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A DESIGN METHODOLOGY FOR MAINTAINABILITY OF AUTOMOTIVE COMPONENTS IN VIRTUAL ENVIRONMENT

G. Di Gironimo, G. Monacellia and S. Patalano

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1. Introduction

New car development has always been carried on to satisfy customer needs and, at the same time, to achieve a high quality and a reliability product. In particular, the need to develop new highly competitive products in terms of quality and costs requires a big effort of integration and synergy among all the departments of a company, development partners and suppliers, along the whole car development flow. Once both performance and reliability expectations are satisfied, the customers define a new car quality also in terms of time spent in assistance repairs. Cars that need minimum assistance time imply competitive costs. To reach this target, it is important that some requirements are safeguarded, since the concept stage, so that it is possible to have fast and cost-saving maintenance operations along the whole car life.
The present paper deals with the study and the development of design methodologies in virtual environment. In particular the authors have been facing the problem of ergonomic aspects in maintenance tasks in automotive industry pursuing the following aims: analyses of Human Modelling Software and their use in automotive task analysis; development of a design methodology for maintainability of the component parts of a car engine compartment in a virtual environment and, finally, individuation of an optimal postural sequence to disassemble such components, taking into account human factors. Nowadays, there are many 3D visualization CAD systems and Digital Mock-Up (DMU) tools (i.e. Division by P.T.C, Vis Mock-Up by E.A.I.-U.G.S.) able to study complex assemblies [Avallone et al. 2001]. They can perform clash and clearance analysis, internal geometrical visualisation with 3D and 2D section automatically updated and, in particular, they allow defining the best assembly/disassembly paths, but none of them take care of human factors during the analysis. In the following sections the authors show how to integrate DMU tools and Digital Human Modelling software in order to individuate the optimal postural sequence of an operator who has to disassemble a component part in a car engine compartment.

2. Fundamentals of Design for Maintainability

When technical systems are not designed and realized taking into account future maintenance operations, they imply higher times and costs even for a simple replacement [Hubka 1994]. In a global market oriented to the customer satisfaction, the limitation of the effects of assistance time represents a fundamental objective, both for the reduction of maintenance costs and, in general, for the improvement of the implicit quality. For these reasons *maintainability* has to be considered a design characteristic and a competitive factor [Ivory et al. 2001]. In fact, the economic weight of maintenance

operations on the Life-Cycle Cost (LCC) of a system, such as a transportation system, can vary between 50% and 75% of the global cost [Serger 1983].
The term *maintainability* represents the synthesis of several characteristics and a maintainability analysis can be performed through the following phases: disassembly analysis, accessibility analysis and manipulability analysis.

2.1 Disassembly analysis

A component of an assembly *can be disassembled* if it can be moved along a prefixed direction without verifying collisions with other parts. Extending this concept to systems constituted by *n* parts, these parts *can be disassembled* if there are *n* movements, each of them corresponding to the removal of a part or of a subassembly from the rest of the assembly. When the *(n-1)* motion is performed, the system is reduced to a single part. First problem of a disassembly analysis is to individualize the right motion sequence and the direction of each motion. Many methods [Beasley et al. 1993] foreseen the division of the assembly in two big subassemblies and the removal of the relative component parts along the normal direction to the separating surface of the same coupling, which, usually, corresponds to the bigger one. This division is often difficult to realize and the assumption of a unique motion direction can bring to wrong solutions.

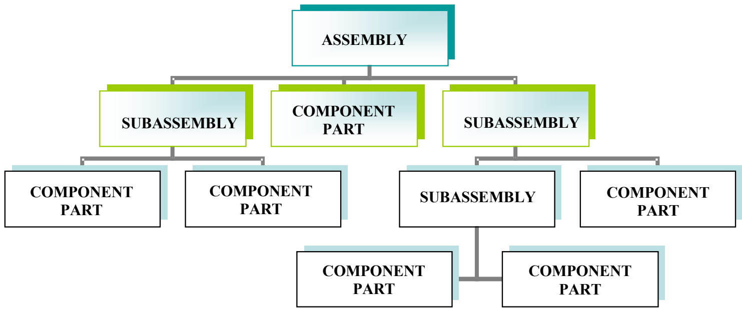

Figure 1. Assembly tree

A first aid to this problem comes by traditional CAD systems that allow individualizing the assembly structure by means of a tree. In such a structure it is possible to find the root, the nodes, the leafs and the branches. In the assembly tree shown in figure 1 these entities represent, respectively, the whole assembly, the subassemblies, the component parts, and the relations between these parts. Unfortunately, the information that can be achieved from this scheme is not geometrical; therefore they don't give any help to the definition of the optimal disassembly sequence.

