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A REVERSE ENGINEERING APPROACH TO ENHANCE MACHINERY DESIGN FOR SAFETY

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1. Introduction

The growing awareness of the importance of safety in the agriculture and forestry fields has been characterizing this sector both from equipment manufacturers and from users point of view. This is mainly due to the latest developments of legislation and standards in the sector, concerning occupational safety and machine safety. Beside this situation, it has to be underlined the fact that difficulties related with the implementation of safety measures are numerous, in particular for small and medium sized companies (SMEs), which can hardly afford additional costs for the compliance with safety requirements. SMEs represent more than the 80% of enterprises operating in the agricultural sector in Italy, and most of them are even run by family members. Another phenomenon has to be stressed: in Italy there is a large number of part-time workers, who are involved in agricultural activities in their spare time. This kind of non-professional users of agricultural machinery and equipment are not officially registered as farmers, avoiding in this way to fall under the scope of the above mentioned legislations. In this ambit, also the fact that a large number of tractors used nowadays is very old (40% of them are more than 30 years old), and thus non in conformity with latest safety issues, makes the situation even worse. Most of serious accidents occur when using a tractor which is not in conformity with safety protection requisites, especially when the roll-over protective structure (ROPS) was not installed, or it was disabled in order to carry out some particular works (e.g. in vineyards). A large effort has been made by public authorities with the aim of reducing at minimum level this phenomenon, but some hindrances exist because of the age of the obsolescence of a large number of tractors nowadays used: to adapt them to safety requisites might be very difficult due to both the costs farmers have to bear, and the strict technical requisites they have to be in compliance with when installing and using these protective systems.

A national working group, led by the former Institute for Occupational Safety and Prevention (now belonging to INAIL, the Italian Workers' Compensation Authority) has been working on providing technical guidelines, of a legal value, which provide technical information on how to adapt tractors with ROPSs. Nevertheless, a difficulty emerged concerning narrow-track tractors, which are used mainly in works where dimensions are smaller than usual (both in height, and in width), such as in vineyards, glasshouses, orchard, etc. The most common ROPSs for this kind of tractors are two posts front mounted foldable structures: they can be folded down only for tractor storage or maintenance (as formally specified also in users’ manuals provided by manufacturers), and always kept upright up the rest of the time the tractor is used. Stating the high percentage of cases of non correct use of this type of ROPSs, a research work was carried out in order to design a non foldable ROPS for narrow-track tractors, which provides rollover protection all the time without making agricultural works more difficult. For this purpose, a reverse engineering methodology was adapted to design for safety traditional procedures: following the methodology proposed by [Wood and Otto 1998] both bottom-up and top-down approaches were combined. As a matter of fact, a large research work was carried out in last three years, including a deeper analysis of the technical system and the users' behaviour [Fargnoli et al. 2010], as well as several case studies were performed in collaboration with farmers/users, before validating results obtained and make them available for both farmers and manufacturers. In this paper the whole framework of the methodological approach and utmost results are presented. More in details, in section 2 the general background is described; thus in section 3 the research approach is presented, and its application is shown in section 4. Discussion of results and conclusion are summarized in section 5.

2. General background

In last years standards and regulations concerning occupational safety have become increasingly severe, following the action of the European Union, aimed at making the framework of safety requisites more and more adequate to social issues of our society. Nevertheless, in EU countries the number of accidents and victims has not significantly decreased. According to official statistics, the situation is particularly critical for small and medium sized enterprises, which often need a very laborious effort to deal with safety regulations due to the lack of resources (in terms of money, competences and know-how). In such a context, agriculture sector certainly seems to be one of the most affected by this situation, especially taking into account the occurrence of serious injuries and fatalities related with the use of machinery and equipment.

2.1 The relevance of the problem

The utmost reports concerning the occurrence of occupational accidents in the sector of agriculture show that the problem is very relevant in Italy both considering its absolute value, as well as taking into account accidents which have occurred in agricultural activities compared to sectors of other activities. On the basis of data published by INAIL, in Table 1 the comparison of accidents which occurred in agriculture and industry sectors is shown [INAIL 2011].

