffin, D.B.: On simulating human reach motions for ergonomics analyses, Hum Factors Ergon. Manuf., 12(3), 2002, 235–247.

[6] Chaffin, D.B.: Human motion simulation for vehicle and workplace design. Hum Factors Ergon. Manuf., 17(5), 2007, 475–484.

[7] Colombo, G.; Cugini, U.: Virtual Humans and Prototypes to Evaluate Ergonomics and Safety, Journal of Engineering Design, 16(2), 2005, 195–207.

[8] Colombo, G.; Facoetti, G.; Rizzi, C.: Virtual testing laboratory for lower limb prosthesis, Computer-Aided Design and Applications, 10(4), 2013, 671–683.

[9] Colombo, G.; et al.: Virtual ergonomics to design auxiliary equipment for commercial refrigeration, Proceedings of TMCE 2012, May 7–11, 2012, Karlsruhe, Germany. Karlsruhe (Germany), 7–11 May 2012, Voorschoten: Emerald Eye R&C, 383–392.

[10] De Lit, P.; Delchambre, A.; Henrioud, J. M.: An Integrated Approach for Product Family and Assembly System Design, EEE Transactions on Robotics and Automation, 19(2), 2003, 324–34.

[11] Li G.; Buckle, P.: Current techniques for assessing physical exposure to work-related musculoskeletal risks with emphasis on posture-based methods, Ergonomics, 42(5), 1999, 674–695.

[12] Kuo, T.C.; Huang, S. H.; Zhang, H.C.: Design for Manufacture and Design for 'X': Concepts, Applications, and Perspectives, Computers and Industrial Engineering, 41(3), 2001, 241–60.

[13] Maguire, M.: Methods to Support Human-Centred Design, International Journal of Human Computer Studies, 55(4), 2001, 587–634.

© 2013 CAD Solutions, LLC, http://www.cadanda.com

[14] Mavrikios, D.; et al.: An Approach to Human Motion Analysis and Modeling, International Journal of Industrial Ergonomics, 36(11), 2006, 979–89.

[15] Skander, A.; Roucoules, L.; Klein Meyer, J. S.: Design and Manufacturing Interface Modeling for Manufacturing Processes Selection and Knowledge Synthesis in Design, International Journal of Advanced Manufacturing Technology, 37(5–6), 2008, 443–54.

[16] Stone, R. B.; McAdams, D. A.; Kayyalethekkel, V. J.: A Product Architecture-Based Conceptual DFA Technique, Design Studies, 25(3), 2004, 301–25.

[17] SIEMENS TECHNOMATIX, http://www.plm.automation.siemens.com/en_us/products/tecnomatix/assembly_planning/jack/, Accessed February 2013.

[18] Tsai, Y.T.; Wang, K-S.; Lo, S.P.: A study of modularity operation of system based on maintenance consideration, Journal of Engineering Design, 14(1), 2003, 41–56.

[19] Vujesovic, R.; et al.: Simulation animation and analysis of design disassembly for maintainability analysis, Int. Journal of Prod. Res., 33(11), 1995, 2999–3022.

[20] 3DS DELMIA, http://www.3ds.com/products/delmia, Accessed February 2013.

© 2013 CAD Solutions, LLC, http://www.cadanda.com