2.2 Accessibility analysis

The aim of an accessibility analysis is the arrangement of each part and each connection to facilitate the inspection, the overhaul or the replacement, taking into account also the encumbrance of the equipment needs to perform the tasks. A system is defined "accessible" when the arrangement of its component parts allows the introduction of hands or of manual tools and the surrounding volume allows performing some maintainability operations, such as the removal of a screw, the screwing of a bolt or the introduction of a measurement tool [Baldin 1988]. During an accessibility analysis it is necessary to verify both the existence, for each component part, of the indispensable access volume to perform the above mentioned operations, and the absence of interferences along the intervention direction. Traditionally, these analyses are based on American Standards in which are specified the minimum area for the grasping and for the introduction of manual tools. These access volumes are strongly dependent on the geometry, the weight and the typology of the specific component part to be removed. These controls can be more easily carried out using parametric CAD systems [Cozzolino et al. 1999]. In fact, access volumes related to different tools can be simulated through the use of *family tables* that allow managing geometrically similar component parts starting from the representation of an archetype of the family [Lanzotti et al. 1996].

2.3 Manipulability analysis

An object is defined "manipulable" when it can be quickly grasped, handled and moved without excessive effort. If the available access volume allows only one operator to perform the task with one hand, the maximum dimension of the component part must not exceed 64 mm and the weight must not exceed 12.5 kg. If the first requirement is not satisfied the object has to be handled with both hands; if also the second requirement is not satisfied and the weight is over 25 kg the task has to be performed by two operators or by smart systems.

3. Limits of traditional CAD systems in maintainability analysis

3D visualization CAD systems allow specific motions of component parts or subassemblies of a complex assembly along any direction. By means of specifically visualization tools and collision detection algorithms 3D visualization CAD systems can individualize free of collision motion paths. Among them, the one that requires the smaller number of motions is the optimal solution. Consequently, these systems are very useful for *disassembly analysis*. Unfortunately, they don't turn out to be equally efficacious for *accessibility and manipulability analysis*. A fundamental request for the maintainability of a system is to assure adequate access volumes in order to introduce hands and tools and to execute simple tasks. While in the virtual environment realized by a CAD system a component part can be moved along any direction simply using keyboard and mouse, in reality the same object has to be grasped and moved by hands or by suitable tools. This simple consideration highlights an intrinsic limit of CAD systems: during disassembly analysis, CAD systems don't take into account the volumes needed to the intervention of hands and tools. Parametric CAD systems could perform accessibility and manipulability analysis by modelling, around the object, the minimum access volumes for the introduction of hands and hand tools and by verifying that also these volumes are free of collision during the whole disassembly task [Cozzolino et al. 1999]. Nevertheless, this approach is particularly hard, in fact, these minimum volumes vary according to the typology of task to be performed and to the tools to be used. This problem can be solved, as explained above, through the use of family tables, but this approach could yield to volumes bigger than those necessary for maintainability aims. Refining the analysis, the hand tools can be correctly modelled with 3D CAD systems and their motions can be simulated (i.e. the rotation of a wrench) in virtual environment by verifying that the available volumes are sufficient. Anyway, all these approaches, allowed by traditional CAD systems, don't take into account that the tasks have to be carried out by a real operator that could assume an incorrect posture to grasp the object and could suffer from a damage to the spine when lifting it.

4. Digital Human Models in the simulation of maintainability tasks: *Virtual Maintenance*

In a previous work [Di Gironimo et al. 2003], have been presented the advantages coming from the simulation, in virtual environment of a Manual Material Handling activity. Other works [Caputo et al. 2001], [Di Gironimo et al. 2001] have shown the behaviours and the characteristics of digital human models and the advantages achieved by the use of ergonomic software in engineering design. *Virtual Maintenance* is a design approach based on the use of these ergonomic software. Virtual Maintenance allows to simulate work environments, operators, and machines and to reproduce, in virtual environments, all the maintenance activities such as access, handling, disassembly, repair and assembly tasks [Abshire et al. 1998]. The Digital Human Models, by simulating behaviours and characteristics of real humans, allow performing accessibility and manipulability analysis in a rigorous and fast way. Virtual simulation of maintainability tasks, by means of Digital Human Models, allows to:

- evaluate visibility, reachability and grasping of component parts during the assembly and disassembly phases;
- verify the possibility for the operators to use the necessary tools. For example, it is possible to simulate the tightening of a bolt with a wrench reproducing the motion of the tool and of the user's hand;

- calculate times and efforts needed for the execution of maintenance tasks;
- foreseen the capability of the workers to support these efforts according to their anthropometric characteristics;
- highlight the risk of damages every time component parts are lifted and handled.