Table 1. Official statistics on occupational accidents

	January – September 2010		January – September 2011	
Sector	**Total**	**Fatalities**	**Total**	**Fatalities**
Agriculture	38.081	85 (0,22 %)	36.200	89 (0,24 %)
Industry	210.160	307 (0,14 %)	196.000	308 (0,15 %)

A deeper analysis of these data shows that in agriculture also the number of permanent injuries is quite large (about 11% of total) and the most dangerous activities (considering the number of permanent injuries and fatalities which occurred) are the ones which involve the use of machines and mechanical equipments, and in particular the use of tractors. Moreover, if we consider that since 1993 in Italy the Compensation Authority does not include in official statistics accidents occurred to self-employed workers, the real number of accidents registered taking into account reports of both police departments and inspectors of the national health service is even larger. Just considering the period January-November 2011, according to the special observatory on the so-called "green death" managed by the ASAPS (Association for Traffic Safety, connected with Italian Policy) 391 accidents involving tractors occurred, with 179 fatalities and 265 people seriously injured. In addition, from the statistics provided by the special observatory of INAIL, which collects all the accidents involving tractors during field activities, one can observe that a substantial part of them are due to tractor roll over and that the trend from 2008 until today is quite constant, as it is shown in Table 2.
On these considerations, it is clear that still additional effort has to be made in order to make the use of agricultural machinery much safer.

Table 2. Fatal accidents involving tractors ((*)until November 2011)

Year	Fatal accidents with tractors	Fatal accident caused by tractors' roll-over (percentage)
2008	153	114 (74,5 %)
2009	146	123 (84,2 %)
2010	135	116 (85,9 %)
2011(*)	133	93 (69,9 %)

2.2 Mandatory requirements

The analysis of data concerning accidents in the agricultural sector brought to light the importance of problems related with the use of tractors. For this reason safety requisites of laws and regulations affecting tractors need to be taken into account. First of all, the so-called "Tractor Directive" (Directive 2003/37/EC) and the OECD Standard Codes, which set common rules (and harmonized procedures) for the Official Testing of Agricultural and Forestry Tractors in OECD countries. Then, requirements of Occupational Health and Safety Law, which takes into account the safety procedures that should be followed during all working activities, the requisites which have to satisfy the Risk Assessment Report, the minimum safety and health requirements for the use of work equipment by workers at work, and for maintenance operations of working equipment. In addition, the Machinery Directive (Directive 2006/42/EC) has to be considered, since, until the process of updating the Tractors Directive is completed, also tractors fall into its scope for the risks not dealt with by Directive 2003/37/EC. Thus manufacturers, for these risks, have to verify the conformity of the tractor with the Essential Health and Safety Requirements (EHSRs) listed in Annex I, following the same process as the one requested for traditional machines. It has to be stressed that these additional requisites for both machine producers and users, as well as the latest issues for the conformity assessment procedures represent an improvement, which makes the safety level of operators higher. At the same time, due to the specific characteristics of the agricultural sector the compliance with new safety requirements results in being more difficult.

2.3 Engineering issues

The large variety of activities usually carried out by companies, the use of obsolete machines and equipments, as well as the continuous change of workplaces are by themselves factors which make the management of agricultural activities more difficult to deal with, as observed by many Authors (e.g. [Myers et al. 2009]). From engineering point of view, this goal can be achieved taking into account both manufacturers and users perspectives. As a matter of fact, on one hand, manufacturers of agricultural machinery have to deal with the obligation of putting on the market products which satisfy mandatory requirements of standards and regulations, and the need to care about the company bottom-line. On the other hand, users need to adapt tractors to new recent requirements (e.g. install seat-belts and ROPSs) and modify their habits while using them (e.g. do not remove protective systems in order to make their work faster or easier). As mentioned above, there exist technical guidelines, of a legal value, which provide technical information on how to adapt tractors with ROPSs. Nevertheless, a difficulty emerged concerning narrow-track tractors, which are used mainly in works where dimensions are smaller than usual (both in height, and in width), such as in vineyards, glasshouses, orchard, etc. Most common ROPSs for this kind of tractors are foldable: they can be folded down only when performing tractor's storage or maintenance operations, and always kept upright up the rest of the time the tractor is used. This solution is certainly the simplest from manufacturers' point of view, since it requires low effort both in designing and testing, in terms of resources (materials, manufacturing processes), as well as in adapting to connection points for installing in accordance with OECD Code 6. In figure 1 a typical foldable ROPS for narrow track tractors is shown.