Usual maintenance activities, such as oil change, air filter change, replacement of the radiator hose, of the driving belt or of the battery, can be simulated on the virtual prototype of the vehicle, answering to the fundamental problems on the feasibleness of the tasks. For example, if the layout of the components allows to perform the task, or if it is possible to execute the movements needed for the fulfilment of the task, or if the execution of the task complies with the safety rules. In conclusion, a *Virtual Maintenance* approach, taking into account anthropometric and physiologic characteristics of the workers, allows establishing if the supposed motions are really executable. Furthermore, it allows performing ergonomic analysis of the postures assumed during the maintenance task. Nevertheless, Human Modelling software, supporting Virtual Maintenance, (i.e. Jack, Safework) use algorithms for collision detection, calculus of interferences, calculus and visualization of traces and envelope volumes that have lower performances than the same available on dedicated CAD systems (i.e. Vis-MockUp, Catia Fitting Simulation and 4D Navigator). Moreover, these dedicated CAD systems have modules that allow individuating the optimal path between several disassembly paths. Generally, these modules are not present in Human Modelling software. The procedure that will be illustrated in the following paragraph is based on the use of three specific tools of a software for ergonomic simulations (the software used to develop the methodology is JACK by EDS): the *Low Back Analysis* (LBA), the *Ovako Working Posture Analysis System* (OWAS) and the *Rapid Upper Limb Assessment Analysis* (RULA).

4.1 Low Back Analysis (LBA)

The Low Back Analysis is a tool that allows evaluating the strengths on the virtual manikin's spine, relating to each posture assumed by the digital human model and any loading action. This tool evaluates, in real time, the actions linked to the tasks imposed to the manikin according to the NIOSH standards and to the studies carried out in this field by Raschke [Raschke 1994]. The Low Back Analysis tool offers information related to the compression and cut strengths on L4 and L5 lumbar disks, together with the reaction-moments in the axial, sagittal and lateral plane on the L4 and L5 lumbar disks and the activity level of the trunk muscles to balance the spine moments. In particular, in the following is used the value, expressed in Newton, of the compression on L4 and L5 lumbar disks.

4.2 Ovako Working Posture Analysis System (OWAS)

The OWAS is a simple method for the verification of comfort degree related to working postures and for the evaluation of the urgency degree that has to be assigning to corrective actions. The method has been developed in the Finn metallurgic industries during the 70's. It founds itself on the classification of the postures and on the observation of working tasks. The OWAS method foresees the use of a four digit code to asses the position of body back side, arms and legs together with the intensity of existing loads during the performing of a specific task. The activity under examination has to be observed according a period of about thirty seconds. During each step, the positions and the applied strengths have to be registered, according to a decomposing technique of complex activities. In this way, the distribution of the postures, the repeated positions and the critical ones are focused. The data collection and the successive analysis allow the re-designing of the working procedure to reduce or eliminate postures that are potentially dangerous. In fact, the tasks are classified using four principal classes: 1) no harmful effect, 2) a limited harmful effect, 3) recognised armful effect on wealth, 4) highly harmful effect on wealth.

4.3 Rapid Upper Limb Assessment Analysis (RULA)

The RULA analysis refers itself to the risk exposition coming from diseases and/or damage to superior limbs. The analysis takes into account loads, biomechanical and postural parameters focusing on the

head, body and superior limbs position. The RULA method is based on a data sheet filling. The sheet makes the user able to quickly compute a value that indicates the urgency degree of an intervention that is necessary to adopt in order to reduce the risk of damages to superior limbs. The method foresees not only the arm and wrist analysis but also the head, body and leg analyses.
The first analysis, together with the information about muscles in use and existing loads, allows to asses the final score that represents the evaluation of working posture. The risk is considered "acceptable" when the score is equal to 1 or 2, required of "further investigation" (score equal to 3 or 4), "further investigation and quick change" (score equal to 5 or 6) or "investigation and immediate change" (score equal to 7).

5. EDIVE: a procedure for the definition of the optimal postural sequence for the disassembly of an automotive component

Considering the bent of 3D visualization CAD systems for virtual disassembly analysis and the capacities of Human Modelling software for accessibility and manipulability analysis it is advisable the joint use of these two typologies of software in order to optimize maintainability analysis. The integration of CAD techniques and virtual maintenance approach may be realized through the definition of a new methodology.
The goal is to elaborate a procedure, applicable during the phase of virtual definition of the vehicle, which allows: the maintainability analysis of a complex system as the engine compartment and the individuation of the optimal postural sequence for the disassembly of a component part of the engine compartment. To reach this goal, the authors have elaborated a procedure, named EDIVE (Ergonomic Disassembly In Virtual Environment), structured in 4 phases (figure 2):

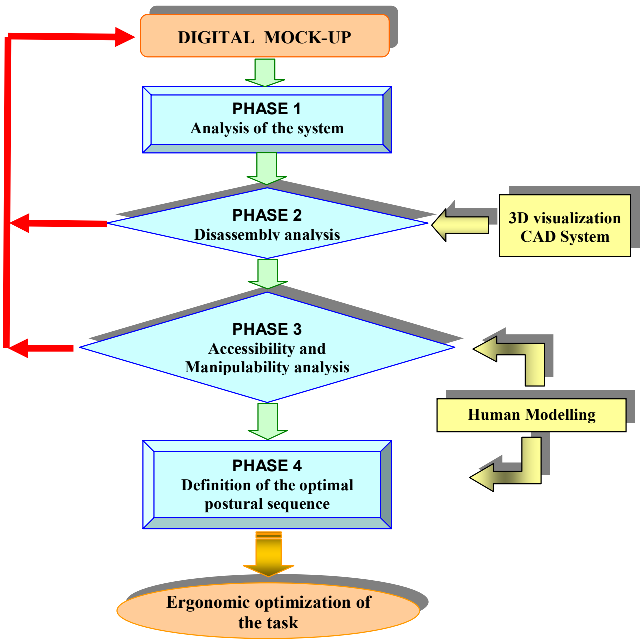

Figure 2. Flow chart of the EDIVE procedure

Phase 1 : ***Analysis of the system***

Once the critical element to be maintained has been individuated, the design team carries out the analysis of the related assembly and of its component parts. The analysis highlights functional relations among component parts, focusing on physical, morphological and geometrical characteristics. By examining the connection typology, it is possible to select the tools and the fixtures necessary for the disassembly task. The objective of this analysis is to determine all the component parts that have to be disassembled and all the disassembly operations that have to be performed in order to remove the critical element. During this phase, priority constraints among elementary operations are individuated and, therefore, the disassembly tree is defined. Reading the tree it is possible to list all the possible disassembly sequences that have to be verified in following phase 2.

Phase 2 : ***Disassembly Analysis***

A disassembly sequence defines component parts handling order and, consequently, the sequence of the elementary activities to be performed. Once a sequence has been fixed, 3D visualization CAD system are used to verify the existence of free of collisions motion paths for each of the elements that have to be removed, according to the fixed order. A theoretical sequence is feasible if each elementary disassembly operation can be associated to a possible path. ***Disassembly analysis of a critical component is positive when it is assured by the existence of "at least" a feasible disassembly sequence.*** If the analysis is unsuccessful, the system should be redesigned by changing the arrangement of the component parts or by modifying the geometry.

In case of various possible solutions, the optimal disassembly sequence has to be chosen. Accessibility, manipulability, minimization of component parts movements and/or run duration of the operations are some of the factors that can guide this choose. Once the optimal sequence is known, the order of elementary disassembly operations is univocally defined.

In the case study, which will be illustrated in the next paragraph, in order to execute disassembly analysis the CAD system *Vis-MockUp (UGS)* has been used.

Phase 3 : ***Accessibility and Manipulability Analysis***

Once the sequence of disassembly operation is defined, following Virtual Maintenance approach it is possible to simulate the whole maintenance process. In fact, the reproduction of real activities in a virtual environment, using Digital Human Models, makes accessibility and manipulability analysis simple and immediate. In fact, without simulating access area and standard manoeuvring volumes, and without using complex procedures to calculate interferences, in order to perform the analysis it is sufficient driving the hand of the manikin until the component part that has to be removed and evaluating visibility, reachability, grasping and the possibility of using fixture. ***This analysis is positive when it is possible to virtually perform each elementary disassembly task respecting available access area and manoeuvring volumes.*** In the following case study, in order to perform virtual accessibility and manipulability analysis the software for ergonomic simulation *Jack (EAI-UGS)* has been used.

Phase 4 : ***Ergonomic analysis of the task and definition of the optimal postural sequence***

A disassembly task can be decomposed in a certain number of simple operations each of them can be performed assuming several postures. Human Modelling software allow individualizing all possible postures and all joints motions that the digital human has to assume in order to execute a specific disassembly task. A task can't be identified with a single posture or a single joint motion but it has to be seen as a consistent and harmonic sequence of postures assumed by the operator. Within a sequence it is possible to individuate the ***critical posture***, which potentially is the more dangerous one in relation with the risk of muscular-skeletal diseases. A task, generally, is not characterized by a unique and defined postural sequence but, on the contrary, it's possible to recognize several sequences that, mainly, depend on the access path and on the geometrical constraints. The discomfort level of each sequence is closely linked to the relative critical posture. The problem consists in individualizing the critical posture related to each execution method of a disassembly task and in selecting the more comfortable one. In this way it is possible to determine the *modus operandi* that involves the lower biomechanical overload in the observance of the effort limits provided for in law.