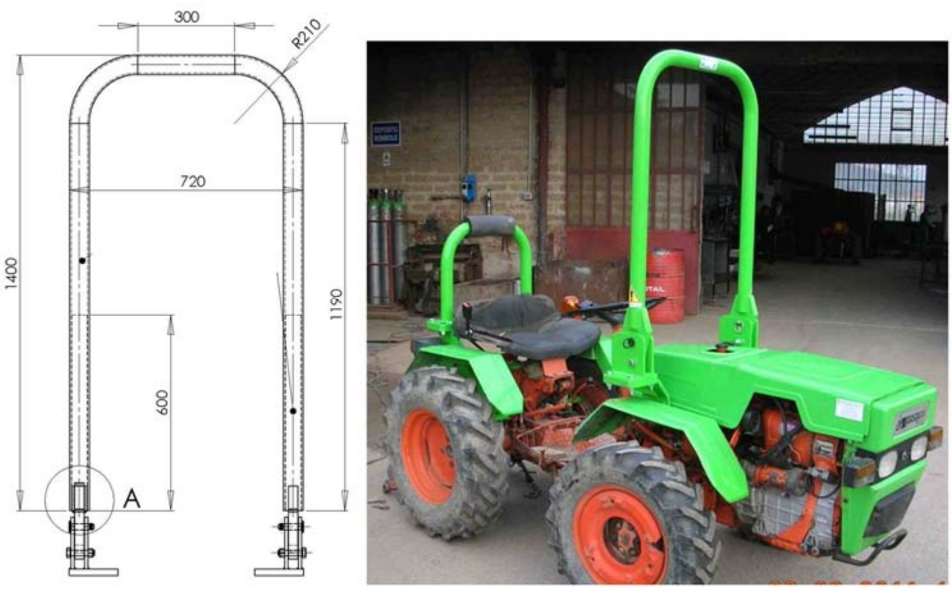

Figure 1. Example of two posts front mounted foldable ROPSs

On the contrary, examples of non foldable ROPSs for narrow-track tractors are not so numerous and mainly concern new models or prototypes, as the one presented by [FACMA 2011]. But these solutions require to make considerable modifications on the tractor structure, so that they cannot be adapted for already existing products, neither can be useful for manufacturers that cannot afford to change their production. In conclusions, on one hand, there is the need to update already used tractors adapting them to new safety requirements, as well as modify the production processes of manufacturers so that they can provide already updated products. On the other hand, stating the high percentage of cases of non correct use of traditional foldable ROPSs, new solutions need to be found taking into account "the intended use and any reasonably foreseeable misuse thereof" of the tractor, as required by EHSRs of machinery directive (Annex I), which specifies that: 'intended use' is "the use of machinery in accordance with the information provided in the instructions for use; 'reasonably foreseeable misuse' means the use of machinery in a way not intended in the instructions for use, but which may result from readily predictable human behaviour". On these considerations, the need to find a solution for providing a non foldable ROPS for adapting already existing narrow-track tractors, which enables rollover protection all the time without making agricultural works more difficult, is necessary. With this aim in mind, the development of a specific design procedure, which combines traditional design for safety issues (i.e. a top-down approach) with reverse engineering (bottom-up approach) was investigated.

3. Methodology

The starting point of the methodology developed for the re-design of a non foldable ROPS for narrow-track tractors is the reverse engineering approach proposed by [Wood and Otto 1998] for a reverse engineering and redesign methodology. This general framework is made of several main steps, which shift from reverse engineering to redesign options:

- predict product behaviour;
- disassembly/analyze product components;
- analyze product functions;
- develop solution principles;
- analyze compatibility between solution principles and associated sub-functions;
- develop a mathematical model of the product, and solve the product model;
- create evolved product variants;
- redesign product sub-systems, and redesign the product.

This general scheme was adapted to a more dynamic procedure, integrating the reverse engineering approach within a general Design for Safety procedure (as the one proposed by [Pighini et al. 2001]). In this way reverse engineering can be used as a design tool as the other traditional design methods. The general scheme of such an approach is represented in figure 2 (Design for Safety Reverse Engineering process). More in details, phases 1 (preliminary analysis) and 2 (concrete experience) correspond to "task analysis", phase 3 (modelling) to "conceptual design", and phase 4 (validation) to "embodiment design" and "testing".

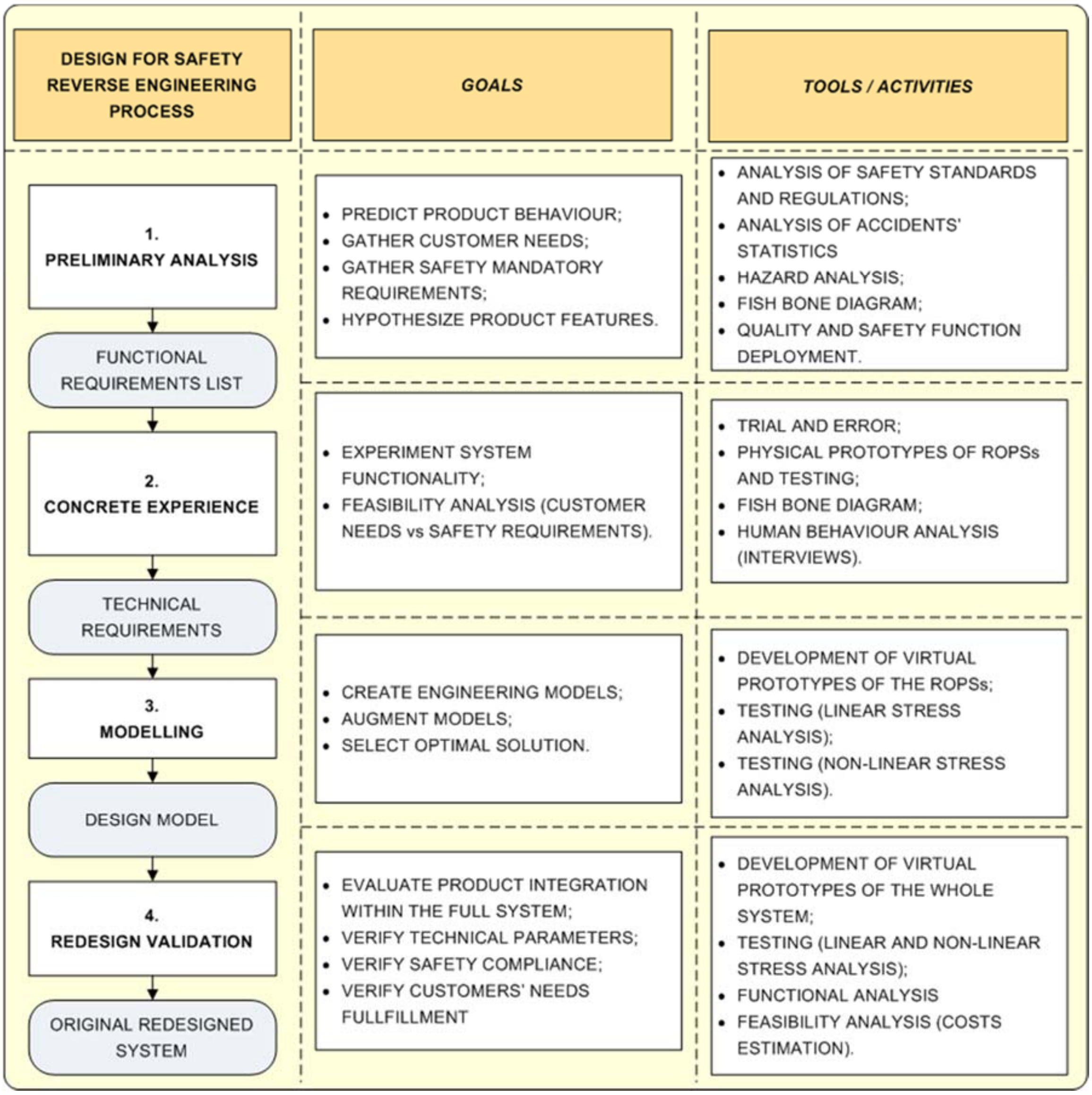

Figure 2. General framework of the methodology

The framework shown in figure 2 represents also the activities carried out in the ambit of the present research work and design tools used: it has to be said that as far as the use of the Quality Function Deployment (QFD) method [Akao 1991] is concerned, only first phase (product planning) was applied.

4. Case study

The proposed methodology was developed for the design a novel non foldable ROPS for a narrow-track tractor. More in details, the research work was carried out as follows.

4.1 Preliminary analysis

The analysis of the design task started considering both safety requirements (i.e. legislation requirements of the above mentioned directives), and the hazard analysis related to the use of the tractor. The latter aspect was performed by means of the use of the Preliminary Hazard Analysis (PHA): this method [Clifton 2005] was applied to the full system (i.e. a narrow-track tractor), to investigate most significant risks of the machine, providing a qualitative estimation of them. In such a context, also statistics and information concerning the occurrence of accidents and related causes were taken into account. The roll-over of the tractor resulted in being the most relevant risk for the operator safety. This aspect was further investigated by analyzing the use of the traditional foldable ROPS during all phases of the tractor usage:

- access to the driving position;
- mechanical coupling between tractor and towed equipment;
- use in the field;
- maintenance operations, and parking.

The Fish Bone Diagram (FBD) method [Clifton 2005], allowed us to draw up the main features of the non correct use of this protection system (an excerpt is shown in figure 3).