First objective of the design of the engine compartment layout is to obtain the right trade-off between encumbrance and performance; from this point of view the feasibility requirement of the maintenance task (in a short time) is more important than the ergonomics of the same activity. The contemporary optimization of both characteristics (feasibility and ergonomics of the disassembly task), is hard because it needs a design solution that should get even with other characteristics of the vehicle like style, dimensions and performances. Nevertheless, if the "best solution" related to the ergonomic design of maintenance activity is practically impossible to obtain, EDIVE method gives the possibility to attain to the "optimal solution" selecting the *modus operandi* that allows executing each elementary task in a more comfortable way. The choose of this optimal solution passes through the individuation of the more comfortable posture, which can be carried out using a ***Posture Evaluation Index (PEI)*** that integrates the results of LBA, OWAS and RULA. In particular, PEI is the weighing sum of three adimensional variables I_1, I_2 and I_3. The variable I_1 is evaluated normalizing *LBA* value with the NIOSH limit for the compression strength (3400 N). The variables I_2 and I_3 are respectively equal to the *OWAS* index normalized with its maximum value ("4") and to the *RULA* index normalized with 7 (maximum level of discomfort for the superior limbs). In particular, I_3 is multiplied by an amplification factor "m_r".

$$\mathbf{PEI = I1 + I2 + mr\ I3} \quad (1)$$

Where: $I_1 = LBA/3400\ N$, $I_2 = OWAS/4$, $I_3 = RULA/7$, $m_r = 1{,}42$

PEI definition and the consequent use of LBA, OWAS and RULA task analysis tools depend on the following consideration. Principal risk factors for those working activities requiring biomechanical overload are: repetition, frequency, posture, effort, recovery time. Maintenance tasks are characterized by lack of repetition, low frequency and sufficient recovery time. The factors that mainly influence the execution of a disassembly task are extreme postures, in particular of the superior limbs, and high efforts. Consequently, the attention has to be pied on the evaluation of compression strengths on L4 and L5 lumbar disks (I_1 determination), on the evaluation of the level of discomfort of the posture (I_2 determination) and on the evaluation of the level of fatigue of superior limbs (I_3 determination). Furthermore, as the superior limbs are subjected to the biggest joint efforts, they quickly get strained and they are much more exposed to risks of muscular-skeletal disease. For this reason, in the expression (1) defining the PEI, it has been introduced the amplification factor "m_r", whose value is imposed equal to *1,42* as in [Colombini et al. 2000]. The PEI allows selecting the *modus operandi* to perform the disassembly task in a simple way. In fact, **the optimal posture associated to an elementary task is the critical posture whose PEI value is the lower**. The variables defining the PEI depend on the discomfort level associated to the examined posture: the bigger is the discomfort the bigger are I_1, I_2 and I_3 and, consequently, the PEI.

The PEI expresses, in a synthetic way, the "quality" of a posture with values varying between a minimum value of *0,47* (no loads applied to the hands, values of joints angles within the acceptability range) and a maximum value depending on the I_1 index. In order to ensure the conformity of the work with the laws protecting health and safety, it is assumed not valid a posture whose I_1 index is more or equal then 1. In fact, in this way the NIOSH limit related to compression strengths on L4 and L5 lumbar disks will be exceed. According to these considerations, the maximum acceptable value for PEI is *3,42* (compression strength on L4 and L5 lumbar disks equal to the NIOSH limit 3400 N; values of joints angles not acceptable). Iterating the procedure for all the elementary tasks of the disassembly sequence, it is possible to associate to each of them the optimal posture to be assumed and to individuate, finally, **the optimal postural sequence for the disassembly task**.

6. Case study

In order to test the EDIVE procedure, it has been analyzed the disassembly of a "battery" (figure 3) of a vehicle.

PHASE 1 : *Analysis of the system*

The analysis of the system has allowed individualizing the elementary operations that have to be executed in order to disassemble the battery according with assistibility criteria [Avallone 2001] and geometrical constraints: a) opening of the positive pole's protection, b) removal of the bracket's right screw, c) removal of the bracket's left screw, d) lifting of the bracket, e) removal of the negative pole's terminal, f) removal of the positive pole's terminal, g) lifting of the battery. First, in order to extract the battery from the basket, the bracket and the cables are to be removed. Before loosening the positive pole terminal, it is necessary to rotate the protection; the lifting of the bracket requires the removal of the screws. All these priority constraints and all the theoretical disassembly sequences can be deduced from the disassembly tree shown in figure 4.

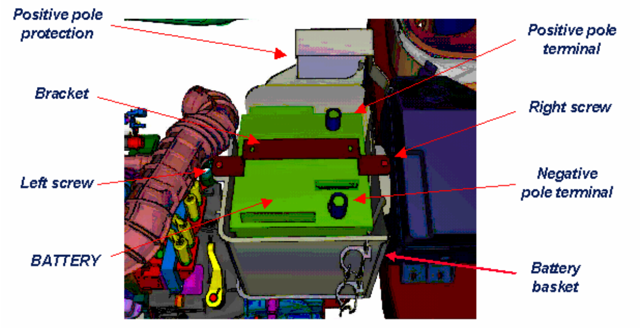

Figure 3. Battery system

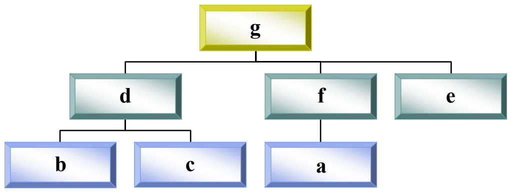

Figure 4. Disassembly tree related to the battery system

It is important to observe that the only elementary operations that don't need induced disassemblies are *a, b, c* and *e.*