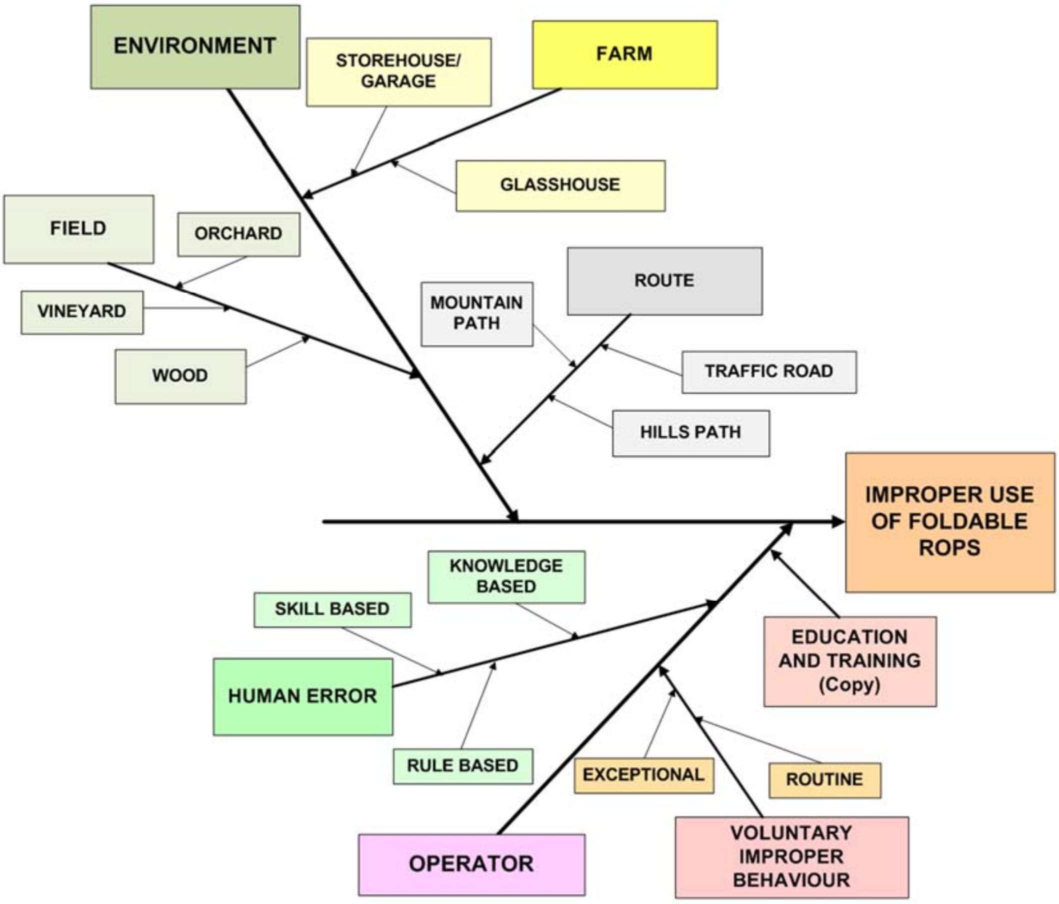

Figure 3. Excerpt of the fish bone diagram

The definition of functional requirements was obtained using the QFD method: in this case a specific Safety-QFD (Quality and Safety Function Deployment) was developed with the aim of combining most mandatory technical requisites together with the users' needs. The aspects which resulted in having higher relative importance in the QSFD (Quality and Safety Function Deployment), relationship matrix as far as mandatory requirements are concerned, are the followings:

- Clearance zone - in case of crash: no parts of the ROPS shall enter in the clearance zone round the driving seat; the clearance zone shall not be outside the protection of the protective structure;
- Mechanical resistance - the ROPS shall be able to absorb a specific amount of plastic energy proportional to the unladen mass of tractor for all the longitudinal loads required by the test and it shall be able to withstand a crushing force equal to 20 times the tractor unladen mass.
- Ergonomics (operating space) – the ROPS shall guarantee an operating space, i.e. the minimum volume of space between any fixed parts of the structure which is available to the driver of the tractor to enable him to operate the tractor from his seat in any way required with complete safety.
- Ergonomics (vision) - both in road traffic and in farm and forest use, the driver shall have an adequate field of vision, under all the usual conditions pertaining to highway use and to work undertaken in fields and forests (the field of vision is considered adequate when the driver has, as far as possible, a view of part of each front wheel).

From the customers' point of view, the most relevant aspect concerned the usability of the tractor even in narrow spaces. As a matter of fact, it has to be noted that the use of narrow-track tractors is largely widespread because of their reduced dimensions which allow farmers to use them for working in greenhouses, between trees and rows. In spite of this, such particular types works usually imply an use of the tractor which is not suitable for using two posts ROPS unless it is foldable.

4.2 Concrete experience

Collaboration with users was fundamental in order to define the operator's behaviour in the different situations. From interviews it emerged that, even though the folded configuration of the ROPS should be used only for tractor storage, it is common practice to fold it while working. Nevertheless, once the operator set the ROPS in its folded configuration, he never put it in safe configuration even during road transport, where the height of the ROPS does not represents a limit at all. The reasons for this behaviour could be found in the weight of the ROPS. In fact, even if the folding operation is achieved by simply removing pins by hand without the use of any specific tool, the ROPS weight is such that it is not possible for a single operator to handle it for replacing in its safe configuration. The easiness of folding operation makes it possible that operators fold the ROPS even during field operation, completely by-passing a fundamental protection device. For these reasons it was decided to focus our attention on the development of a non foldable ROPS.

4.3 Modelling

This phase was put into practice mainly using a "trial and error" approach: a series of case studies were carried out in collaboration with different companies, proceeding step by step (e.g. information concerning one of these studies can be found in [OSHA 2011]). In other words, for each type of tractor used by the company, already equipped with a front mounted ROPS or not, a prototype of ROPS was designed, tested and then consecutive improvements were implemented. Differently from the model proposed by [Wood and Otto 1998], it was indeed in this phase that the process of reverse engineering was applied, with the aim of obtaining digital representations of the physical prototypes that were produced in the earlier stages of our product development process. Experiences collected during the above mentioned activities allowed us to define technical requirements for developing a novel model of non foldable ROPS, called CROPS (Compact Roll-Over Protective Structure). In particular a specific study was carried out on the analysis of the clearance zone characteristics in order to be in compliance with the standard ANSI/ASAE S478:1995 concerning "Roll-Over Protective Structures (ROPS) for Compact Utility Tractors requirements" (in figure 4 the specifications related to the clearance zone are shown).
Starting from the standard requirements, the reverse engineering approach was applied for acquiring and modelling the main tractor features (e.g. location of seat, steering wheel, mountings connection points, etc.), and to correctly reproduce on it the aforementioned clearance zone. Then, the CROPS was shaped in its upper portion according to the profile of the clearance zone and in its lower portion

in such a way to smoothly reach the mountings connection points. In figure 5 an example of the CROPS obtained with this reverse engineering and redesign methodology is shown.