PHASE 2 : *Disassembly Analysis*

Disassembly Analysis has been executed using CAD system *VisMock-Up (UGS).* Once any sequence of the tree has been chosen, each element of the assembly can be moved, according to the predetermined sequence, orthogonally to the face of the battery without collisions or interferences (figure 5). The disassembly analysis has been verified for all the sequences deriving from the tree. In particular, it has been assured the possibility of removing the protection of the positive pole without induced disassemblies, according to the assistibility criteria. As it has been ascertained the general equivalence between the disassembly sequences, the following Accessibility and Manipulability analysis have been executed for the sequence **{*a, b, c, d, e, f, g*}** that minimizes the moving of the operator in changing tools.

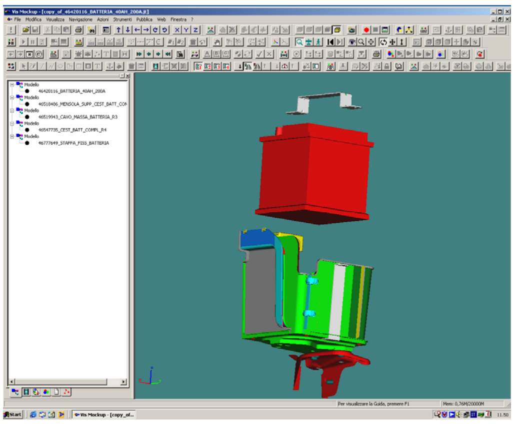

Figure 5. Disassembly Analysis of the battery system using VisMock-Up

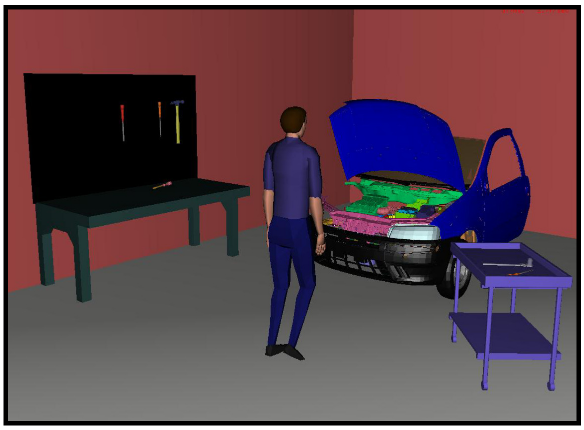

Figure 6. Virtual garage

PHASE 3 : *Accessibility and Manipulability Analysis*

Accessibility and Manipulability Analysis has been executed using the software for ergonomic simulation *Jack (EAI-UGS).* After the reconstruction of the virtual garage in Jack environment (figure 6), each elementary operation has been analyzed according to the sequence. For example, in figure 7 is shown the task (a), opening of the positive pole's protection. In this case, the analysis highlights that the access of the right hand and, consequently, the grasping of the element are difficult. In fact, there is a collision between a segment of the hand and the protection of the positive pole. In figure 8 is shown the task (g), the lifting of the battery. This task needs the use of both hands; as the element doesn't contain handles, the only way to lift the object is to grasp it at the top border, whose access is strongly limited by the shape and the dimensions of the basket.

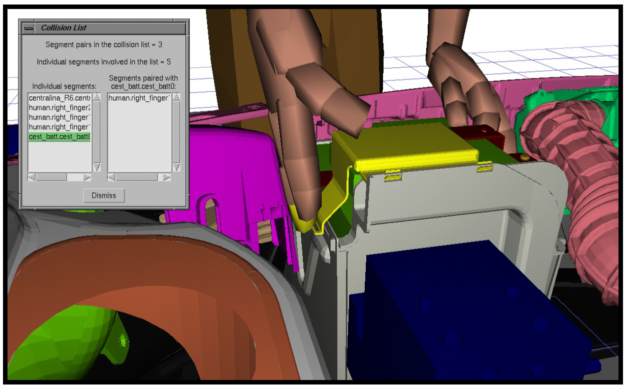

Figure 7. Opening of the positive pole's protection; collision detection

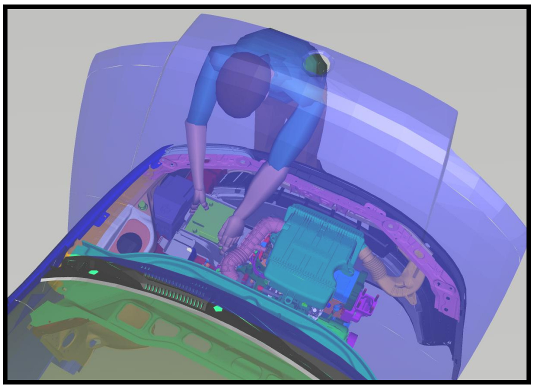

Figure 8. Lifting of the battery

In table 1 are synthesized the results of the virtual maintenance analyses.