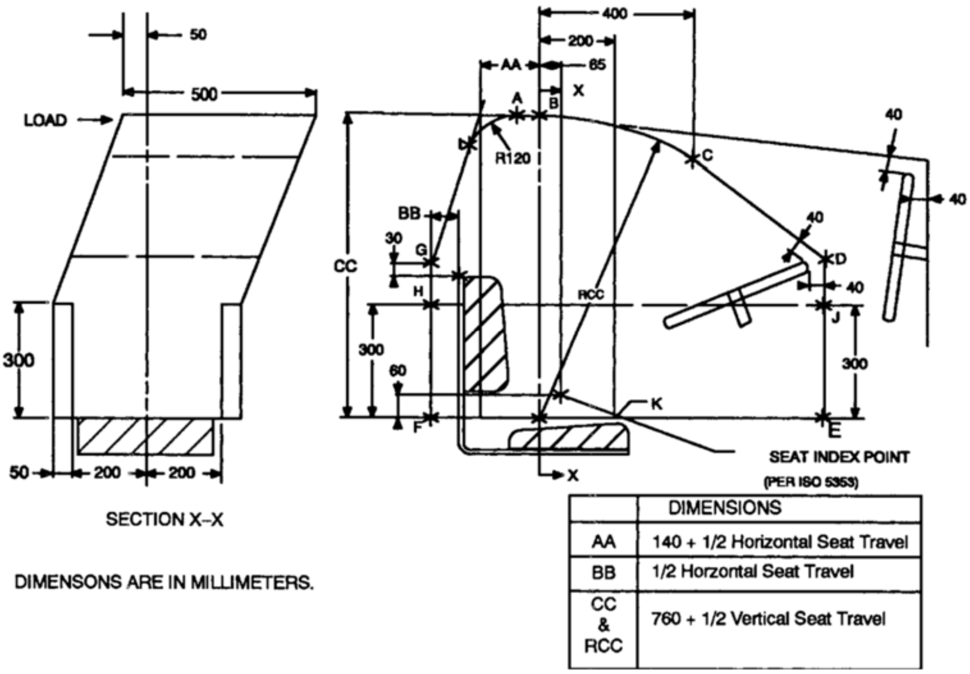

Figure 4. Clearance zone according to [ANSI/ASAE S478:1995] standard

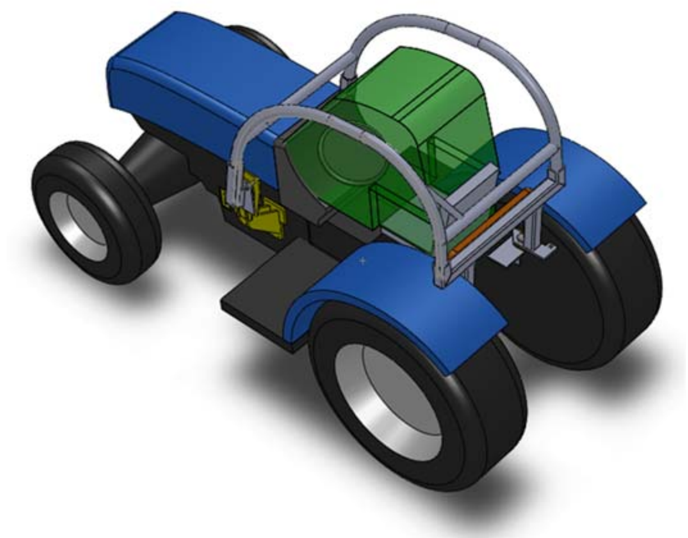

Figure 5. CROPS reverse engineering: model of the whole system

4.4 Redesign validation

The integration of the CROPS with the structure of the tractor was analysed: in particular, in order to make it usable for most models of tractors already on the market both already equipped with a front mounted two posts ROPS and not equipped with a ROPS at all. On one hand, for the first type of tractors examined, connection points correspond to the bolts and pin joint of the foldable portion of the most common two posts protective structures have been considered as mountings also suitable for the CROPS. Several models of narrow-track tractors were taken into account, as the one in [OSHA 2011]. On the other hand, for tractors not yet equipped with a ROPS (including old tractors already on the market) a preliminary study was developed in order to identify suitable (in term of strength) parts/points of the tractor where to apply CROPS mountings. In both cases, the final model was developed in details (embodiment design), verifying shape and dimensions of all components throughout the use of the following tools:

1. Finite Element Analysis (FEA) of CROPS according to [ANSI/ASAE S478:1995] standard;
2. Computer Aided Design (CAD), for the optimization of shape and dimensions in accordance with in-field tractor handling analysis, ergonomic principles and visibility.

In figure 6 the contour diagrams of side and longitudinal tests developed on CROPS by means of FEA are reported.

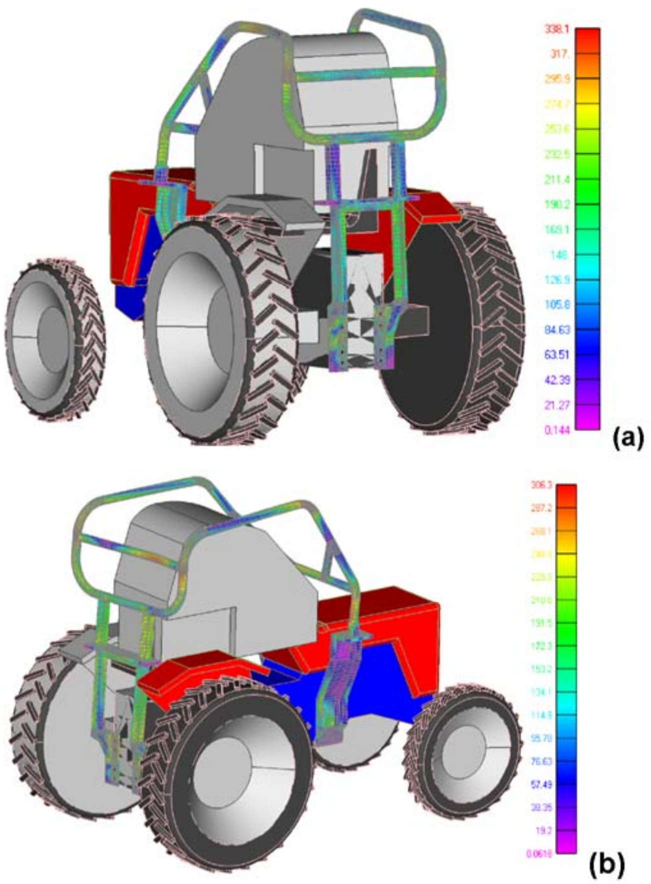

Figure 6. CROPS's FEA contour diagrams: (a) side test; (b) longitudinal test

The finite elements analysis is necessary in order to verify the fulfilment of most important requisites emerged from QSFD method reported in sub-section 4.1:

- verify the strength of the protective structure;
- verify that any part of it has not entered the clearance zone round the driving seat;
- verify that the clearance zone is not outside the protection of the protective structure.

Once verified the aforementioned requirements the CROPS is shape optimized with reference to previous point 2. It is important to note that any modification of CROPS' shape or dimensions at this stage might affect its structural strength. Thus, it is necessary to perform another finite element analysis to recursively verify the compliance with the above point 1.

5. Conclusions

The use of the Reverse Engineering approach as a tool for augmenting the product design and development process oriented to the improvement of the safety level of the narrow-track tractors resulted in being very useful. As underlined by several Authors (e.g. in [Mengoni et al. 2007], [Varady et al. 1997]), such an approach can be used in early design stages, allowing designers to draw up virtual prototypes of physical ones, which can be further analyzed to obtain detailed layouts of the product. For these reasons, it can be successfully applied in all cases where a redesign is needed, starting from already existing systems, especially for the purposes of their adaptation to technical progress. The combination of reverse engineering and design for safety approaches allowed us to punctually verify all design options, while carrying out the product development activities. In practical, it allowed us to define an indeed novel solution, i.e. a non-foldable roll over protective structure for narrow-track wheeled tractors with the aim of reducing the overall tractor height in order to permit the safe use of tractor during field operations. Data and information for the reverse engineering process could be collected thanks to several collaborations with farmers and users. This brought to light that in general efficiency of the Reverse Engineering Approach (REA) decreases with the complexity of the system. As also observed by [Urbanic and El Maraghy 2009], most effective results can be achieved when a component/part of a technical system has to be designed, as in the case of ROPS/CROPS systems. At the moment several prototypes of CROPS were realized and they have been tested in the field, in particular in collaboration with farmers operating in the hazelnut sector. First feedback from these users can be considered very positive, since the functionality of the tractors with CROPSs is higher than the one of tractors equipped with traditional ROPSs. As far as costs are concerned, a detailed analysis could not be carried out yet, since only several prototypes were prepared so far. Anyway the cost of these handcrafts is comparable with the cost for realizing a two posts front mounted ROPS. Results obtained will be implemented in official national guidelines for both manufacturers and users for adapting their tractors in conformity with safety mandatory requirements. At the same time further work is foreseen to validate the CROPS for a larger number of different tractors.

References

Clifton, A. E., "Hazard Analysis Techniques for System Safety", John Wiley & Sons, NY, 2005.

FACMA, http://www.facma.it/dettaglioNews.asp?IDNews=27 (last access in November 2011)

Fargnoli, M., Laurendi, V., Tronci, M., "Design for Safety in Agricultural Machinery", Proceedings of DESIGN 2004, Marjanovic D., Storga M., Pavkovic N., Bojcetic N. (Ed.), FMENA, Zagreb, 2010, pp. 701-710.

Mengoni, M., Germani, M., Mandorli, F., "Reverse engineering of aesthetic products: use of hand-made sketches for the design intent formalization", Journal of Engineering Design, Vol. 18, N. 5, 2007, pp. 413-435.

Myers, M. L., Cole, H. P., Westneat, C., "Injury severity related to overturn characteristics of tractors", Journal of Safety Research, Vol. 40, 2009, pp.165:170.

OSHA, http://osha.europa.eu/data/case-studies/crops-compact-roll-over-protective-structure (acc. Nov. 2011)

Otto, K. N., Wood, K. L., "Product evolution: a reverse engineering and redesign methodology", Research in Engineering Design, Vol. 10, N. 4, 1998, pp. 226–243.

Pighini, U., Fargnoli, M., Geraci, D., "A design procedure for the safety of mechanical systems", Proceedings of 13th International Conference on Engineering Design - ICED01, Glasgow, C586/052, 2001, pp.11-18.

Urbanic, R. J., ElMaraghy, W., "A design recovery framework for mechanical components", Journal of Engineering Design, Vol. 20, N. 2, 2009, pp.195-215.

Varady, T., Martin, R., Cox, J., "Reverse engineering of geometric models – an introduction", Computer Aided Design, Vol. 29,1997, pp. 255–269.

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