Table 1. Results of the virtual maintenance analyses

COMPONENTS	DISASSEMBLY	ACCESSIBILITY	MANIPULABILITY
Protection	VERIFIED	INSUFFICIENT	INSUFFICIENT
Right screw	VERIFIED	GOOD	VERY GOOD
Left screw	VERIFIED	GOOD	VERY GOOD
Bracket	VERIFIED	VERY GOOD	VERY GOOD
Negative pole's terminal	VERIFIED	SUFFICIENT	SUFFICIENT
Positive pole's terminal	VERIFIED	SUFFICIENT	SUFFICIENT
Battery	VERIFIED	INSUFFICIENT	INSUFFICIENT

PHASE 4 : *Ergonomic analysis of the task and definition of the optimal postural sequence*
Observing the Digital Mock Up of the engine compartment of the vehicle it is possible to notice that there are two main access directions to the battery system: **frontal** access and **lateral** access (figure 9).

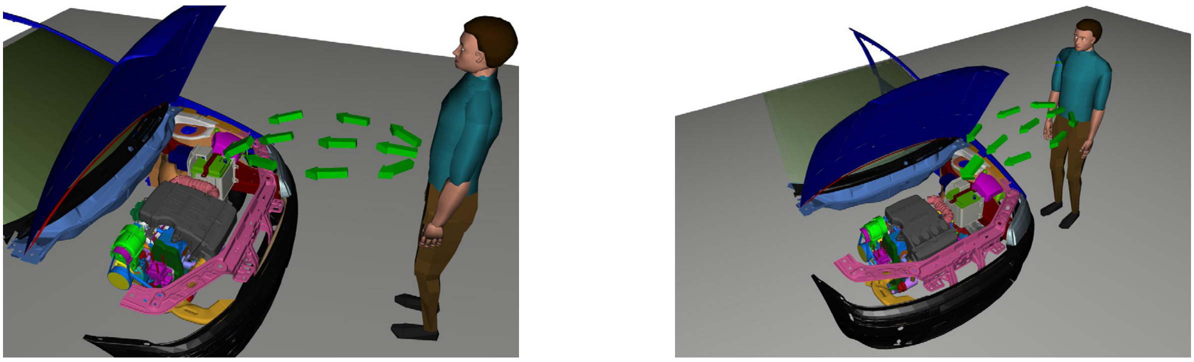

Figure 9. Main access direction to the battery system (frontal and lateral)

The ergonomic study has been performed considering, for each elementary operation of the selected disassembly sequence, two *critical postures* belonging to two different classes: 1) the class of frontal postures and 2) the class of lateral postures. The definition of the optimal postural disassembly sequence has been executed according to the following hypotheses: the elementary disassembly operations can't be performed at the same time; it has been used a 50° percentile digital human model. The index I_1, I_2 and I_3 have been calculated ignoring the reduction of the strengths acting on the human

model due to the fact that during some tasks the human puts an hand on the vehicle. For this reason the postural analysis has been performed considering conditions more onerous than real (*worst case*).
Table 2 synthesizes the results of the EDIVE procedure and indicates the **optimal postural disassembly sequence.**

Table 2. Results of ergonomic analysis

TASKS	POSTURE	I_1	I_2	I_3	PEI	OPTIMAL SEQUENCE
a) Opening of the positive pole's protection	Frontal	0,45	0,75	0,42	**1,80**	**Frontal**
	Lateral	0,47	0,75	1	**2,63**	
b) Removal of the bracket's right screw	Frontal	0,61	0,75	0,86	**2,58**	**Lateral**
	Lateral	0,45	0,75	0,86	**2,42**	
c) Removal of the bracket's left screw	Frontal	0,62	1	1	**3,04**	**Lateral**
	Lateral	0,57	0,75	1	**2,73**	
d) Lifting of the bracket	Frontal	0,46	0,75	1	**2,02**	**Frontal**
	Lateral	0,49	0,75	1	**2,04**	
e) Removal of the negative pole's terminal	Frontal	0,45	1	1	**2,87**	**Lateral**
	Lateral	0,47	0,75	1	**2,64**	
f) Removal of the negative pole's terminal	Frontal	0,58	0,5	1	**2,5**	**Frontal**
	Lateral	0,43	0,75	1	**2,6**	
g) Lifting of the battery	Frontal	0,98	0,75	1	**3,15**	**Frontal**
	Lateral	1,02	1	1	**3,44**	

Figure 10 shows PEI variation respectively for Frontal, Lateral and Optimal sequences.

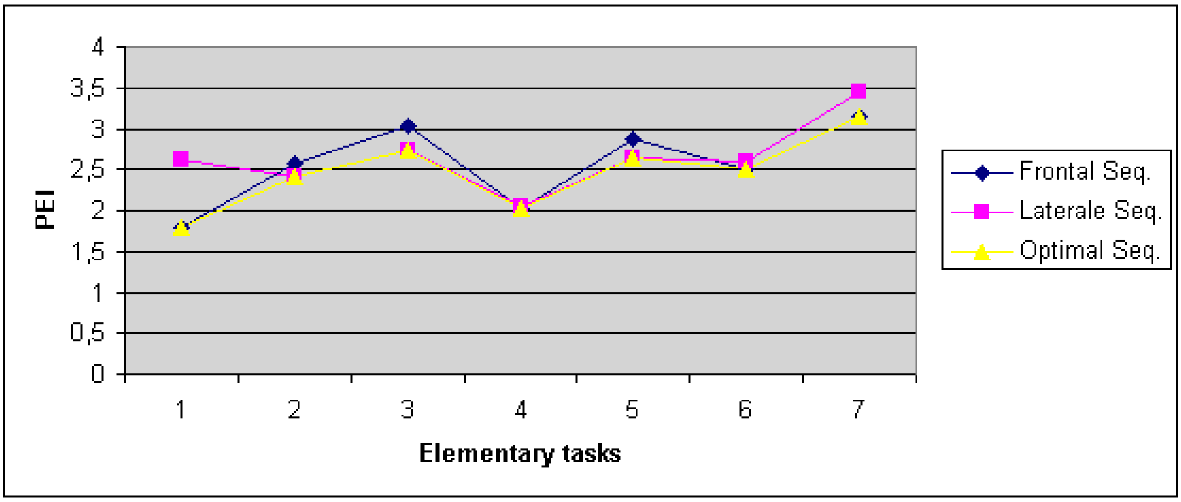

Figure 10. PEI variation for Frontal, Lateral and Optimal sequences

Notice that in task (g) the lateral posture can't be considered because it exceeds NIOSH limit *(I_1 >1)* and PEI value for frontal posture is close to the maximum (3,42). In order to improve the ergonomics of this task could be used an auto lift (figure 11) that allows the human assuming a more comfortable posture (figure 12) and, consequently, allows the reducing of PEI value to 2,26.

7. Conclusions and further works

EDIVE methodology represents an innovative approach to design for maintainability based on the integration between 3D parametric CAD systems, DMU tools, ergonomic tools and digital human models.

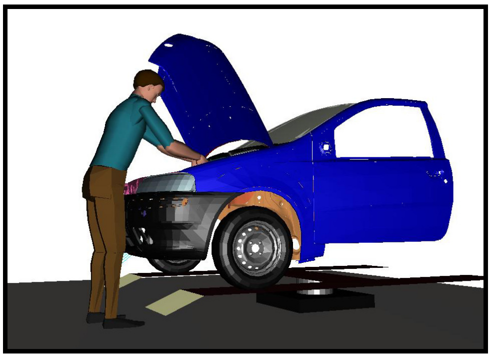

Figure 11. Using an auto lift to improve posture

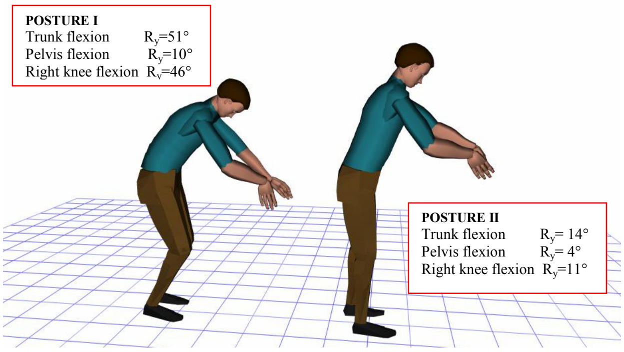

Figure 12. Comparing postures

The analyzed case study, even if quite simple, emphasize the potentialities of the procedure in relation to accessibility and manipulability analysis of component parts to be maintained and to ergonomic studies of maintenance activities.

Nevertheless, in the application related to the battery system there are some restrictive hypotheses that could be removed. In particular, for the simulation it has been used a 50° percentile digital human male. Further application of the procedure will foresee the use of models characterized by different anthropometric measurement, from 1° to 99° percentile, in order to establish if the same task can be executed by operators of different size. Furthermore, also the *worst case* hypothesis should be removed evaluating the reduction of the strengths acting on the human model due to the fact that during some tasks the human put one hand on the vehicle.

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Ing. Giuseppe Di Gironimo
University of Naples Federico II
Dipartimento di Progettazione e Gestione Industriale
P.le Tecchio, 80 – 80125 Naples, Italy
Telephone: +39 081 7682593, Telefax :+39 081 7682466
E-mail: giuseppe.digironimo@unina.it